Combating User-Behaviour Variations with Robustness in Building Design

A Study of Two Existing German Office Buildings

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Dedicated to my parents.

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Declaration of Authorship

I confirm that this Master's thesis is my own work and I have documented all the sources and materials used. This thesis was not previously presented to another exam board and has not been published

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02.10.2018, Stuttgart

Erklärung

Ich versichere hiermit, dass ich die von mir eingereichte Abschlussarbeit selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

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Abstract

Motivation: In the current design practice, many assumptions about the building operation are considered by the complex dynamic computer simulations to estimate building performance. But occupant behaviour is one of the most fluctuating boundary conditions that has a significant influence on a building's performance. A holistic solution to tackle the regularly expected variations in occupant behaviour and, in turn, reduce Performance Gap is to design robust buildings. Robustness in building performance is the ability of the building to withstand variations without significantly affecting its performance in terms of energy consumption or thermal comfort. In simpler terms, robustness is the stability and reliability of a building's performance. An evaluation of robustness of constructed buildings can provide insights about the practical implications of their design decisions and support the theoretical studies of building robustness and robust optimization.

Methodology: An uncertainty analysis of variable user behaviour of two constructed office buildings in Germany was done to compare their performance robustness in terms of energy consumption as well as thermal comfort. A Post Occupancy evaluation and a behaviour analysis was conducted. The offices of four occupants in each building were monitored and their interaction with the building was studied.

Conclusion: The observed behaviour of the occupants of these two buildings does not match the assumed behaviour used for BP simulations. This can lead to inaccurate energy demand consumption predictions. The behaviour analysis found that occupant behaviour is inconsistent and unpredictable. For example, the measured CO2 levels when windows were opened ranged from 400-2000 ppm; Automatic shading controls were often overridden by 80% of the sample group; Decentralized mechanical ventilation systems were under used because the occupants may not know how to operate it.

The theoretical robustness analysis found that the more robust building had smaller windows, higher thermal mass, automated shading systems and slightly higher room volume had a lower overall heating and cooling energy demand. The parameters that most influence energy demand (amongst those than can be altered by an occupant) are: thermostat set point temperatures, shading, CO2 threshold and number of occupants. It was found that a two degree increase in the heating setpoint could double the heating energy demand. In conclusion, the findings indicate that a more robust building can perform better in combating the regular variations caused by occupants than a sensitive one.

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Abbreviations

POE – Post Occupancy Evaluation

BPS – Building Performance Simulation

WUH – Weighted Under-heating Hours

WOH – Weighted Overheating Hours

Ppm – Parts per Million

Kh – Kelvin hour

1 Introduction

1.1 Motivation

"Observations throughout the world make it clear that climate change is occurring, and rigorous scientific research demonstrates that the greenhouse gases emitted by human activities are the primary driver." (NASA, a statement from 18 scientific associations 2009).

Globally, buildings account for 30% of the total greenhouse gas emission (Levine 2007). The power production industry reduced carbon emissions by 17% since 2012, while the building sector increased by 5% in the UK (Committee on Climate Change UK 2016).

An important part of successfully designing energy efficient buildings is their accurate energy performance predictions. Findings from studies such as PROBE (Post Occupancy Review of Buildings and their Engineering) found that the actual consumption was often twice the predicted among the 23 buildings featured as ‘exemplar designs’ in the building services journal (Orme 2014). While a building may satisfy the building regulations, it may not perform as well as predicted. This gap in the prediction and actual performance is known as performance gap (Robinson, Taylor, Foxon 2015). Accurate performance predictions are also important in making zero carbon as well as near-zero carbon building design work practically (Kotireddy, Hoes, Henson 2017). This, consequently, can facilitate carbon emission reduction goals.

Why is robustness needed?

In the current design practice, many assumptions about the building operation are considered by the complex dynamic computer simulations to estimate building performance (Kotireddy, Hoes, Henson 2017). This is usually done either to simplify the calculations, reduce computation efforts and time; or it is simply due to lack of reliable data. The impact of these uncertainties is higher and more critical in low/net-zero energy buildings (Maler, Krzaczek, Tejchman 2009). There are many uncertainties that cause performance gap and they cannot be accurately predicted. User behaviour, automated system malfunctioning, climate change are some examples. These are rarely considered during the design process. One of the most common and ‘certain' uncertainty is user behaviour because humans have individual preferences and thresholds which are hard to generalise. User behaviour also has a great impact on the energy consumption of a building. A ‘wasteful' usage pattern can easily have double the consumption of a ‘conservative' behaviour (Doda 2017). However, “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' (Fabi et Al. 2013). Therefore, it is important to look at causes of discomfort to reduce the changes users make.

Good building performance relies on the efficient behaviour of users. Automation of building systems is done to reduce this dependency since user behaviour is inconsistent. For example: HVAC/ mechanical ventilation to replace window operation, automated shading systems to avoid summer overheating when occupants do not manually close it or are not present, or motion-sensor/ daylight-controlled lighting. In theory, these systems are meant to improve building performance, but malfunctioning and occupants overriding them occur frequently. “Manual override is essential for the high-performance operation of dynamic facades” (Bakker et al. 2014). “the level of automation should be made carefully, taking account of the special qualities of each system without neglecting the individual differences between users. Full automation is not suitable for systems that considerably affect indoor environmental comfort” (Karjalainen 2013). Further uncertainties are added such as system malfunction, incorrect control signals due to insufficient sensors, incorrect/incomplete programming which can annoy occupants and trigger manual override.

A holistic solution to tackle the issue of uncertainty and, in turn, performance gap is to design buildings to withstand these variations instead of trying to make the simulations and boundary condition predictions more accurate, which yet may not remain valid throughout the lifespan of a building. For example, a change in the function of a building, sometime during its lifespan, changes the performance. Performance robustness assessments which take uncertainties into account, should be an integral part of the design decision-making process (Kotireddy, Hoes, Henson 2017). A robust building is one that performs reliably in terms of energy and comfort regardless of variations. Simply put, a building that is less reactive or insensitive to external changes.

The concept of robustness is already in vogue in fields like structural engineering, but the research and practice are not comparably cultivated in the field of building performance and passive design. Although robustness is about realistic building performance, not much literature exists on the performance robustness of constructed buildings. An evaluation of robustness of constructed buildings can provide insights about the practical implications of their design decisions and support the theoretical studies of building robustness and robust optimization.

Consequently, this thesis conducts a case study to assess the 'performance robustness' of two constructed office buildings in Germany. Two are studied for comparison since there are no established standard metrics to measure performance robustness. They were designed for having a low net- as well as source- energy consumption. Furthermore, behaviour patterns are studied by surveying, interviewing and monitoring the current users in order to understand, justify and emphasize the necessity for performance robustness in building. The thermal energy simulation details from the designers are compared with the observed behaviour. A parametric analysis to compare the performance robustness of the buildings. A second analysis is done to identify and highlight the parameters that critically affect the performance of these particular buildings and these parameters should be given importance while designing for a similar climate.

1.2 Hypothesis

Robust optimization in building design can help tackle the inevitable variations in the boundary conditions caused by users, and in turn, reduce the performance gap.

Complete or partial Automation alone without passive building design measures may not be the solution to the 'problem' of varying user behaviour.

1.3 Structure

This study investigates the robustness of two office buildings which are in use and studies the effect of user-behaviour variations on building performance. To establish the necessity and importance of designing buildings which are robust against behaviour variations, the behaviour of the users of both buildings is studied. This is done to find, understand and emphasize the existence of user behaviour variations. Studying user behaviour is an extended part of the Post Occupancy Evaluation (POE) and is required to find out the perceived satisfaction of users. Hence, the thesis is divided into the following parts:

I. ***Literature study***: This chapter explains the concepts that are central to the thesis such as 'Post Occupancy Evaluation', 'Performance Gap', 'Robustness', and 'robust optimization in building design'; as well as the current research literature that exists on them.

II. ***Post-occupancy evaluation***: This chapter studies both the buildings in detail and outlines the similarities, differences in the architecture, planning, climate and energy concept. The building's performance and the perceived satisfaction of the occupants are investigated. The findings and consequential recommendations from the interviews, anonymous surveys and monitoring are outlined.

III. ***User-behaviour analysis***: This chapter studies the user behaviour by interviewing and monitoring some occupants' offices and by an anonymous survey in an effort to derive a realistic understanding of how they operate the different systems they have access to such as windows, shading, heating etc. The consistency of the behaviour and general thresholds and personal preferences are examined and compared with the conventional building energy simulations methods. This emphasizes the importance of correct behavioural assumptions in predicting energy performance accurately, which is a highly important aspect of minimizing the performance gap. These findings also provide the justification for the need for robustness in building design as well as for the values used for the boundary conditions in the sensitivity analysis performed in the next chapter.

IV. ***Robustness analysis***: In this chapter, sensitivity analysis of both the buildings is done by parametrically simulating hundreds of behaviour patterns to find out how they perform and how robust they are in terms of energy consumption and in their ability to provide thermal comfort under the 'worst' behaviours. The validation of both the models is also explained.

V. ***Parameter influence***: The influence of parameters is investigated so that the parameters which have the greatest influence on the performance can be identified. These critical parameters should be given more importance by designers while designing buildings in a similar climate.

VI. ***Discussions & conclusions***: this chapter ties all the parts of the thesis together and discusses, in further depth, the findings of all the chapters with reference to the central hypothesis.

Literature review

1.4 What is Performance Gap in Buildings?

‘Performance Gap’ is the existence of a difference between the predicted energy demand of a building and its actual energy consumption after construction (Robinson et al. 2015). But ‘performance gap’ is not a new concept and it exists in various fields. In the context of employee performance, for example, when the profits are below expected, and the main reason is found to be the underperformance of the employee, it is called Performance Gap. If the machine is not as efficient as it is supposed to be for some reason, it can be said that there is a performance gap. Similarly, a building, which is essentially a complicated machine, can under-perform and that would be called a performance gap. However, unlike a machine, which is manufactured in ideal factory conditions and with identical specifications, a building has many more reasons to deviate from the ideal. A building’s specification changes depending on the climate, aesthetic design, client’s budget, availability of materials etc, which is also more difficult to be executed exactly as specified on site. Never the less, literature study found that even the building featured in the buildings services journal as ‘exemplar designs’ had a measured energy consumption of up to two times the predicted value (Orme 2014).

Modern dynamic energy models are sophisticated tools but are only as good as the input data. The accurate simulation of an occupied building is not very easy because it involves many inputs that may not be known or may have changed in design and not updated in the thermal simulation model. This could be aided with good feedback from existing buildings to give a better understanding of the effects of operation and controls (Austin 2013). A Performance Gap project commenced by the Zero Carbon Hub in the UK in 2013 to aid the achievement of the '2020 Ambition' which entails that 90% of the buildings should perform better than or at least meet their designed performance and recommended that future performance standards should be linked to 'as-built' performance to help fulfil this ambition (Zero Carbon Hub 2014)

The existence of a performance gap may be comprehensible, but its widespread existence can be a problem for lowering our carbon emissions and to making buildings more practically efficient. According to Carbon Trust: Gap can vary within 16% in best practices to five times in worst one (Carbon Trust, 2011). Performance gap in buildings is a widely researched and established topic because it has far more magnitude and common occurrence than it should. According to the Property data survey programme's report only 5% of the surveyed schools performed as intended. "*Of the 59,967 blocks surveyed, 3,039 blocks have all survey records graded A*" (PDSP report 2015), where grade A has been defined as "*Good – Performing as intended and operating efficiently*".

There have been advances in building technology and design to optimize performance and reduce energy consumption. Today it is even possible to create buildings that produce more energy than they consume. This is only possible with advances in the production as well as the demand side. In other words, maximising production and minimising energy consumption. Even with sufficient technical knowledge, the existence of Performance gap is widespread. Investigating the reasons for performance gap and educating the working public about it is vital to reducing it.

1.4.1 Causes of Performance Gap

The literature on the causes of Performance Gap is vast and it shows that Performance gap can be caused due to a variety of reasons. This is because building science is a complicated. It not only involves theoretical expertise but also perfect execution, management and operation involving several entities which need to work together and communicate. The literature consists numerous research exploring the causes and also of many different explanations simplifying and organizing the causes to better illustrate and educate the entities in the related fields, some of which are described here.

The 'three-fold link' is one of the theories which divides the causes of those that can occur in different stages of a building's development – Design, construction and operation, illustrated in Figure 0.1. Recommendations to reduce performance gap are described for these three phases. A building's design must be robust and understandable, without mistakes or omissions of details, so that it can be correctly executed as well as operated when special climate concepts are used. The assumptions made in energy simulation modelling must be as accurate as possible without omitting areas or underestimating loads and behaviours. The construction must be carried out faithful to the drawings and in the case of missing information of designs, they must not be solved without consultation of the designers or energetic considerations of the alternate solution, for example, changes in materials, joining details, etc. The mechanical systems must be monitored and streamline correct functioning ensured after construction. The operation must be as intended by the design and mechanical systems must be regularly checked and maintained for efficiency (Austin 2013).

Two of the four conclusions mentioned by the Zero Carbon Hub in the report highlights the inaccuracy in current building simulation modelling and stresses the importance of conducting tests on completed buildings. It mentions that the simulation inputs "do not truly reflect the features of a completed home, this could significantly contribute to the Performance Gap". They recommend that sensitivity tests must be done to analyse the risks associated with the different potential errors due to assumptions made in the inputs while calculating the energy consumption. On the other side, "Testing of completed dwellings is important to establish the nature and scale of the Performance Gap, both in terms of components and the whole system. While testing of individual products takes place to the

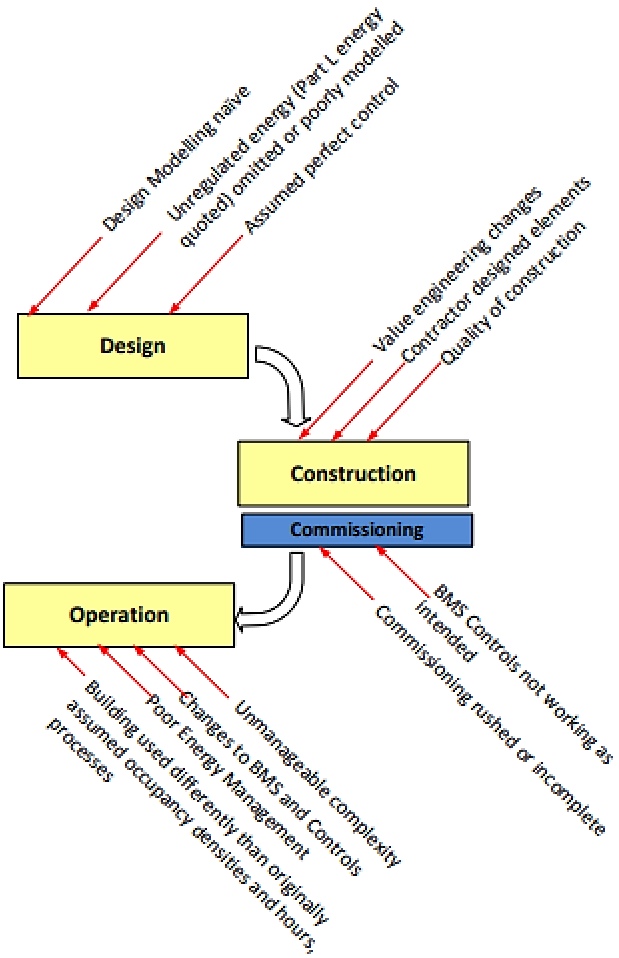


Figure 0.1 Factors affecting Performance Gap (Austin 2013)

relevant British and ISO standards under specified conditions, it is important to understand how products perform on-site in conjunction with one another." (Zero Carbon Hub 2014).

There are many assumptions used for the calculation of building energy and it is almost impossible to avoid them entirely. A dynamic building energy simulation model calculates the various heat gains, through solar heat gains, ventilation gains, internal loads such as people, equipment, heating systems, etc., and parallelly the heat losses through radiation through windows, conduction through walls/ windows/frames, ventilation losses when windows are opened, etc. Natural ventilation is affected by wind direction, speed, internal and external temperatures, etc. These are just some of the factors that affect the complicated simulation which calculates this heat balance for a year in the defined timestep and collectively provides the estimated energy consumption. The simulation only calculates based on approximated inputs due to the many uncertainties that exist in real life. Although the physical aspects of the building such as wall materials, windows and their U-value, can be accurate. Assumptions are made about occupancy, window/ shading/ lighting.

The driving factors of energy use in buildings were identified by the International Energy Agency as:

(1) climate,

(2) building envelope,

(3) building energy and services systems,

(4) indoor design criteria,

(5) building operation and maintenance, and

(6) occupant behaviour.

"There lacks scientific and robust methods to define and model energy-related occupant behaviour in buildings. These behaviours include occupants' interactions with operable windows, lights, blinds, thermostats, and plug-in appliances. The importance of the "human factor" in building performance simulation is evident" (Yan et al. pp 2015)

"Occupant behaviour affects building energy consumption significantly and is a leading source of uncertainty in predicting building energy use" (Hoes et al. 2009) Tests on the occupant behaviour's influence on building energy consumption highlights the importance of understanding behaviour and its effects. For example, the energy saving potential by increasing building insulation depends heavily on the occupants' use of heating systems (Mathioulakis 2002). A monitoring of light control in 10 offices found that the illuminance threshold of individuals for switching the lights on varied significantly from one another. Another study found the variation to be between 230 and 1000 lux (Al-Mumin et al. 2003) Thermostat setpoint could vary from below 19°C to above 25°C according to another study (Brager et al. 2004)

Understanding the reasoning behind occupant behaviour can be complicated since they vary from individual to individual. The same research found that windows were opened by some and closed by others under the same thermal conditions (Brager et al 2004). Indoor air quality is indicated to be the primary factor for opening windows during winter, while outdoor noise for closing them in the summers (Haldi 2008). Some other reasons for window operations were indoor humidity and weather conditions (Mahdavi 2012).

The operations of the shading may have a psychological driving factor in addition. Occupants kept the shading open to maintain view and a connection to the outside in a study of a naturally ventilated building (Zang, Barrett 2012). While occupants were found preferring to keep them shut when their windows faced other building for privacy reasons (Foster, Oreszczyn 2001). The reasoning for each behaviour from these finding may seem understandable and obvious, however, deriving a common behaviour to assume in the energy modelling becomes an almost impossible task considering the number of variations.

Static uniform schedules are used to represent occupants in building simulation tools (Hoes 2009). For example, while modelling an office building, the inputs assume that an occupant is present from 9 am to 6 pm for five days in the week. This does not consider vacations or visitors which can affect the energy consumption. The complex influence of occupant behaviour on building energy consumption and the indoor environment cannot be correctly modelled and calculated with simplifications (Dong 2014). A case study comparing occupant behaviour to the energy concept of a naturally ventilated building in Germany found inconsistencies. “The window opening times in winter are in 10–25% of the days too long. The window opening in summer is in 10–40% of the times not supporting the building concept due to windows being opened while the outdoor temperature is higher than the indoor air temperature.” (Schakib-Ekbatan et al. 2014). Indicating a less than ideal behaviour which is not assumed during designing.

Automated systems such as automatic shading, automated lights, mechanical ventilation or air conditioning with non-openable windows started trending in an attempt to minimise occupants operating the systems or windows. However, some problems with the automated systems are often technical malfunction, insufficient control programming, inaccurate sensors signalling the controls, and occupants overriding them. When the automated operation is overridden, the energy consumption deviates from the prediction. For example, when the shading is manually opened when is supposed to be closed to block solar radiation, space can get overheated and extra energy would be needed to cool. A five-month study on 40 office buildings having automated exterior shading found that 73.6% of all the blind adjustments were initiated by the user and that in a majority of the offices, the automatic mode was permanently switched off. Although, the comfort ratings were slightly lower by manual mode users (Meerbeek 2014).

It is important for the productivity and health of the users for them to be comfortable in a building in which they spend a major amount of their time. A study shows that a real financial yield can be obtained by increased employee work engagement with good user comfort of the workspace and social sustainability. “The positive impact of certain features, such as operable windows and the absence of air conditioning, can be clearly identified.” (Feige at al. 2013). “Manual override is essential for the high-performance operation of dynamic facades” (Bakker et al. 2014). “Full automation is not suitable for systems that considerably affect indoor environmental comfort.” (Karjalainen 2013). Which means that forcing a completely automated system without the freedom to override is not the best option. It is necessary to find a balance between user comfort and optimized building performance. In this context, it becomes important to understand the behaviour of the user: why are they unsatisfied with the operation, what is their preference or priority of one comfort parameter over the other which leads them to override the automatic operation. E.g. Is ‘view to the outside’ more important than preventing overheating by blocking solar radiation?

This thesis, therefore, studies the occupants with interviews and monitoring to better understand their interaction with the building, and thus, compare in the inputs of building energy simulations and the reality. This would help increase accuracy in energy predictions and, in turn, reduce performance gap.

1.5 Post-Occupancy Evaluation needed to reduce Performance Gap

Post-Occupancy Evaluation or POE is the process of evaluation buildings in a systematic and rigorous manner after they have been built and occupied for some time.

(Wolfgang et al. 1988). In other words, it is the investigation of a building to find out its functioning, success and shortcomings while it is already in use. This may be done by various interested entities such as architects, clients etc. The precise definition of POE is adaptive as it is used to address a variety of issues and embraces a variety of methodologies to do so (Rowena et al. 2018).

Evaluation and feedback are key to the improvement of building design and technology. POE studies can provide knowledge about the success and failure of designs and systems. They can help identify and solve any issues that the building might have or streamline operations to make the building more efficient in its energy consumption and satisfactory to the users. The widespread occurrence of performance gap, as mentioned earlier in the literature study, highlights the importance for the need of POEs.

Some of the benefits of POE as mentioned by a Guide by the University of Westminster and the Higher Education Funding Council for England (HEFCE 2006).

i. Finding and solving problems in buildings
ii. Feedback directly from user needs/ dissatisfactions
iii. Informed decision making
iv. For building's adaptation for efficient usage or to change in usage
v. Accountability of designers for the building's performance
vi. Long-term improvements/maintenance of building performance

The most important benefit of a POE is that it helps ensure the practical success of a (theoretical) design, helps designers understand what works practically and learn not only from their own experience but from the experiences of other designers, leading to a faster and better evolution of building design. Benefits can be maximised if the information from POEs is made available to a wider audience and not just within the institution which is evaluating. Information from POEs can help create a database about success stories and learning from failures and provide useful benchmark data with which other projects can be compared.

It can be used for many purposes such as to audit the construction process, to ensure good quality design, monitor building performance or to improve the strategic decision process. It is useful to Architects, building physicists, users, building owners, developers, or people in other related fields such as home automation, or manufacturer or certain components because a POE investigates the success and shortcomings of the building for learning and future improvements (HEFCE, 2006).

Since the definition of POE encompasses a holistic overview of a constructed building, it can include many aspects of interest, from the qualitative user satisfaction with interior design to monitoring of mechanical systems. For example, an Architect might be interested to find out the satisfaction with a new circulation and arrangement pattern implemented in the planning. A mechanical engineer might be interested in the functioning of the automated systems. A Client might be interested in the energy performance of the building and not about the user satisfaction with the interior design. For this reason, each POE is generally adapted to the interest of the entity conducting it.

Performance Gap can occur due to a variety of reasons as mentioned in the previous chapter, a big portion of which occurs in the operation and usage of the building. POEs are essential to the diagnosis and rectification of these problems, which can, in turn, reduce the actual energy consumption and bring it closer to its designed value. The Royal Institute of British Architects (RIBA), mentions, “Post Occupancy (or Building Performance) Evaluations also help designers to close the performance gap, that of designed energy and organisational performance, and the actual measured performance of these areas.” (RIBA 2017). The POE of a building helps to close the loop between design and performance for building owners, designers and operators based on quantitative feedback from building occupants (Candido, Kim, Dear & Thomas 2016). In the case of this study, POE is conducted to help the study of robustness which can help reduce the widely existing Performance Gap.

Current Methodology of POE

There have been many developments in the process of POEs and they have several different approaches and can include assessment of the architectural quality, space usage, etc, all of which are not in the scope of this thesis. It is generally adapted to specific cases depending on the interest of the entity conducting it, however, it is recommended to use tested standard processes to maintain comparability and quality and to reduce redundancy in the evaluation process. Recommendations for the POE process developed by BOSSA (Building Occupants Survey System Australia) mentions some general steps which are listed below:

a. Walk-through and observation
b. Interviews
c. Focus groups
d. Workshops
e. Measurements

f. Monitoring
g. Questionnaires for different entities such as facility manager, contractor occupants etc.
h. Benchmarking
i. Preparing an abstract and report for documenting the learnings and making it available to others.

1.6 Robustness to reduce Performance Gap

1.6.1 What is Robustness?

The concept of robust optimization or robustness is well established in many fields, for example, structural engineering and aeronautical engineering (Frangopol, Maute, & Zan et al. cited in Maderspracher 2017) due to the strict requirements by law for safety and reliability. In the field of building design for robust performance, however, it is still not a very established concept and still being extensively researched (Nguyen et al. cited in Maderspracher 2017).

A broad definition of Yao et al. (2011) with respect to SH Park (1996), G.-J. Park et al. (2006) and Beyer and Sendhoff (2007) for the concept of "Robust Optimization" is: "The robust optimization is a method to optimize a concept or system, with the aim of the system to be insensitive to different types of variations".

“Robustness” in terms of building performance was defined as “the sensitivity of identified performance indicators of a building design for errors in the design assumptions” (Hoes et al.2009) In simpler terms, robustness is the stability of building performance withstanding variations. It can also be described as the insensitivity of a building to the changes in its boundary conditions which may be due to various uncertainties. This is explained by the Figure 0.2, where the change in boundary condition of a parameter is plotted again a performance indicator such as energy consumption (Rhein 2014). The global minimum value of a curve while is the steep trough in the graph (Hopfe 2009). However, Robust optimization the search for an optimum that satisfies the original target criteria as best as possible but at the same time exhibits the smallest possible fluctuations of the target variables (Rhein 2014). In other words, it is not the global minimum but a value which shows a lower deviation in the performance at for the same deviation in the boundary condition. The same concept can be used to view the entire building’s performance with design variations for instance.

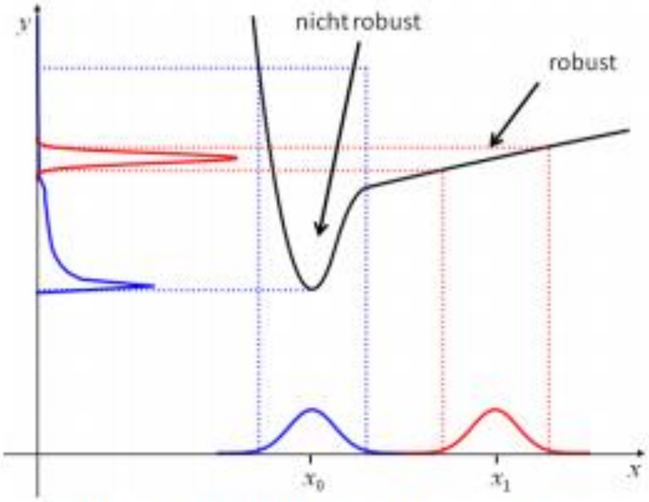


Abb. 4.2: Grundidee des robusten Designs

Figure 0.2 example of the difference between a global optimum and a robust optimum (Rhein 2014)

Some of these uncertainties were mentioned when explaining the causes of Performance Gap in the previous chapter. Uncertainties are unforeseeable deviations from the expected scenario which can lead to a difference in performance. Some examples for uncertainties are: Change in climate, User behaviour variations, BMS failures, inaccuracies in construction, uncertainties due to assumptions that need to be made in simulation, uncertainties in the calculations inside the simulation software etc. The potential impact of these uncertainties is very high in low-energy buildings (Kottireddy et al. 2018).

1.6.2 Why Robustness?

Various entities can benefit from knowing the robustness of a design or a building. It essentially indicates its reliability in terms of stable thermal comfort as well as energy consumption which translates financially to electricity bills and better productivity of the occupants. Since the process of robustness analysis takes uncertainties into account, which were the main causes of performance gap, energy consumption predictions can be more accurate, providing owners with an expected, stable management costs and continued comfort. More importantly, this can help correctly predict the expected carbon emissions, helping the 2050 goal of lower carbon emissions have realistic outcomes.

Robustness analysis during the design phase and robust optimization of building design can provide designers with information which can help make the design decisions for better performance. It can help policy makers define energy performance requirements in the future building regulations to safeguard the intended policy targets. They can define policies which promote considering robustness to support adaptations of current buildings to improve their performance and also increase their lifespan. It would also benefit homeowners' wishes of having ensured performance over the lifespan of their building. Energy performance contractors can also benefit by lower performance gap and better accuracy in predictions. (Kotireddy, Hoes, Hensen 2017)

1.6.3 Are 'resilience' and 'robustness' different?

Resilience is a building design concept that is getting increasing attention after increasing natural disasters caused by climate change. For example, eight people died due to power cuts after the hurricane causing the failure of air conditioning in a nursing home in 2017, "Three days after the hurricane had howled through South Florida, some of the most vulnerable people in the state were dying, not of wind, not of floods, but of what seemed to be an electrical failure." (NY times). In the most recent news, the hurricane in Peutro Rico resulted in about 3000 deaths (BBC news). Greater importance is being focused on building design which can withstand such natural disasters or quickly return back to functioning.

The Cambridge definition of resilience is "the quality of being able to return quickly to a previous good condition after problems". The US Green Building Council (USGBC) and their partners have defined resilience as the "ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." In other words, resilient buildings are those that can bounce back from extreme environmental conditions such as high winds, heavy rain, flooding, intense sun, earthquake, and fire, which can be considered as uncommon or irregular. Resilient building design concept focuses on the capacity of the building to passively withstand extreme conditions.

Whereas, the definition of 'Robust' in the Cambridge dictionary is "strong and unlikely to break or fail". Robustness is in the context of regularly occurring everyday scenarios. These uncertainties are significant and should be considered because they are not a rare occurrence, they are the normal usage. In other words, a resilient building can be robust, but a robust building need not be resilient to extreme climate calamities. Never the less, they may perform better than a sensitive building.

1.6.4 Methodology for robustness analysis

To test the sensitivity of a building's performance towards these uncertainties, 'uncertainty or sensitivity analysis' can be done. The less sensitive a building, the smaller its reaction to external changes, hence, more robust is its performance.

Uncertainty analysis and sensitivity analysis may be confused with each other due to their similarity. While sensitivity analysis checks the effect of small changes in the designed parameters, uncertainty analysis tests the reaction of the model to variations in the inputs which are probable to occur after construction (Macdonald 2002). The Procedure for the analysis can be identical however, sensitivity analysis aims to help design decisions about size/ material specifications, while uncertainty analysis can include a sensitivity analysis but also account external uncertainties such as climate change, policy change, occupant behaviour, malfunction etc.

The benefits and uses of uncertainty analysis are best explained in a study about quantifying the effects of uncertainty in building simulation by Macdonald, "Uncertainty analysis is an important experimental technique and can be used in simulation to address the following issues:

• Model realism: How well (and to what resolution) does the model represent reality?

• Input parameters: What values should be used in the absence of measured data?

• Stochastic processes: To what extent do the assumptions made regarding future weather, occupancy and operational factors affect the predictions?

• Simulation program capabilities: What uncertainties are associated with the choice of algorithms for the various heat and mass transfer processes?

• Design variations: What will be the effect of changing one aspect of the design?" (Macdonald 2002).

All the methods of analysing robustness or for robust optimization involves computing a test model in a BPS programme with numerous variations in its boundary conditions to study the magnitude of the reaction in performance.

Recent papers by Kotireddy, hoes & Hensen has outlined a clear methodology for evaluating the robustness and is described below and illustrated in Figure 0.3. This is also adapted and used for this thesis. 'This method comprises multi-criteria performance assessment and multi-criteria decision making considering multiple performance indicators and their corresponding robustness' (Kotireddy, et al. 2017). It is explained here simple terms: A number of test-models are considered for the analysis. They vary in their design, material usage, energy concept, size usage etc. These are each simulated in Building Performance Simulation (BPS) software with different 'future scenarios' to calculate the annual energy demand of each design option in each scenario. These future scenarios can be anything of interest – various user behaviour patterns, climate change scenarios, possible mechanical system malfunctions or policy change etc. these future scenarios are set by defining different boundary conditions for parameters. For example, to test variations in user behaviour, the number of hours of occupation, the frequency of window and shading operations can be varied. The permutations and combination of all the boundary conditions for each of the parameters being varied can result in hundreds of future scenarios. The mean and standard deviations of the results of each case are analysed in a single box and whiskers graph, which is shown in the third column of Figure 0.3. The shorter boxes indicate smaller reaction and thus more robustness.

Other studies of robustness optimization involve a similar process; however, a multi-objective optimization process commonly use the Monte-carlo sampling technique which is the standard process for Robust optimization in other fields of engineering. Assessment of a Pareto curve can provide an understanding about how the change in a single or multiple parameter affects performance.

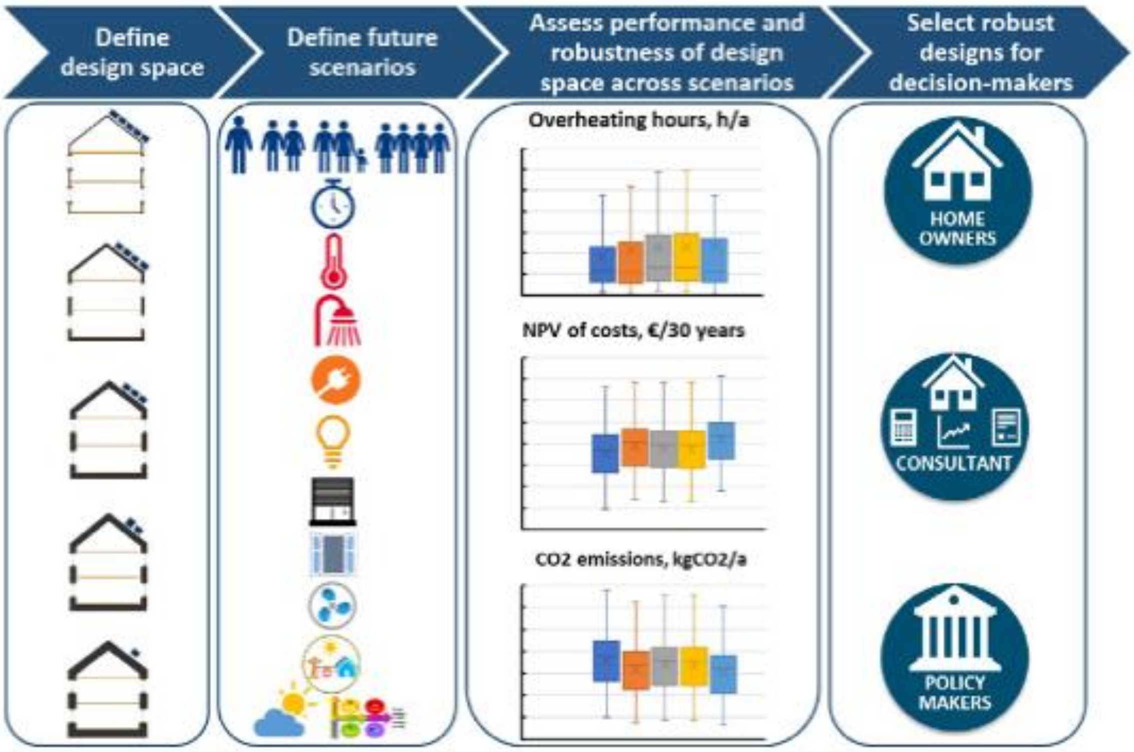


Figure 0.3 Graphical overview of Performance robustness assessment methodology. (Kotireddy et.al. 2017)

1.6.5 Current state of the art of robustness analysis

From the analysis of measured data, building energy simulation or sensitivity analysis, it is generally concluded that occupant behaviour greatly impacts building system operation and energy consumption. (Zhou 2013)

A study which conducted numerous parametric simulations of test-models of different designs under varying user behaviour found that the test-model with the lowest thermal mass and largest window sizes had a smaller deviation in the energy consumption but had unacceptable thermal comfort with temperatures reaching 48°C. (Hoes et al. 2009) In other words, this test-model was robust in energy consumption but not in thermal comfort. This conclusion, however, cannot be applied for designs with natural ventilation since only mechanical ventilation was considered for this study.

A study of the robust performance of different building designs against variations caused by Occupant behaviour found that the design with a massive envelope, a closed façade and fixed shading showed the lowest fluctuations in the results in the climate context of Frankfurt and Stockholm. But in the climate conditions in Athens, designers have more possibility of choice for the envelope’s features since they do not affect the results to the same degree (Fabi et Al. 2013).

Another paper uses a case study of residence in Turin to study the sensitivity of the building towards climate uncertainties with different refurbishment options22 different options for refurbishment were each simulated with 18 different weather files (present and future scenarios). The Annual heating energy demand, annual cooling energy demand were graphically compared in a box and whiskers floating bar graph. A Robustness Index is used for better comparison of cases which have close results, However, it does not convey the magnitude of the energy usage. It concludes that design choices based on just one weather file may not be the same made for a different climate as the design would behave differently. However, the main purpose of the paper was more about developing a methodology which could be implemented by designers which consider the implication of future climate change on building performance and comfort (Chinazzo et Al. 2015).

22 different options for refurbishment were each simulated with 18 different weather files (present and future scenarios). The Annual heating energy demand, annual cooling energy demand were graphically compared in a box and whiskers floating bar graph. However, with cases which have close results, it is difficult to identify it graphically. In which case, the Robustness Index is used, which a graph that is plotted.

2 Post Occupancy Evaluation

2.1 Importance and necessity

The Performance Gap project commenced by the Zero Carbon Hub in the UK in 2013 to aid the achievement of the '2020 Ambition' which entails that 90% of the buildings should perform better than or at least meet their designed performance and recommended that future performance standards should be linked to 'as-built' performance to help fulfil this ambition (Zero Carbon Hub 2014). This suggests the growing necessity for widespread POEs.

A study of the performance robustness of a constructed building entails the need for a conducting a POE because it can provide valuable insights into the realistic behaviour of the occupants, the building's real performance as well as the people's satisfaction with thermal comfort. The lack of a universal metric to measure performance robustness requires the study of at least two buildings of similar use and located in a similar climate for comparison.

The access to the climate designers of both the buildings provides invaluable insights into the details of the concept, the thermal simulation model details as well as a good understanding of the intended operation. These are key information necessary to compare the designed energy consumption prediction and actual performance.

Furthermore, some of the occupants' offices are monitored to analyse their behaviour, i.e. how they operate the window, shading etc, which is elaborated in the next chapter.

2.2 Case study selection

These buildings were selected for their similarity in usage, climate, mechanical systems and differences in some of the details of the systems in place as well as physical architectural parameters like window sizes, thermal mass etc. These are discussed in detail in the coming sub-chapters

The two buildings chosen are administrative office buildings or Rathaus (Deutsch) in South Germany, one in Ravensburg, Baden-Wüttemberg, and the other in Kolbermoor, Bayern. The floor plan is similar with mostly individual offices for employee and they receive a considerable number of visitors during the day.

The town hall of Ravensburg, refer to Figure 2.2, was designed for 76 regular occupants by the architecture firm, Kohlmayer Oberst Architekten and has been in operation for just one year (June 2017), thus, has seen only one winter and two summers and might still be in the 'teething period' where mechanical systems need fine tuning and monitoring for streamlined functioning.

The town hall of Kolbermoor, refer to Figure 2.1, was designed for 46 regular occupants by the architecture firm, Behnisch Architekten. It also contains large halls for marriage ceremonies and meetings, a public library and school. However, the study only includes the offices which have daily occupancy. It has been in operation for 5 years (2013) at the time of this study which was conducted between April and July of 2018.

The climate concept and energy performance prediction of both buildings was done by a company called Transsolar climate engineering and the original concepts and details for the energy simulations for the later robustness study is taken from the report provided by them as a recommendation for the design. However, they were not involved in the later phases of design or in the execution.

Figure 2.2 Photo of the townhall of Ravensburg.

(photo from Ravensburg.de)
Function: Office use
Architect: Kohlmayer Oberst Architekten
Climadesign: Transsolar Klima Engineering
Total Occupants: 76
Year of construction: 2017

Figure 2.1 Photo of the townhall of Kolbermoor.

(photo by David Mathiessen)
Function: Office use
Architect: Behnisch Architekten
Climadesign: Transsolar Klima Engineering
Total Occupants: 46
Year of construction: 2013

2.3 Methodology

The method of assessment of the perceived comfort, which parallelly gathers the information needed for the behaviour analysis, is adapted with the base being the recommendations for POE process developed by BOSSA (Building Occupants Survey System Australia). The regular POE process also includes assessment of the architectural quality, space usage, etc, which is not in the scope of this thesis. Aspects needed particularly for this study, like the occupant behaviour monitoring, are specially inserted. The final methodology, after customization, is summarized in the list below and later explained individually in the sub-chapters.

- Building study: Background study of plans, climate concept and systems etc - Chapter 2.3.1
- Evaluation: Physical inspection & Semi-structured interviews with some occupants - Chapter 2.3.3
- Monitoring: Measurement of the indoor climate of offices- Indoor air temp., Humidity, CO2 level, Illuminance, and Noise - Chapter 2.3.4
- Interview: Interview of the facility manager and climate engineers: Chapter 2.3.5
- Survey: Anonymous online survey - Chapter 2.3.6
- Findings and recommendations - Chapter 2.4

2.3.1 Building Study

Background study of plans, climate concept and systems

Plans:

The floor plan of both buildings is quite similar, containing mostly individual offices of similar sizes. The four office rooms were selected to face different orientations - North, South, East and West. However, the unavailability of willing participants led to monitoring a South-East office instead of South in Kolbermoor and a second East office instead of West in Ravensburg as shown in Figure 2.4 and Figure 2.3.

Ravensburg’s townhall generally has smaller windows with an average Window to Wall Ratio (WWR) 34% smaller than Kolbermoor. The WWR in the offices monitored is 21-43%, while those in Kolbermoor have between 39-60%, better illustrated in the table. Never the less, the window fulfil the minimum size required by the German code. Smaller windows can mean lower daylight penetration but also lower solar heat gains in summer and heat losses through the glass in winter.

The volumes and floor areas of both buildings also differ, with Kolbermoor's offices having 16% smaller average floor areas than ones on Ravensburg. Floor areas range between 12-17.1 sqm. In Kolbermoor while they range between 12-22 sqm. in Ravensburg. Smaller volumes of offices can mean higher internal loads with the same number of occupants.

Figure 2.4 monitored zones on plan of Kolbermoor

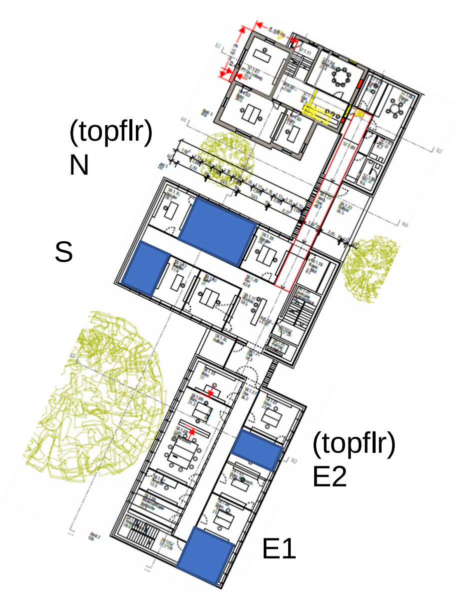


Figure 2.3 monitored zones on plan of Ravensburg

Kolbermoor	Ravensburg
South-East	South
17.1 m²	18.5 m²
41%; 14%	21%
1	1
East	East 1
15.6 m²	18.5 m²
39%	43%
1	1
West	East 2 (top floor)
12 m²	12 m²
60 %	33 %
1	1
North	North (top floor)
12.9 m²	22 m²
52 %	29 %
1	2
16% smaller floor areas	34% smaller glazing ratio

2.3.2 Climate concept and energy concept:

The buildings are new and so, have well performing insulated outer envelopes with low infiltrations and thermal bridges. The climate concept for the individual offices is explained for both buildings separately.

Kolbermoor (Figure 2.6):

Heating: A low-temperature heating system consumes lower energy, Thus, a floor heating system was used which is also used for cooling. At the time of construction, the town did not have a district heating network. The climate designers found an opportunity for using the waste heat being generated by a near-by laundry service. It was proposed to the city to install a district heating network which can be connected to the sister town, Rosenheim, and also collect the 'waste heat' and successfully executed.

Cooling: There is a seasonal switch depending on the outdoor temperature and the cooling period usually begins in May. The carpeted floor has a lower heat conducting capacity than concrete or rubber, thus lowering the cooling capacity. Hence, an additional slab cooling is used in the ceiling to compensate. Underground water is used as the cooling source with a 24-hour free cooling availability. It has an annual average temperature of 10°C and so needs no heat pump. The only electrical energy required is for the pumps. With a pump of good efficiency, it is possible to have very low source energy consumption for both heating and cooling.

Individual control: Each room has a thermostat which allows the users to view the indoor air temperature and to set the desired temperature for heating/ cooling, however, the control is technically not possible for individual offices but only for a larger area in each floor.

Ventilation: Decentralized mechanical ventilation with a 70% heat recovery reduces the necessity for long and expensive ductwork and losses in transmission. Never the less, it only provides a base air supply of 30 cubic meter which is insufficient and has to be coupled with natural window ventilation. The installed ventilation systems has three supply modes which suppl 15, 30 or 60 m^3 but it is not connected to the central BMS nor does it have an automatic programmed schedule and therefore, only individual control is possible,

Shading: Manually operated lamella external shading is used and it is only wind controlled, i.e. at high wind speeds, the shading opens to protect itself. There is also a vertical lamella fabric internal shading for glare protection.

Ravensburg (Figure 2.5):

Heating: Ravensburg's town hall also has floor heating but not additional ceiling cooling. The flooring is natural rubber which is a good conductor of heat. It is also connected to the district heating network of the city

Cooling: The floor heating system is used for cooling during the cooling period. There is a seasonal switch to cooling similar to Kolbermoor.

Individual control: Each office has a thermostat which shows the room air temp. and can also control the heating and cooling set point. However, since the floor heating/cooling system is slow acting and maintains an average temperature in the entire building, it is not possible to have extreme deviations in the temperature settings.

Ventilation: Unlike in Kolbermoor, this building is only ventilated naturally with manually operated windows. Mechanical ventilation was discarded from the climate concept due to the high visitors received. This creates high traffic moving in and out of the building which lets the heat escape through the doors. The mechanical ventilation is ideal for a constant occupancy as it is usually designed to provide enough fresh air to combat the exact CO2 produced. additional visitors cause a sharp increase in the CO2 level and would require additional natural ventilation through the windows. This would negate the benefits of the mechanical ventilation which limits ventilation heat losses through the windows and recovers heat from the exhaust air.

Shading: The building has an external fabric shading which is automatic controlled depending on the solar radiation on the façade. It also controlled by a wind sensor for its protection, similar to Kolbermoor. However, it is possible to easily manually override it. The fabric shading was chosen for aesthetic reasons and it is supposed to provide better glare protection while maintaining a view to the outside, this is, however, debated and depends on personal preference.

To briefly summarise the above:

Similarities:

1. Floor heating & cooling.
2. Openable windows for natural ventilation.
3. External Shading which is automatically opened at high wind speeds for damage protection.
4. Single- or double- person offices with individual thermostat for temperature control.

Differences:

1. Kolbermoor's Building has an extra ceiling cooling.
2. Kolbermoor's Building has decentralized mechanical ventilation with an individual control which does not condition the air but recovers heat during winter (70%).
3. Kolbermoor's building has external Lamella shading as well as internal lamella blinds which are only manually controlled. Whereas, in Ravensburg's building has a fabric external shading and no internal blinds which are automated by solar radiation

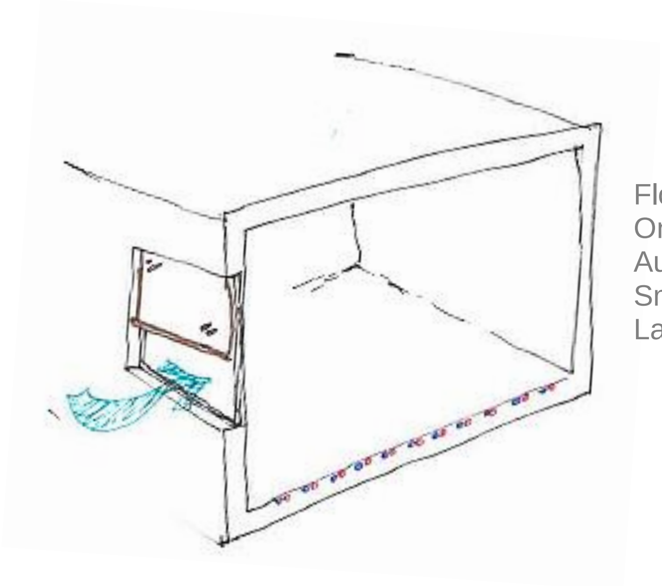


Figure 2.5 Climate concept illustration of Ravensburg's townhall.

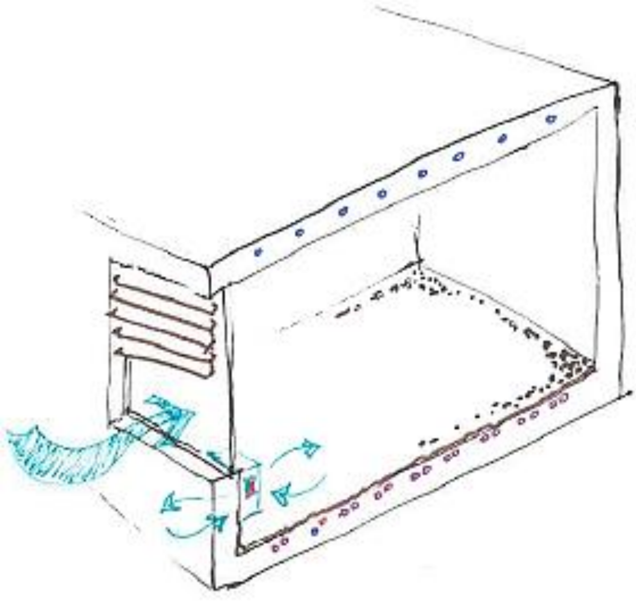


Figure 2.6 climate concept illustration of Kolbermoor's townhall.

2.3.3 Physical Evaluation

Physical inspection & Semi-structured interviews with occupants

Even though semi-structured interviews usually do not involve detailed questionnaires, it was prepared in the initial stage to maintain focus on the topic during the interview and to form the basis for the shorter and more specific online anonymous survey. A copy of the questionnaire written in German is included in the annexure A and the translated online survey results are included in annexure B & C. One of the challenges of preparing a semi-structured interview questionnaire is to limit its length. It includes questions only about thermal and visual comfort, air quality, occupants' interaction with the building systems, specifically, the windows, shading and heating/cooling systems. Questions about architectural and interior quality were excluded. The questions were translated to German and the interview was conducted with the support and translation of a native German speaker.

Kolbermoor

Kolbermoor's townhall was visited first, visually inspected and the occupants interviewed. The offices, as well as the corridors, were well lit because of the large windows, refer Figure 2.7. The initial analysis found the occupants satisfied, never the less, when asked about issues, some mentioned their dissatisfaction with the shading, that it opens with 'slight' wind and would not close again leading to an overheated room in the morning in an East facing façade.

Figure 2.7 A monitored office in Kolbermoor's building.

The women mentioned that the floor feels too cold in the summer and they cannot wear open summer shoes. This is perhaps not a problem for the men since they normally wear closed shoes.

It was unsure whether everyone used the mechanical ventilation as some did not know how to operate it. Since it was not possible to conclude this with such a small sample size, more information was gathered from the anonymous survey. If it was not being used widely in the winter, then its benefits of heat recovery and minimal ventilation losses could be wasted.

Ravensburg

Ravensburg's townhall was visited and visually inspected. The corridor space on the top floor has plenty of light due to the skylights but the ones on the first floor did not. The offices with two occupants and two windows were quite bright, but the single office, especially facing south seemed to lack enough natural daylight and the occupants usually had the table lamps switched on, as seen in Figure 2.8

Figure 2.8 A monitored office in Ravensburg's building.

The facility manager explained the teething problems with floor cooling and heating system control, which was not functioning according to the set temperatures. Example, in the summer one floor, was too cold and another too warm, so much so that some people wore sweaters indoors in the summer. The occupants expressed their dissatisfaction with the same issue. Never the less, it was fixed before monitoring for the thesis began. The complaints about the flooring cooling malfunction could only be checked after the cooling period began and more information can be gathered from the monitoring. There were no complaints about winter discomfort from these interviewees.

Dissatisfaction was expressed about the shading. A complaint was that the shading closed even when the window is shaded by a leafy tree in the summer. Another was that the shading needs to be manually closed in the morning when there is glare and potential overheating since it does not automatically. The occupants also mentioned that the shading closed around the same time every day.

The findings and resolutions suggested for the issues mentioned above are discussed in detail in the chapter: *Findings and recommendation*.

2.3.4 Indoor climate Monitoring

Measurement of indoor climate

A purely qualitative survey cannot accurately assess thermal comfort because, for instance, it is important to know if an occupant considers 23°C as too cold when they complain of cold. Therefore, sensors were installed in the offices to measure the indoor climate for a scientific and accurate understanding of the occupant's personal comfort thresholds as well as their interaction with the building. The monitoring period was from May – June in Kolbermoor and May – July 2018 in Ravensburg. Ravensburg was monitored a month longer because the active cooling only began in mid- June. Results are in annexure D, E, F & G.

The 'IC meter', which measure temperature, humidity, noise, and CO2, the recorded measurements are available to view over the internet, making assessments of repairs or complaints faster. They were either placed vertically on the wall next to the entrance door close to the thermostat or on an open shelf just under the desk but away from the occupant. The illuminance was measured with a 'HOBO' sensor which was placed horizontally near the window, but away from the table lamp to identify the sudden change in illuminance when the shading is closed/opened. The sensors measured the following:

a. Air temperature; to understand thermal comfort.
b. CO2; to interpret the window operation and confirm the occupancy period.
c. Humidity; to understand thermal comfort
d. Noise; to interpret occupancy periods
e. Illuminance; to interpret shading operation

In Ravensburg's building, the cooling had an issue and had not started functioning even by the 1st week of June where outdoor temperatures were already reaching 28°C.

The monitoring showed high temperatures of 27-28°C in the top floor offices in Ravensburg and it was quickly found that, although the malfunction of the previous year was fixed, the floor cooling was still not functioning. This feedback was brought to the attention of the facility manager. The reason was found that the cooling fluid inflow setpoint temperature was lower than the dew point temperature, which would cause condensation and the automatic safety function would not allow any cooling fluid to flow. This was fixed when the temperature was increased from 18° to 20°C.

After the fix, the indoor air temperature dropped from 28° to 24°C with the same outdoor conditions. As a second check, the surface temperature was measured using an infrared laser thermometer and compared with the room air temperature and the thermostat setting and was found to match the expected values. An example is illustrated in Figure 2.9 where the thermostat setting was 25°C (the highest it can be, and there was no cooling fluid flowing in the floor), the floor surface temperature was 23.5 and the room temperature was 24°C.

With active cooling, the indoor air temperatures ranged between 21-25°C in Kolbermoor and 23-26°C after the fix in Ravensburg, which can be considered as comfortable. However, according to the German adaptive thermal comfort standards, temperatures below 23°C is considered 'too cold' in Summers with an Outdoor temperature of 28°C

Air temperature Thermostat Foor Surface

Figure 2.9 Inspection photo at Ravensburg showing air temp., thermostat temp. & surface temp

2.3.5 Interview

Interview of the facility manager and climate engineers

The facility managers for both buildings provided valuable information about the current working. They also provided the annual heating and cooling energy consumption of the previous year, viz. June 2017 to June 2018. This is key to finding out how well the buildings perform as compared to their intended design. They also clarified various doubts and in Ravensburg, was key to fixing the floor cooling.

The climate engineers of both buildings are a firm called Transsolar Klimaengineering GmbH. They provided valuable information about the intended climate design, the predicted energy consumption and the reasoning behind the strategies, the details of which are mentioned in sub-chapter 0. The details of the settings and assumptions considered for the dynamic thermal model was also gathered and this is mentioned later in the chapter: Robustness analysis.

2.3.6 Survey

Anonymous online survey

An online anonymous survey was conducted to investigate the majority opinion about the perceived comfort and can validate the finding from the interviews and from the monitoring. The survey is significant to all parts of the thesis as it helps uncover answers about behaviour and comfort thresholds that cannot be found by monitoring or only interviewing a small number. The online survey results are paired with the monitoring observations to derive inferences about user behaviour patterns.

The test for robustness is done by testing several behaviour patterns which try to mimic real-life scenarios. The findings from the online survey questions about comfort form the basis for the behaviour patterns used for the test. The survey was also helpful for the behaviour analysis and will be discussed further in that chapter.

The questions and responses received are included in the annexure B & C. Several online survey software were considered and 'Google forms' wwas chosen because it offered no limitations on the number of questions or a responses. Since written in German, the one included in the annexure is also in German.

The USGBC or US Green Building Council recommends a response rate of 30% and corrective measures are recommended when more than 20% are dissatisfied. The response from Kolbermoor townhall was better, with a response rate of 58.6% (26 out of the 46 occupants) than to that of Ravensburg's town hall, with only 37% (28 out of 76), owing to the summer holiday season clashing with the time of this study and therefore, there is a possibility of non-representative conclusions.

2.4 Findings and Recommendations

Discussed in the following sub-chapter is the finding of the perceived comfort and investigation into the issues mentioned by the occupants during the initial inspection and interviews.

2.4.1 Analysis of perceived comfort

Thermal comfort:

There was a 55% dissatisfaction recorded at Kolbermoor as compared to 37% dissatisfaction at Ravensburg (refer annexure C). it is important to note sample group does not consist of a large number of people and so each person's vote contributes to a large percentage. For example, in Kolbermoor 5 people make up 20% of the sample group. Furthermore, the no. of participants compared to the total occupants in Ravensburg is much lower than in Kolbermoor and there is a possibility of non-representative conclusions.

The graphs 3.9.1 and 3.9.2 show the satisfaction in specific seasons, with the central yellow bar representing 'satisfied', the bars on its right (green & purple) represent 'sometimes too cold' and 'often too cold' respectively. The ones to its left (red and blue) represent 'sometimes too warm' and 'often too warm' respectively.

In Kolbermoor, 57% are satisfied during the shoulder seasons and 34% in summer and winter. In winter, 50% find it too cold, while 15% too warm sometimes or often. In the summer, 30% find it too warm sometimes or often while 34% too cold. The complaint of cold in the summer or warm in the winter indicates unnecessary over-cooling/heating. However, one of the reasons could be that the floor cooling/heating systems maintain an average temperature over the entire building, or that the surface being too cold/hot, makes it uncomfortable. This emphasizes the importance of having individual controls. In conclusion, the highest percentage of satisfaction is during the shoulder seasons when the heating and cooling are usually switched off and the outdoor temperatures are moderate. 58 and 62% mention that the reason for their dissatisfaction is due to insufficient individual control and slow reaction of the heating/cooling respectively. 41% find the heating not strong enough while 46% & 42% find the cooling too strong and the floor too cold in the summer respectively.

In Ravensburg, 42% are satisfied in the shoulder seasons, 46% in summer and 38% in winter, summer and winter being higher than that of Kolbermoor. In winter, 42% find it too cold and 21% too warm sometimes or often. In summer, 32% find it too warm and 21% too cold. Even with the teething problems of the floor cooling, the summer satisfaction is quite high. 45 and 50% mention that the reason for their dissatisfaction is due to insufficient individual control and slow reaction of the heating/cooling respectively. 33% find the heating/cooling too weak and 29% say that the floor is too cold in the summer (refer Annexure C)

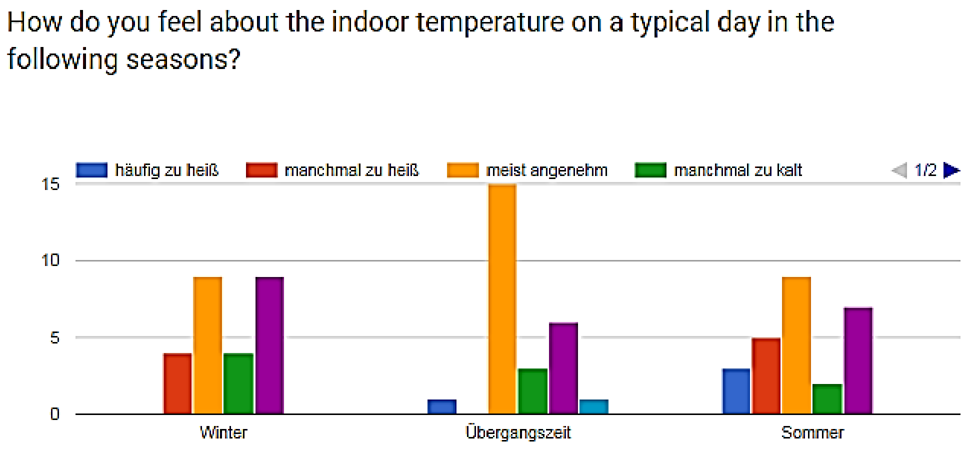


Figure 2.11 screen capture of survey result showing thermal comfort in different seasons at Kolbermoor. (annexure C)

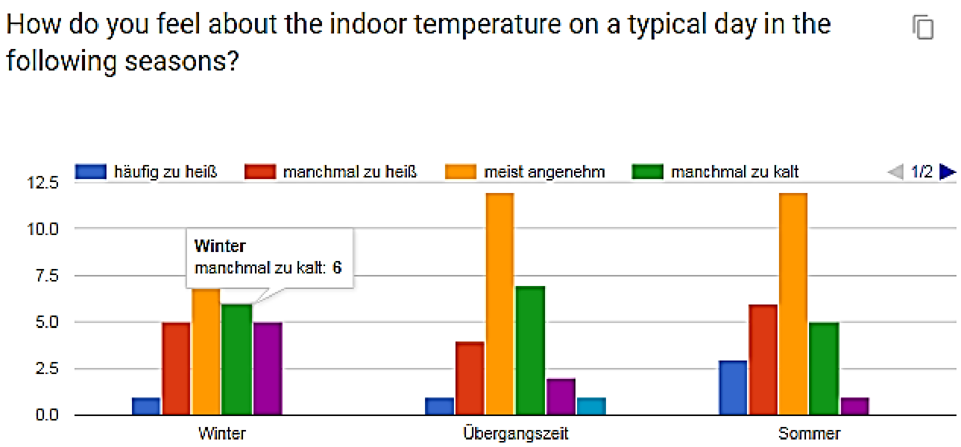


Figure 2.11 screen capture of survey result showing thermal comfort in different seasons at Ravensburg (annexure C)

In summary, the biggest dissatisfaction in both buildings is with the slow reaction of the heating/ cooling and insufficient individual control. The next important dissatisfaction is with the uneven surface temperatures and overcooling in the summer. The percentage of people who are 'often' in discomfort in any season is lower indicating more stability in thermal comfort in Ravensburg than that in Kolbermoor, as seen in the Figure 2.11 and Figure 2.11 respectively. The middle yellow bar indicating satisfaction is tallest and the bars on the extremes are shortest.

Visual comfort:

The surveys show a high satisfaction with the overall visual comfort in both buildings with only 0.04% dissatisfied in Kolbermoor and 0.14% in Ravensburg.

In Kolbermoor, greater satisfaction is with daylight and view and dissatisfaction with glare protection. While in Ravensburg, better satisfaction with glare protection and artificial lighting than with daylight or view (refer annexure B & C)

Air quality:

Survey at Kolbermoor found only a 20% dissatisfaction with the air quality while Ravensburg recorded 41%. (refer annexure B & C)

2.4.2 Findings & Recommendations - Kolbermoor

Investigation of the initial complaints:

The initial physical inspections, semi-structured interviews, and received positive feedback about the basic comfort and functionality of the various systems. Information from the interviews revealed some issues:

1. The floor may be too cold when the cooling period starts.
2. The shading seems to open at low wind speeds and does not close again.
3. Some people might not use the mechanical ventilation.

Recommendations

1. The floor may be too cold when the cooling period starts.

Although this complaint was made by only one participant interviewed, the online survey revealed that this opinion was shared by 42% of the sample group along with 46% saying that the cooling in summer is too strong.

Overcooling in summers is a waste of resources and money. This was brought to the attention of the facility manager. The suggested solution was to use only the ceiling but not the floor cooling and/or increase the inflow setpoint temperature of the coolant. The result of this suggestion is not yet confirmed.

2. The shading seems to open at low wind speeds and does not close again.

The rooms can get overheated if the shades remain open and this can occur when occupants are absent during the weekend or early mornings. The malfunctioning of the shading was brought to the attention of the concerned contact from the building but cannot be corrected as reprogramming the shading controls is expensive and difficult. However, the online survey shows that only 31.6% of the sample group, refer to Figure 2.13, were dissatisfied with the automatic control and 73.5%, refer to Figure 2.13, manually closed it less than twice a week out of which 35% never closed it at all. Some guesses for the number not being very high could be because this malfunction would most affect only East facing offices which receive most solar radiation in the early mornings when no one is present, leading to an overheated room for the rest of the day; or perhaps because the frequency of the shades opening is low. This situation highlights the importance of correct controlling of the automated systems, in this case, the re-closure of the shading.

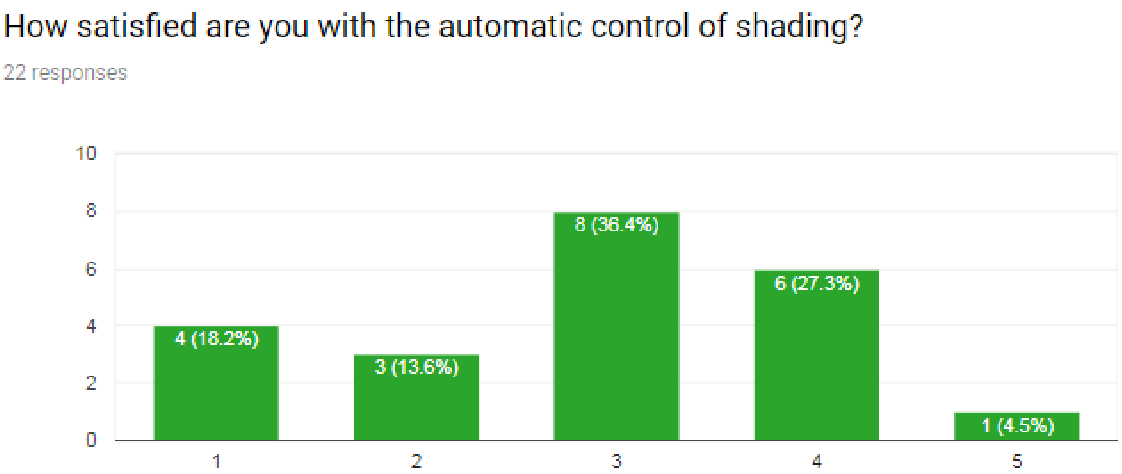


Figure 2.13 screen capture of survey result showing satisfaction with automatic operation of the shading in Kolbermoor (annexure B)

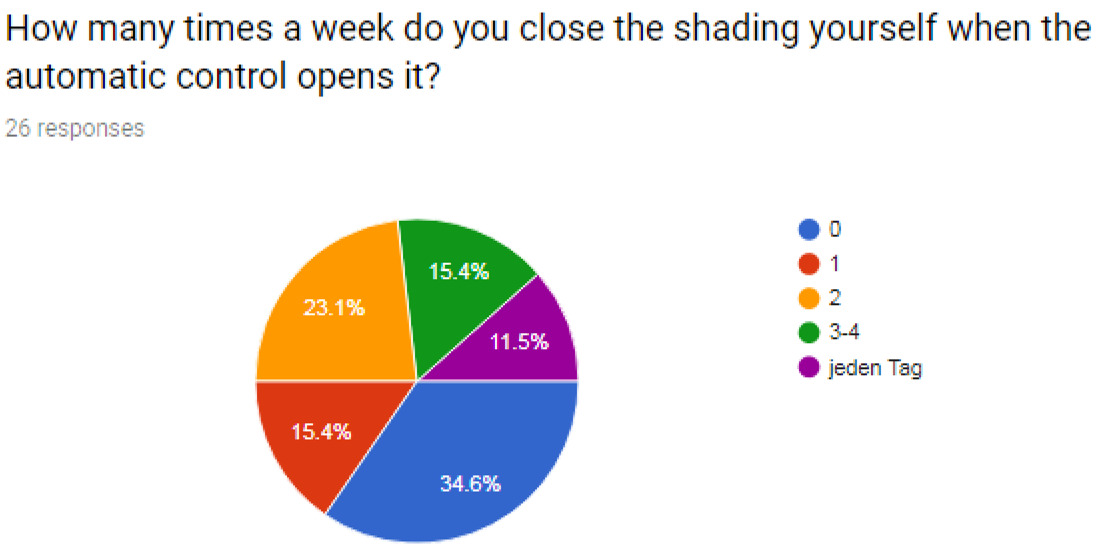


Figure 2.13 screen capture of survey result showing Frequency of overriding of automatic opening of the shading for wind protection in Kolbermoor. (annexure B)

3. Some people did not use the mechanical ventilation.

With more discussions with the four participants, online surveys and the analysis of the monitoring, the problems were better understood. The initial interviews revealed that some people were not using the mechanical ventilation even during winter because they did not know how they are supposed to operate it. The anonymous survey showed that people would prefer to also naturally ventilate regardless of the existence of mechanical ventilation (refer Figure 2.14) A high frequency of window opening would negate its benefits of heat recovery and reduction of ventilation heat losses. It is only designed to supply 30 m³ per hour which is insufficient for the complete dependence on the mechanical ventilation. Indoor smells or a large number of visitors resulting in a high CO_2 production could also be some of the reasons for people preferring to naturally ventilate. Discussions with the facility manager led to a possible solution of conducting a compulsory workshop to educate the employees on the correct usage of the various systems in their office.

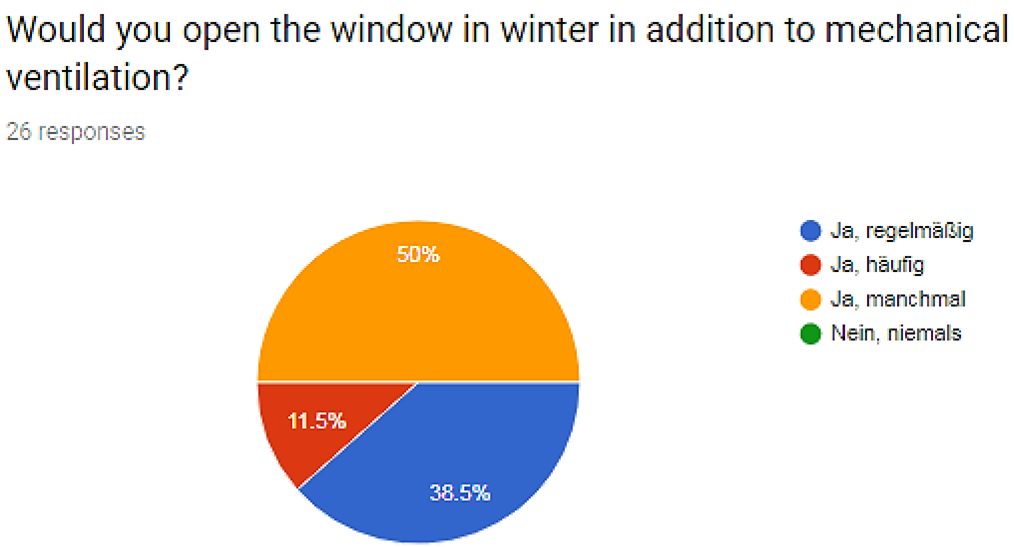


Figure 2.14 screen capture of survey result showing frequency of overriding of automatic opening of the shading for wind protection in Kolbermoor. (annexure B)

2.4.3 Findings & Recommendations - Ravensburg

Investigation of the initial complaints:

The initial feedback was similar to that received at Kolbermoor, largely satisfied with thermal and visual comfort. Although, being a new building, the floor heating and cooling had some initial problems with streamlined function as mentioned earlier in the sub-chapter ‘monitoring’. The controls were mismatched leading to one floor overheating and the other overcooling. Naturally, most complaints during the initial interviews were about this. These problems were fixed before the monitoring for this thesis was conducted.

The other issues that surfaced were:

1. The automatic control of the shading was not satisfactory
2. Some found the summer too warm, while others too cold.

Recommendations:

1. The automatic control of the shading was not satisfactory

The survey shows a higher dissatisfaction with the automatic shading control of 44% as compared to the number of satisfied users of only 12% Low daylight is seen to be the reason for most of the dissatisfaction with 84% of the sample group choosing this option. Some interviewees complained that even with the shades completely open, there was insufficient daylight for reading.

It was observed that on the East facing office, the shading was closing at around 9 am, which is already allows a maximum of 350 W/m² of solar radiation from 5am nor does it provide glare protection when the sun angle is low. The reason for this was found after receiving the information of the shading controls by the electrical consultants who initially installed it. There is one illuminance sensor which reads the horizontal illuminance and the controls were set such that at 25000 lux (horizontal) the East façade shadings were signalled to close however, vertically the façade already receives a higher amount which can be seen from Figure 2.4. This threshold value should be lowered further so that the shading can prevent overheating. The recommendation of the solution was communicated with the facility manager.

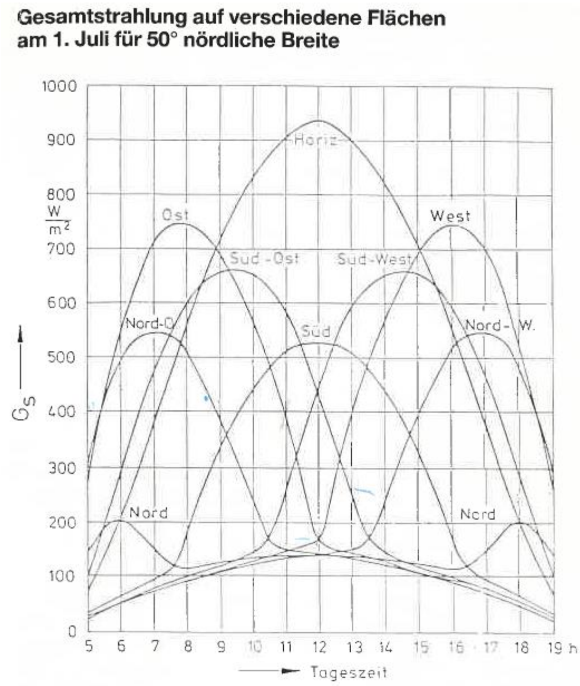


Figure 2.15 solar radiation on different orientations

(Steimle el at. 1998)

2. Some found the summer too warm, while others too cold.

The occupant in the South facing zone in the intermediate floor complained of cold summers and this goes against the common expectation of south-facing rooms overheating because of the high solar radiation it receives. When investigated, it was found that the office had the lowest window to wall ratio of only 21%, in addition, it was shaded by a large leafy tree and also self-shaded by the other part of the building which was perpendicular to it leading to a great reduction in the solar gains. Even with no floor cooling activated, the room is cooler than expected, with a temperature ranging between 22°-24°C which never the less, can be considered as comfortable by some people.

Since this is an architectural issue, the possible solutions at this stage can only be local solutions such as a portable heater (which should not be preferred due to its high energy consumption and low efficiency), keeping the shades open to maximise solar gain, wearing warmer clothes, or having a carpet on the floor to avoid the cold surface temperatures of floor. These solutions were suggested to the concerned occupant.

The offices on the top floor were overheating and the floor cooling was not functioning. This feedback was brought to the attention of the facility manager. The cooling fluid inflow setpoint temperature being lower than the dew point temperature, which would cause condensation, was the reason for the cooling not working. The automatic check allowed the cooling fluid to restart its flow when this temperature was increased from 18° to 20°.

The functioning was confirmed by the air temperature measurements in the offices which dropped from 28° to 24°C. The room temperature was compared with the surface temperature of the floor, measured with an infrared laser thermometer, as well as with the thermostat setting and was found to match the expected values, as seen in Figure 2.9 **on page 32.**

2.5 Conclusion

The learnings from this study are:

a. The communication between the users and the facility manager is important and a good communication protocol must be set in place to ensure simple issues can be rectified in time. E.g. Redundant over cooling during summer could be avoided. One of the results of this post-occupancy evaluation was the repair of the floor cooling in Ravensburg by directing the feedback from the users to the responsible entities.

b. Due-point temperature limits and the region's humidity must always be kept in mind when active layers are involved in the design. This was found to be the reason for the floor cooling malfunction in Ravensburg, which started working well after the inflow temperature was increased from 18° to 20°C.
c. Individual control of the heating/ cooling system becomes very important when there is an activated floor or ceiling to ensure higher satisfaction among the users. For example, Women, due to differences in physical metabolism, lose heat easier than men and complained about cold floors during the summer. Although it is possible to have individual control for each room in Ravensburg, even with no cooling for a room, there is an average minimum temperature of the floor throughout the building. A local solution can be to place a carpet which is later removed for winter to not block the floor heating.
d. Systems, such as the decentralized mechanical ventilation in Kolbermoor, become redundant if not used properly and the capital costs and energy benefits get wasted. It was found from the online survey that users opened the window even with mechanical ventilation and this would result in unnecessary loss of heat from infiltrations. Since the system is not controlled by the BMS, it is completely dependent on the user's operation and its actual operation was not found. A solution can be to a comprehensive workshop for all employees to educate them in the correct usage and operation of the various systems in the building. E.g. mechanical ventilation, thermostat for floor heating/cooling, guidelines for window and shading operation etc., and subsequently, this information should be included in the briefing of new employees.
e. Automated shading controls must be monitored after it is in use to check for correct functioning. It was found at Ravensburg, that the shading closed too late in the East facing room. This is caused by a mismanagement in the programming. A single sensor measures the illuminance on the roof and controls by calculating the azimuth angle and difference in the horizontal and vertical orientations. This threshold value should be lowered further so that the shading can prevent overheating. The recommendation of the solution was communicated with the facility manager.

3 User Behaviour Analysis

3.1 Introduction

User behaviour is one of the boundary conditions that is most difficult to define or predict. It is also one of the most important variables that considerably impacts the energy consumption and comfort, as demonstrated in the literature studies in ***chapter 2***. It is usually assumed based on the guideline standards which are developed from studies and observations: but widely generalised.

The trend of office building design is leaning towards automation of almost all aspects of the building operation, such as the light controlled movable shading, mechanical ventilation, motion-sensitive lights, etc., all designed to minimize human interaction with the building to avoid wastage of energy by human 'ineptness'. This approach, in theory, makes sense, however, studies show that there is a lower level of satisfaction when there is a lower possibility of manual control. The primary purpose of a building is to provide protection and comfort to people. If users are unhappy and feel restricted when there is no manual control possibility. Then obviously, manual overriding possibility must be provided. But the benefits of the automation are usually lost when overridden manually. Ideally, a robust building should be able to perform well in these cases of uncertainties, which seem to be unavoidable.

The hypothesis is that user behaviour is inconsistent and that users override automatic operations. The assumptions about user behaviour made for the conventional simulations do not accurately match the reality. This chapter aims to study the behaviour of the four participants in each building by interviews and measuring the indoor climate with the intention of finding a common threshold for the operation for windows, shading and the thermostat.

3.2 Methodology

As mentioned in the previous chapter, the indoor climate data were recorded for CO2, air temperature, humidity, noise & illuminance for 2 months (May& June) and extended in Ravensburg until July, essentially covering a part of summer and the shoulder season. Measurements of an entire year would be ideal to fully understand the behaviour in all seasons, however, due to the restriction in time, it was only possible to measure for the above-mentioned limited duration.

This data was analysed after plotting graphs of identical scale using the software rhino and grasshopper. The measured data, as well as the survey results, are studied, and conclusions derived. Three parameters, that a user can change, were focused on:

a. **Thermostat operation** being dependent solely on the individual threshold to warm and cold, explained in section 4.3.
b. **Window operation** being dependent on CO2 concentration, outdoor temperature and indoor temperature explained in section 4.4.
c. **Shading operation** which is dependent on automated wind protection and personal preference affected by glare, season and daylight. In Ravensburg, it is mainly dependent on solar radiation as it is automated and explained in section 4.5.

The observations about behaviour are compared to the current settings used to simulate user behaviour in the conventional building energy simulations and is illustrated in section 4.6. The differences in what is assumed, and the reality can cause a performance gap in the building performance.

3.3 Thermostat operation

To better understand individuals' thermal comfort thresholds and to justify the boundary conditions set in the variants in the robustness study, questions about temperature were asked in the online survey. This was only possible because the occupants have thermostats in their individual offices displaying the current room temperature and allow them to adjust the floor heating/cooling systems. The initial personal interview gave the impression that people were aware and informed about temperatures in their offices.

Heating setpoint:

It was found that 82-85% of the sample group in Kolbermoor and Ravensburg respectively were comfortable above the temperature of 22°C, out of which 49-50% comfortable above 20°C, as shown in Figure 3.1. Hence, 20°C and 22°C were considered as the heating setpoints for the robustness study simulations.

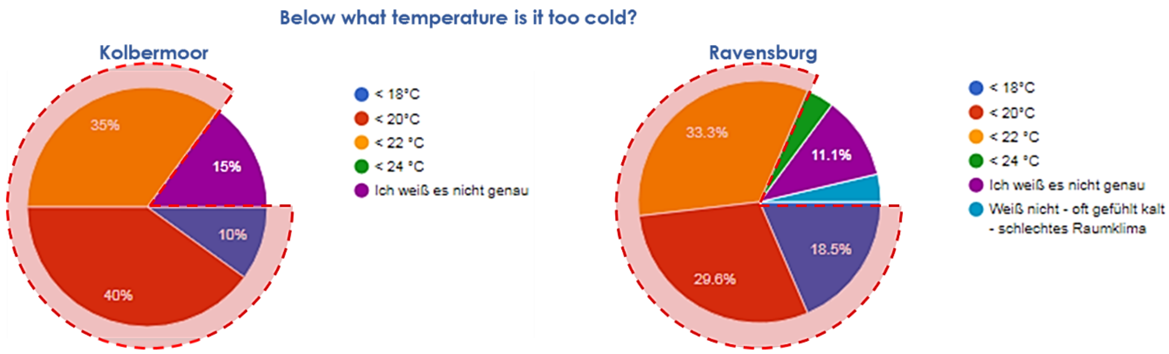


Figure 3.1 screen capture of survey result of the question 'below what temperature is it too cold?' (annexure B & C)

Cooling setpoint:

70% of the sample group in both buildings were comfortable below the temperature of 24°C out of which 33- 40% are comfortable below 26°C. 15% in Kolbermoor said that it was warm only above 28°C and hence, the setting for the maximum temperature in the zone was considered as 24°C, 26°C and 28°C for the robustness study simulations. Note that the above percentages can be higher because about 15% of the sample group in both buildings mentioned that they do not know the exact temperature at which they are comfortable.

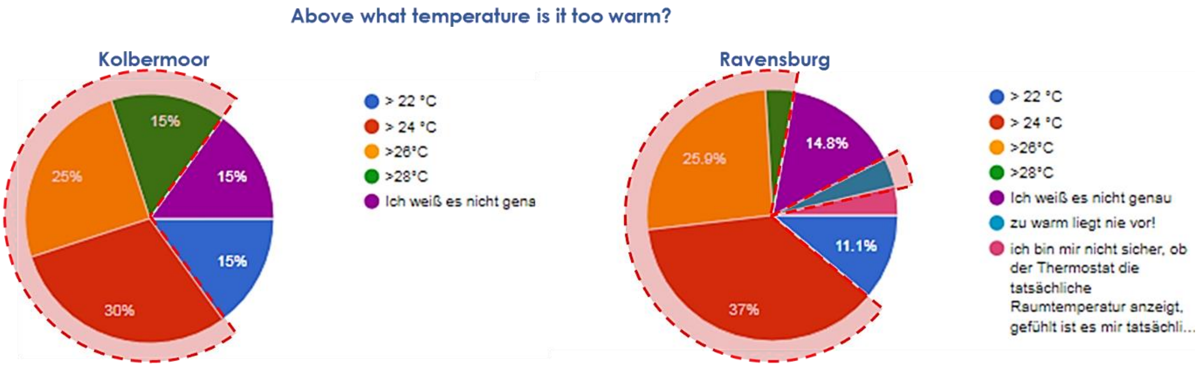


Figure 3.2 screen capture of survey result showing the question 'above what temperature is it too warm?' (annexure B & C)

3.4 Analysis of window operation

A combination of the measured data and survey results forms the study of the window operation. Opening/ closing of the window is dependent on four main drivers:

i. **CO2 level**, which can be associated with the feeling of 'stuffiness'. Occupants open the window when the CO2 level increases, in other words, when the air feels too 'stuffy'
ii. **Outdoor temperature**. When it is too cold outside, occupants are not likely to open the windows; In other cases, they open or keep it closed depending on their personal choices about stuffiness and temperature.
iii. **Indoor temperature**. Occupants open the window when it is too warm indoors and close it when it gets too cold.
iv. Number of occupants.
v. Other unquantifiable drivers such as **preference, noise, smell or draught** etc.

A steep increase in CO2 indicates the presence of one or more occupant/s. A sudden drop in the CO2 level indicates fresh air entry, which can be assumed to be the manual opening of a window because the effect of mechanical ventilation would see a gradual decrease. Therefore, the CO2 level is the main observed parameter to understand the operation of the window. The four drivers mentioned above are investigated separately and explained below:

i. CO2 level:

Conventional simulation methods consider 800 ppm as the ideal CO2 threshold at which the windows should be opened or as the target for mechanical ventilation. However, this threshold varies for different people, for different indoor and outdoor conditions. Understanding these relationships and to find a common CO2 threshold which could be used for simulations is the aim of this part of the study. Only the interesting periods are shown here as examples to illustrate the observations and were selected based on clarity and regularity in occupancy, outdoor & indoor temperature.

A consistent CO2 threshold was not found among users or even in the behaviour of the same user. It ranges between 400-2000 ppm.

The relationship between CO2 level and outdoor temperature was studied:

a. *CO2 threshold varies for different users at the same ambient temp.*

Shown in **Error! Reference source not found.**, the windows were opened in the N orth office at Kolbermoor at 1600-1800 ppm at an outdoor temperature of 24-26°C between 4th and 11th June. However, in the West office, it was opened at 700-800 on the same days, shown in Figure 3.3.

b. *CO2 threshold varies for the same user at the same ambient temp.*

The CO2 threshold in the East office in Ravensburg changes from 1800 to 900 ppm when the outdoor temperature is around 15°C, as seen in Figure 3.4.

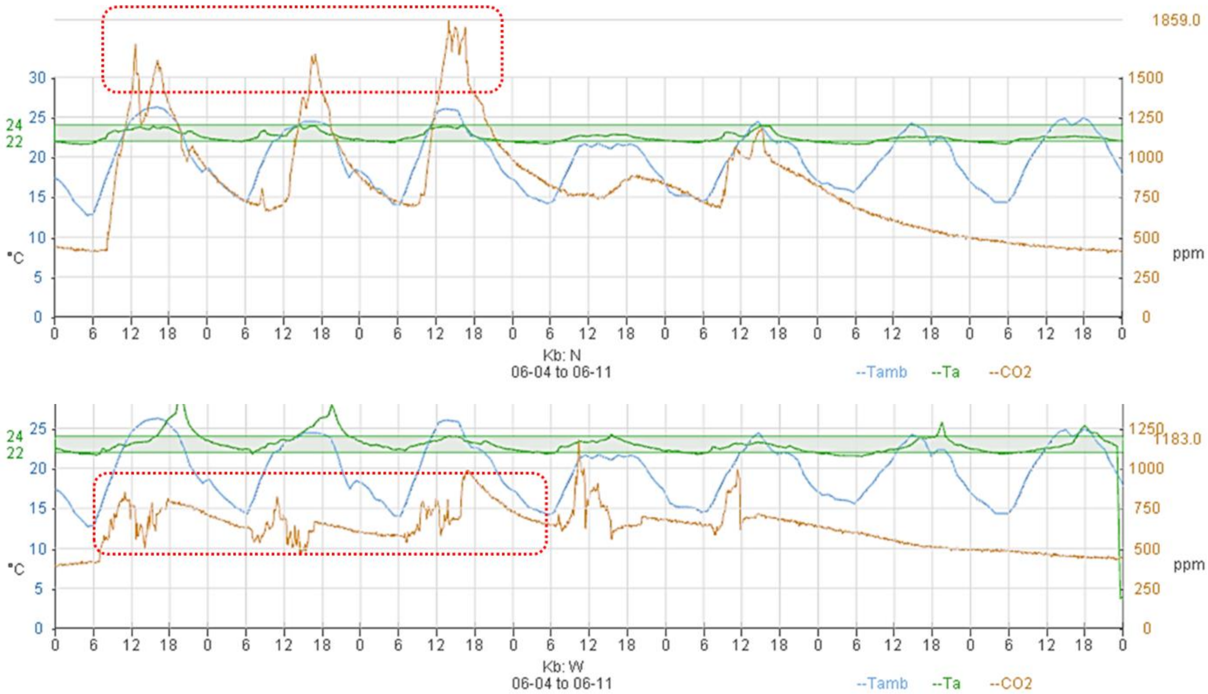


Figure 3.3 CO2 levels 1800 and 1200 ppm in North & West office in Kolbermoor

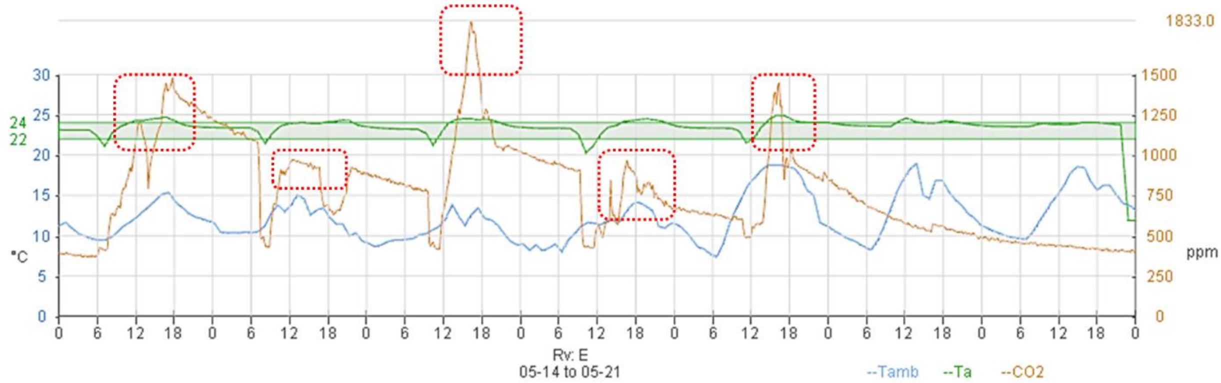


Figure 3.4 CO2 levels of 900 & 1800 ppm in East office in Ravensburg.

ii. Outdoor temperature

CO2 threshold decreases when the outdoor ambient temperature increases.

People would not want to open the windows when it is cold outside, but they may keep it open when it is warmer. To find common window operation trends, a further detailed study was done. The CO2 threshold is represented in a scatter graph as a function of the outdoor temperature of each user. The CO2 level before a sudden drop is noted along with the corresponding max daily temperature that day. But this sudden drop cannot be seen when the window is kept fully or partially open, instead, some fluctuations at a low ppm at around 400-600 can be seen. These instances are recorded as 400 ppm (the outdoor ppm level) to differentiate between the window being opened from being kept open for a longer period. A polynomial trendline was then plotted for each occupant. This is a curved line that is used to understand the general trend of data that contains fluctuations. Refer Figure 3.5**.**

Most trend lines show a reduction in the CO2 threshold as outdoor temperature increases. In other words, people tend to open the window more often or simply keep it open when it is not so cold outside. Below 18°C, Occupants limit opening the window and almost never keep it open. This is indicated by the higher ppm levels below 18°C as seen in Figure 3.5**.** This may not be applicable to all occupants as, found from the survey, about 7% -10% never open the window even if it is 'nice and warm' outdoor temperature.

A user's behaviour is not consistent on different days even with the same outdoor temperature and this is illustrated by the line graph in Figure 3.6**.** This graph shows the same data as Figure 3.5 but isolates two occupants for better readability. The fluctuations in the line represent different behaviour at the same outdoor temperature on different days.

However, this is not true in all cases. For instance, an occupant mentioned that they do not like the draught from the outside and so they keep the window shut even if it is

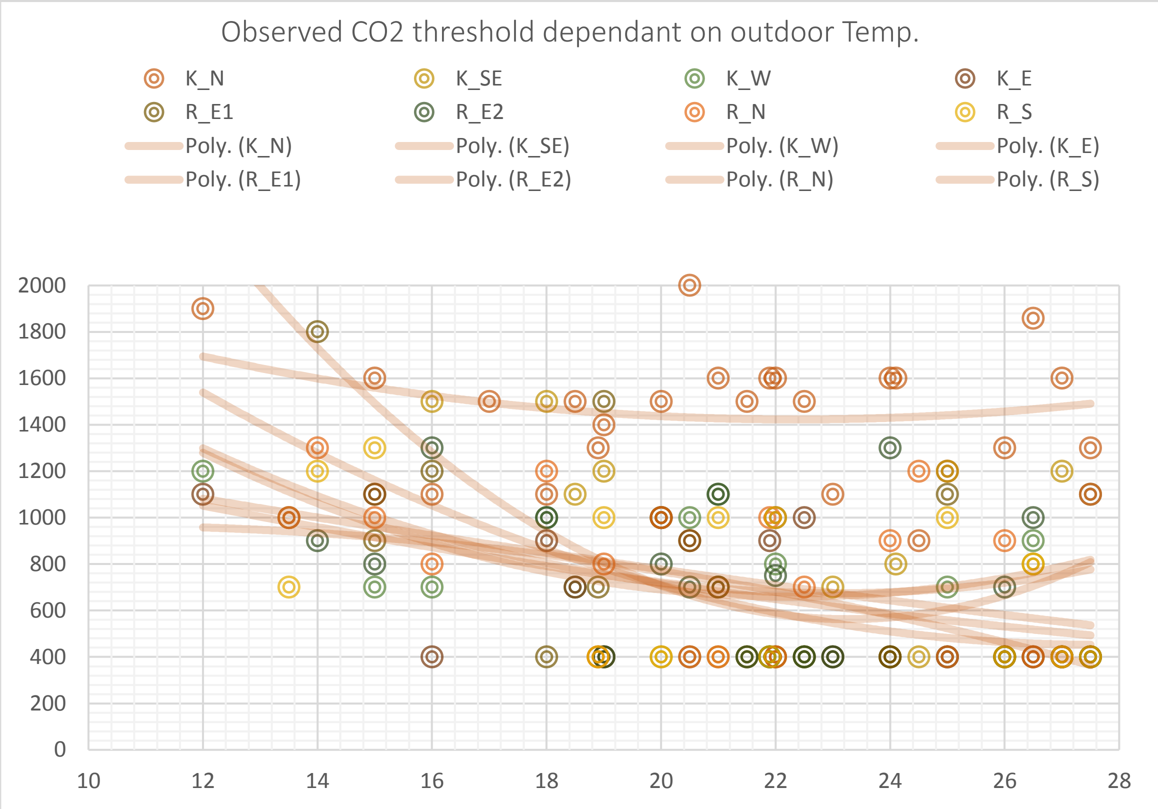


Figure 3.5 Scatter graph showing CO2 thresholds of occupants as a function of ambient temp with polynomial trend lines.

pleasant outside. Personal preference against draught, noise, smell, even memory etc., are factors that heavily influence behaviour but cannot be simulated or predicted.

It is also interesting to note that 90-74% of sample group said that they would NOT keep their window closed when it is warmer outside than the inside. While the conventional building performance simulations assumes that they do.

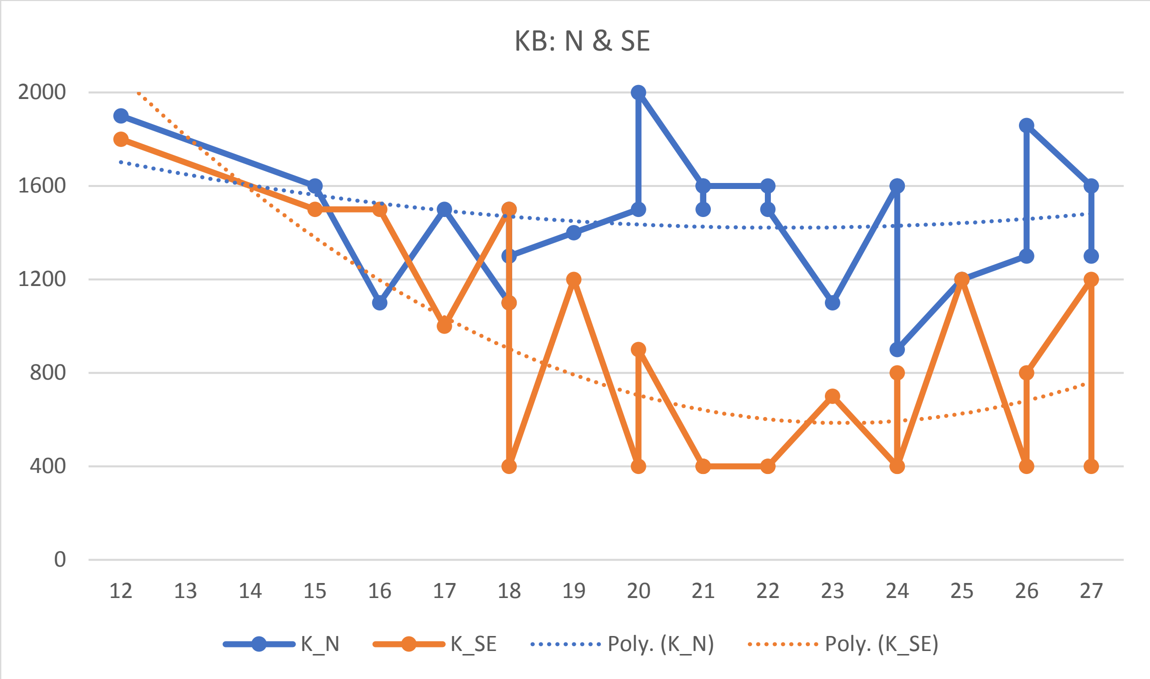


Figure 3.6 Line graph showing CO2 thresholds of occupants of North & South-East offices in Kolbermoor as a function of ambient temp with polynomial trendlines.

iii. Indoor temperature

84% of the sample group answered that they open the window when it is too warm inside. However, this can only be observed in users who keep their window closed most of the time. In a study of the eight occupants, only one kept the window mostly closed and this is an insufficient amount of data for a valid analysis. Hence, for the robustness study, the cooling setpoint temperature is assumed as the temperature at which the window is opened to help avoid overheating during cooler weather.

iv. No. of occupants

An increase in the number of occupants accelerates the build-up of CO2. For example, when an employee receives one or sometimes two visitors, making it three people in an area of 15m², the CO2 level rises very fast, thus increasing the frequency of the need for opening the window. 86% & 85% of the sample group in Ravensburg and Kolbermoor respectively receive visitors every day for at least 1 hour. Up to two visitors are received on average. This makes occupancy an important but underestimated parameter that greatly affects window operation behaviour. The Figure 3.7 shows survey results.

Figure 3.7 Screen capture of survey result showing the number of visitors received each day at Kolbermoor.

3.5 Analysis of shading operation

Ravensburg's town hall has a fabric external shading which is automated to close above solar radiation of 150 W/m² with a hysteresis of 50 W/m². Kolbermoor's townhall has lamella external shading which is manually controlled. There is a wind protection control in both buildings, which means that the shading will open at higher wind speeds for the physical damage protection of the shading systems.

Illuminance sensors were placed in five of the offices and this data is studied to understand shading operation. Due to limited illuminance sensors for this study, only a few offices were measured and so the analysis is not representative of the whole building but simply to understand the operation scientifically.

The illuminance was plotted for each week in a line graph along with outdoor ambient temperature and CO2 level to know the current weather and occupancy hours respectively. A sudden reduction in the illuminance levels indicates the closing of the shading. This behaviour was then corroborated during the personal interviews.

Ravensburg:

The base value of illuminance and the automated shading operation can be observed during the weekend since there would be no human interference. This can later be compared to the weekday illuminance levels to find out if users override the automated shading controls. In the Fig 4.5.1., it can clearly be seen that whenever the occupant is present, the shading is always manually opened after it closes automatically.

The sudden drop in illuminance on the weekends, which can be seen in Figure 3.8, occurs at 9 am and this is quite late for an East-facing room because it begins receiving solar gains from 5 am in the summers. Allowing this could lead to an overheated heated room before the occupant arrives to work. The shading control is calculated by the signal of only one illuminance sensor on the roof. The horizontal Lux levels are first converted to what would be for the vertical surfaces in different orientations. The current closing signal is set at a solar radiation of about 350 W/m² rather than the recommended 150 W/m². This was communicated to the facility manager of the building to be corrected.

The illuminance levels increase immediately afterwards on the weekdays when the occupant is present, showing that they manually override and open the shading. The interview with this occupant revealed that they opened the shading almost every day but sometimes kept it half closed, however, it is important to note that this cannot be detected

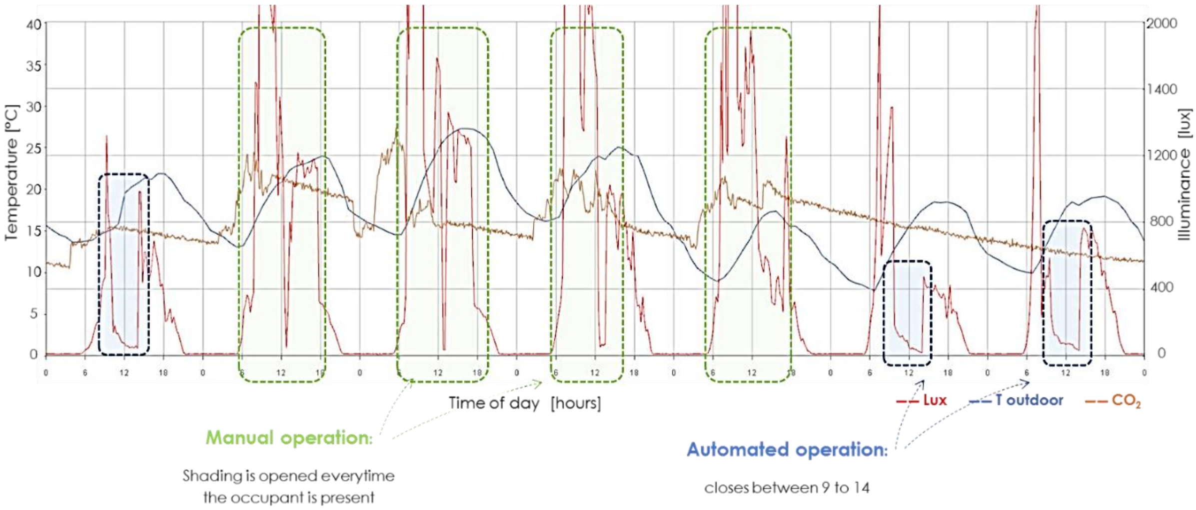


Figure 3.8 Shows illuminance, CO2 and outdoor temp. measured East office in Ravensburg. (annexure G)

in the values of the graph, but it affects the solar heat gains. Similar small mis-management of the shading's automatic controls were expressed by the other occupants that it does not provide good glare protection or close early enough to prevent overheating.

The survey found that 75% of the sample group open the shading when it automatically closes, out of which 56% override it every day and 39% closes it when it opens automatically as shown in Figure 3.9**.**

The reasons for manually opening the shading as mentioned by 80% was 'to receive more daylight'; by 50% was 'because the shading automatically closes even with low solar radiation'; by 35% was 'to have a view to the outside' and by 19% was' because the shading does not open again' Some of the reasons for manually closing the shading as mentioned by 79% was to avoid glare and by 37% was to prevent overheating.

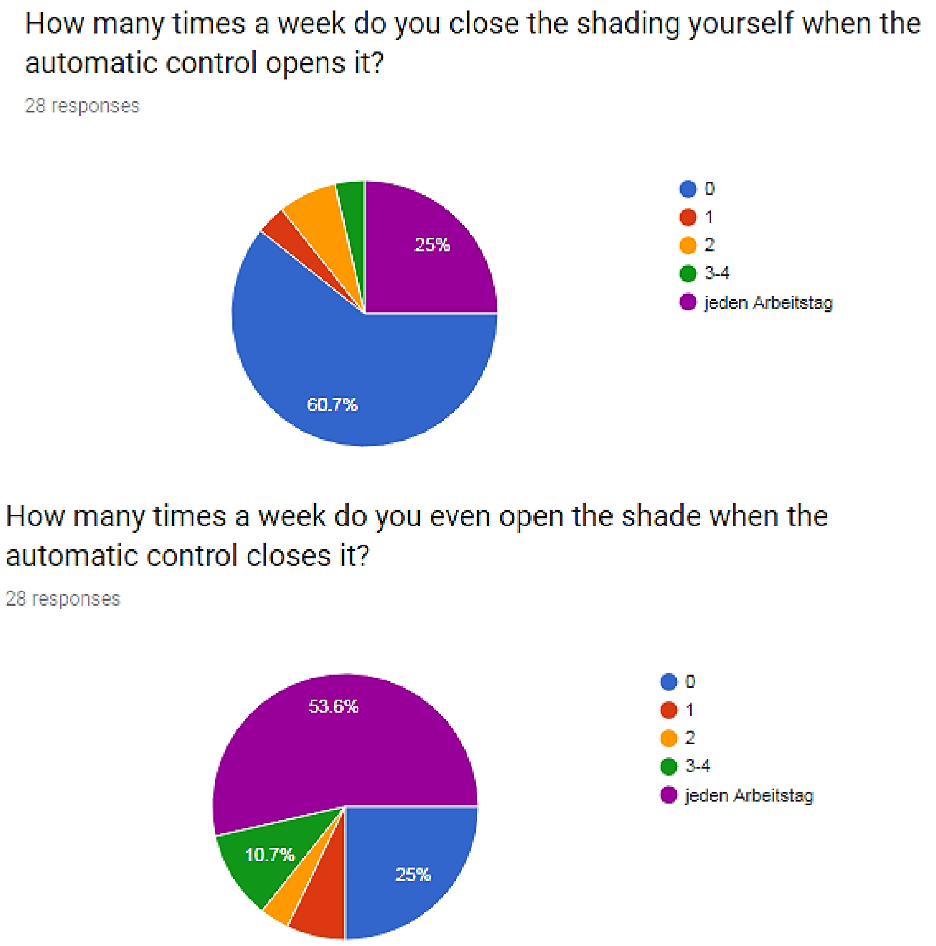


Figure 3.9 survey results about overriding of automatic shading in Ravensburg

Kolbermoor:

It was found that 55% of the sample group overrides the shading when it automatically opens at a frequency of once a week to every day. 70% of the sample mentioned that they manually closed the shading to avoid glare; 44% to avoid overheating; 35% said the shading does not close again after opening; 43% felt that the shading opens even with light winds.

The reason for the frequency of overriding being lower in Kolbermoor can be because of the lower intervention of the automatic control since it only opens the shades at high wind speeds to avoid physical damage. It is difficult to assess the behaviour with certainty by studying the measured illuminance data since there is no automated shading operation and, hence, no base illuminance value to compare with. Ideally, there should be a second illuminance sensor outside the window to compare with, however, this can be challenging practically and financially. Instead, the solar radiation data from a local weather station was collected and compared with.

The illuminance data measured in the East facing office, in Figure 3.10, indicates that the shading was closed after the occupant arrived in the morning on a clear and sunny day. It seems like the shading is usually never closed on the other days. However, no inferences could be made with certainty due to lack of information. The illuminance levels when the shading is closed is needed for comparison. A another drawback is that a half closed shading would not be seen on this data. Three illluminance sensors would be needed ideally to accurately study shading operation of a single window.

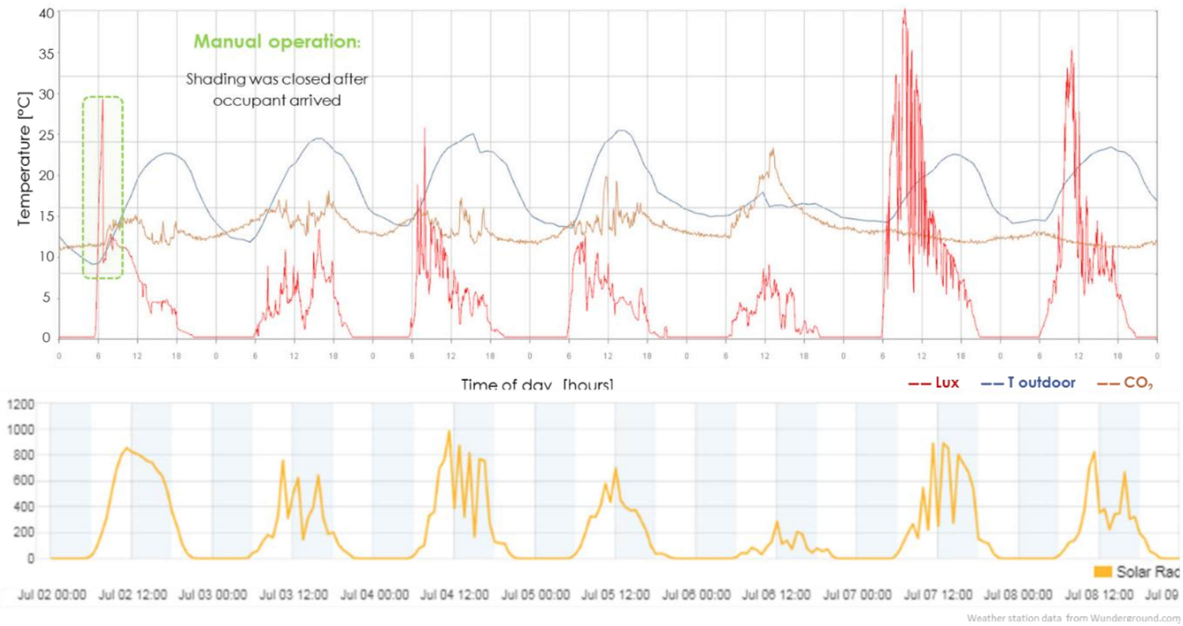


Figure 3.10 Shows illuminance, CO2 & outdoor temp. measured in Kolbermoor compared with solar radiation data from a local weather station.

3.6 Observed behaviour and conventional simulation inputs

Below are tables that concisely compare the settings used in conventional BP simulation methods and the behaviour that was observed in both the buildings. The user behaviour settings in BP simulations are assumed and simplified and usually follow the guidelines set by the country. This is done to reduce the computational time which is an important factor in the practical world. However, at today’s speed of innovation in technology, it may not be too long until it is possible to compute large amounts of data to become more accurate in the predictions of a building’s energy performance.

Thermostat operation:

Table 1 Thermostat control comparison of surveyed and simulated

	Conv. Simulation method	Observed behaviour
Heating setpoint	20°/ 22°C/ adaptive / or as discussed with client	49-50% comfortable with >20°C 82-85% comfortable with >22°C
Outdoor temp	24°- 28°C / adaptive / or as discussed with client / no active cooling.	33-40% comfortable with <26°C 70-70% comfortable with <24°C

Window operation:

Table 2 window operation comparison of observed and simulated.

	Conv. Simulation method	Observed behaviour
CO2 level	800 ppm	400-2000 ppm. Different for everyone. Changes with outdoor temp
Outdoor temp	Usually not considered	Most people keep it open for longer periods above 18°C
	Closed when outdoor temp. Higher than indoor temp.	7-25% open windows even when it is around 30°C outside.
Indoor temp	Open above 23°C	84% open when 'too hot' depending on individual thresholds
No of occupants	Constant, usually dependent on the no. of desks in the architectural plan.	Around 85% receive visitors every day for at least 1 hour. 1 or sometimes 2 visitors, making it 3 occupants at once.
Smell /draught/preference	Cannot be considered	Varies with individuals and cannot be generalized

Shading operation:

Table 3 Shading operation comparison of observed and simulated

	Conv. Simulation method	Observed behaviour
Solar radiation	Close at 150 W/m², open again at 200 W/m²	75% override it; 54% override it daily at Ravensburg
wind	Closed at high speeds between 5 m/s -12 m/s depending on shading	55% override wind control at Kolbermoor and 13% every day
Indoor temp	closed above 23°C indoor temp.	could not be identified
Glare	Only controlled by solar radiation	79% in Ravensburg who manually close the shading said it was for glare protection indicating that automatic control does not work perfectly against glare or glare from reflection etc.

Preference	Cannot be considered	Varies in individuals and cannot be generalized

3.7 Conclusions

The various parameters whose boundary conditions can be changed by a user were studied in the two buildings, which are, thermostat, window and shading operation.

a. **Thermostat operation** is dependent on the individual's personal threshold and can vary between 18°-24°C for heating setpoint and 28°-24°C for cooling setpoint. People prefer the individual control of their spaces and also a reactive system.

b. The **window operation** is dependent on CO2 level, outdoor temperature, indoor temperature, no of occupants and other unquantifiable factors such as smells, noise, preference etc.
    i. CO2 level: It was found that the CO2 threshold is not consistent among the users nor is there a consistent behaviour seen in the same person.
    ii. Outdoor temperature: The frequency and duration of the opening of windows increases with the increase in outdoor temperature.
    iii. Indoor temperature: windows are opened by the users when the temperature is above the individual's threshold which varies.
    iv. Occupants: The frequency of window opening increased with an increase in the number of occupants.
    v. Other: factors such as smells, outdoor noises, memory, preference, wind draughts affect the window operation, and these cannot be quantified or predicted.

c. The **Shading operation** is dependent on solar radiation, glare, view to the outside and daylight. Even when the shading is completely automatic, that is, controlled by solar radiation and protected for winds, there is dissatisfaction about the glare protection and is overridden by 75% of the sample group for reasons such as glare protection, more natural daylight, view to the outside, the wrong functioning of the automatic control. The wind-controlled shading is also overridden by 55% of the sample group.

The comparison of the observed behaviour versus the assumptions made about behaviour in the BP simulation shows that there is a large variation between the two and this can result in inaccurate predictions of a building's performance

It is evident from the occupant study that the behaviour of the occupants is varied, inconsistent and unpredictable. Some aspects like preference, smells or noises from the outside which affect behaviour, cannot be quantified or predicted. In conclusion, variations in the boundary conditions are very common, or even certain, and thus, must be expected and considered when predicting the performance of a building.

Inconsistency and unpredictability in boundary conditions highlights the importance of the sensitivity of the building and the reliability of its performance. A sensitive building, for example, a completely glazed façade with automatic shading, is designed to be controlled in a very precise manner, with the help of the BP simulations which makes many assumptions about user behaviour. If there are failure or malfunction in a mechanical system or deviations in users' behaviour from the strictly assumed values, which is very common as learnt from this study, there is a greater risk of bad performance in terms of energy consumption and the comfort provided, than the risk from that of a robust building.

4 Robustness of Building Performance

4.1 Introduction

Since it is clear from the literature studies as well as behavioural analysis, conducted specifically for this study, that occupant behaviour is inconsistent and cannot be accurately defined, it becomes important for buildings to perform robustly to withstand the changes caused by users. A process for testing the performance robustness was developed in this study and is explained in detail in this chapter.

This part of the study aims to compare the energetic performance and thermal comfort performance of both the town hall buildings in Kolbermoor and Ravensburg with fluctuating occupant behaviour and, in turn, comparing their robustness in performance. This is done by running thermal simulations of a variety of behaviour patterns and is then compared to each other as well as their real performance for a deeper insight.

Although ‘Robust optimization’ for defining and designing physical attributes of a building during design stage is a topic that is gaining popularity in research, this study limits itself only to the analysis of the two constructed buildings and not of their redesign. However, the differences in the attributes, such as window size, construction material, shading devices etc, are analysed and compared for the reasoning of the difference in their performance.

4.2 Methodology

4.2.1 Thermal Simulation Model setup

Simple shoebox models of 6 zones in Kolbermoor and 8 in Ravensburg were set up and their energetic performances were calculated by simulating in TRNSYS with TRNLizard on Grasshopper and Rhino as a user interface. These zones were validated with the older model which was built during the design stage which, however, did not use TRNLizard and so some variations in results are normal and expected. It was then validated with the constructed building by setting up the boundary conditions as close to the observed behaviour of one of the occupants as possible, and the indoor temperature patterns were matched for one selected week. The validation process and results are further elaborated in the chapter ahead. The successfully validated model was then simulated with a range of different behaviour patterns to assess the reaction of the building in energy efficient performance and thermal comfort. The less reactive, in other words, less sensitive the building, the more robust it is.

Individual offices were simulated but not the areas with other functions, such as meeting rooms, in order to keep the model as simple and light and minimise simulation time and complications. The details of the floor areas of each of the zones are listed below.

Table 4 Definition of zone floor areas and orientations

Kolbermoor				**Ravensburg**			
Orientation	WWR [%]	Zone area [m²]	Total area [m²]	Orientation	WWR [%]	Zone area [m²]	Total area [m²]
N	52	12.9	275	N	29	22.0	225.6
S	52	12.9	198	S	21	18.5	75.5
E	39	15.6	371	E	43	18.5	295.7
W	60	11.96	438	W	33	18.5	237.5
SE	41,14	17.1	95	N ext roof	29	22.0	69.4
NW	41,14	17.1	101	S ext roof	21	18.5	61.0
				E ext roof	43	12.0	152.3
				W ext roof	33	12.0	78.7
Total floor area:			1478				1195.7

Variable occupant behaviour pattern definition:

The occupant behaviour patterns defined for this study is carefully selected to be as realistic as possible while maintaining simplicity for simulation speed. The parameters, which an occupant has access to change, and the values of the boundary conditions are based on the findings from the occupant behaviour study conducted. They are listed in the table below:

Table 5 Boundary-condition variations definition for uncertainty analysis

Parameter	**Control strategy**	**Boundary conditions**		**Notes**
		Ravensburg	Kolbermoor	
Window operation	Window opened by a CO2 threshold [ppm] Window opened by Outdoor temperature. [°C]	800, 1100, 1500 18, 22, 'closed'	800, 1100, 1500 16, 22, 'closed'	Both conditions operate the window in parallel and the airflow is calculated by stack ventilation with the window height. Outdoor temp control works when the 24-hour avg. temp is above 12° & outdoor temp. is not more than 3°C higher than indoor temp. *Also opened when indoor temp above DIN or cooling setpoint & closed again at = heating setpoint + 1°C. 8 ACH max.
Shading operation	Shading opened by Solar radiation on façade. [W/m²]	150, 250, 500	250, 500 (only during work hours)	Ravensburg has automated shading control while KB does not, so shading operation during work hours only and higher threshold.
Heating	Setpoint for min required temperature in zone. [°C]	20, 22	20, 22	Heating starts 0.5° before the given threshold is crossed.
Cooling	Setpoint for max allowed temperature in zone. [°C]	24,26 (Only during work hours)	24°, 26	Cooling starts 0.5° before the given threshold is crossed.
Visitors	No. of occupants per room	1, 2	1, 2	2 is considered as an average though there can be 3 at once because not everyone receives visitors or for the whole day.
Mechanical ventilation	Person-related volume flow[m³]	-	30, 0	30 m³ being the design concept and 15m³ to simulate incorrect under usage. Heat recovery =70%. During work hours only

These boundary conditions, when combined in all possible combinations, makes 288 and 216 behaviour patterns, each of which are simulated to understand the thermal performance. They are simulated parallelly, in batches to reduce simulation time. The numerous results need to be assessed in a simple manner to derive conclusions. The two performance indicators which were decided to be used to compare the results were energy and weighted hours outside a temperature threshold. These values indicate the thermal and energetic performance and they are:

Table 6 Layer and material property definition

Specifications	Kolbermoor	Ravensburg	Unit
Window			
U-value of Glass	1.11	0.72	W/m²K
U-Value of frame	1.2	2.0	W/m²K
U-value of window	1.2	1.0	W/m²K
Light transmittance: T	70	70	%
Solar transmittance: G-value	44	49	%
Frame portion of the window	20	20	%
Shading factor of shading Fc	25	25	%
Building components U value			
External walls	0.27	0.28	W/m²K
Internal walls	0.36	0.32	W/m²K
Internal floor	0.37	0.38	W/m²K
Internal ceiling	0.37	0.38	W/m²K
External ceiling	-not considered-	0.19	W/m²K

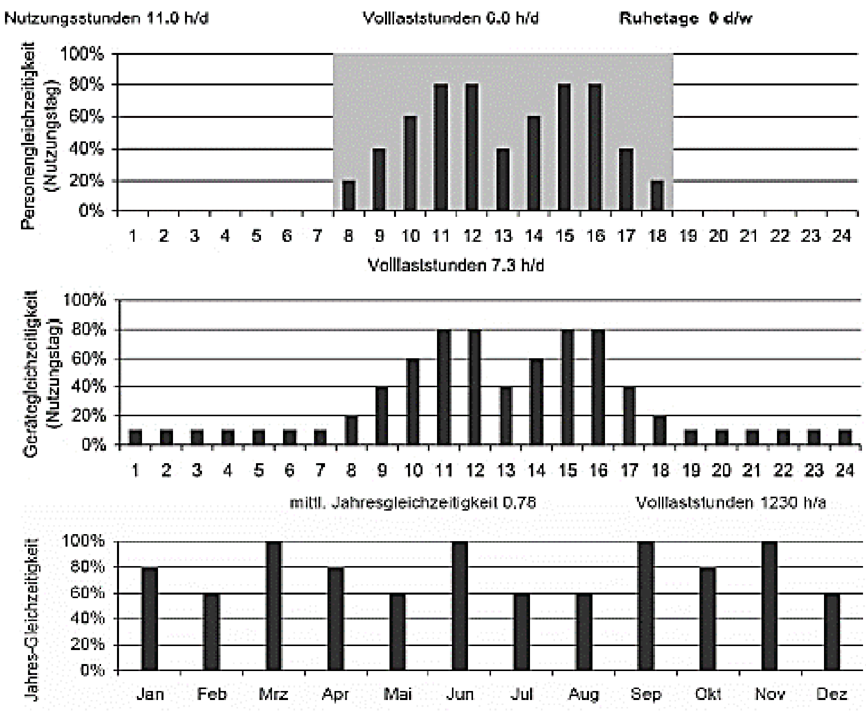


Figure 4.1 Daily and annual occupancy schedule definitions

Loads and schedules:

i. Internal load specifications for both buildings:
ii. Person load @ 70 W per person (50% radiative, 50% convectively)
iii. Lighting: On during work hours.
iv. Artificial light of 10 W/m² (70% radiatively, convectively 30%)
v. Equipment load of 140 W/person (20% radiatively, convectively 80%)
vi. Domestic hot water demand of 15 L/person
vii. Occupancy period:

7.00 – 19.00, Mon - Fri. The characteristic Occupancy load curve is considered from the SIA 2024 standards (swiss society of engineers and architects) as shown in Figure 4.1, for both energy demand as well as comfort calculations. The standard is developed to represent the average characteristic internal loads in an office building.

4.2.2 Performance indicators for robustness in thermal comfort

To understand the performance of thermal comfort in a single number in order compare the numerous variations, Weighted overheating hours and weighted under-heating hours are used as performance indicators.

Definition of weighted overheating & under-heating hours (WOH/WUH):

The amount by which the indoor operative temperature exceeds a pre-set temperature limit is calculated for each occupied hour of the year and summed up, providing the ‘weighted overheating hours’. This is the number of hours that a space is warmer than a defined temperature multiplied by the number of degrees by which it exceeds it. Weighted underheating hours is the same, except that it represents when it is colder than the defined temperature.

Weighted overheating hours (WOH [Kelvin hours]) are calculated with the simplified formula: $$WOH = \sum_{i=1}^{n} h_i \cdot (T_{op} - T_{max}) > 0$$

where

h is the number of occupied hours,

Top is the operative temperature [°C],

Tmax is the maximum allowed temperature.The same formula is adapted for calculating weighted under-heating hours with (**Tmin – Top**).

For a better understanding of the thermal performance of the buildings, three different values were considered for Tmax and Tmin.

a. ***Adaptive standard WOH/WUH***: Tmax & Tmin are based on the German standards of DIN EN15251 NA as shown in Figure 4.2. This method of comparison also considers overheating during winters (Fraunhofer IBP, Thermischer komfort im Büro für die Planungspraxis). Good performance in this indicator, 'Adaptive WOH/WUH' would mean that the building's ability to provide good adaptive thermal comfort as recommended by the German and European standards.

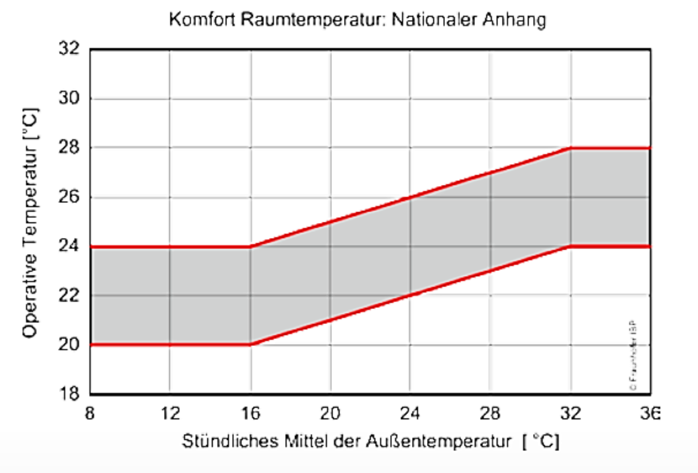


Figure 4.2 Adaptive standard DIN 15251 temperature limit recommendations

b. ***Individual setpoints WOH/WUH:*** Tmax and Tmin are the cooling and heating setpoints in each of the corresponding variants which vary among 27°/ 25° and 21°/19° (since the max allowed set point temperature are 26°, 24°C & 22°, 20°C for cooling and heating respectively). This method can provide insights into the building's ability to provide more than just the basic comfort ensured by the German standards but also the comfort demanded by individual users.

c. ***Basic WOH/WUH:*** Tmax & Tmin is assumed to be 28°C & 20°, corresponding to Class D temperature summer limits in actively cooled buildings (Boerstra, van Hoof, and van Weele2015).

A comparison between the 'adaptive standard' and 'basic' indicators can help identify if the overheating & underheating hours occur at the 'extreme' limits of under 20°C or over 28°C. If the results from the Adaptive WOH/WUH are higher than the absolute WOH/WUH, it indicates that those hours occur in during the shoulder periods and these issues created by incorrect operation. For example, the difference in the two results are hours of overheating occurring during the shoulder seasons or in the winter and temperatures being between 24° to 28°. This is illustrated in an example graph, fig 5.2.2.1, where the indoor operative temperature is plotted against outdoor temperature. The red dots represent the average indoor temperature of each hour. The ones above the red line are the overheated hours and they occur when the outdoor temperature is below 20°C. This can easily be solved by simply opening the window and underheating by closing the window before it gets too cold or by reducing active cooling.

4.2.3 Performance indicators for robustness in energy performance

To compare the energetic robustness of each building, the annual Heating energy and cooling energy per square meter are considered as indicators. This is calculated by, first, mathematically dividing the floor areas of architectural plans of both buildings based on usage and orientation to make a few representative zones, in this study 6 and 8 zones were considered for Kolbermoor and Ravensburg respectively, then, thermally simulating all the variants for each representative zone and lastly, calculating a weighted average of the heating & cooling energy for the entire building based on the floor areas in kilo watt-hours per square meter [kWh/m²].

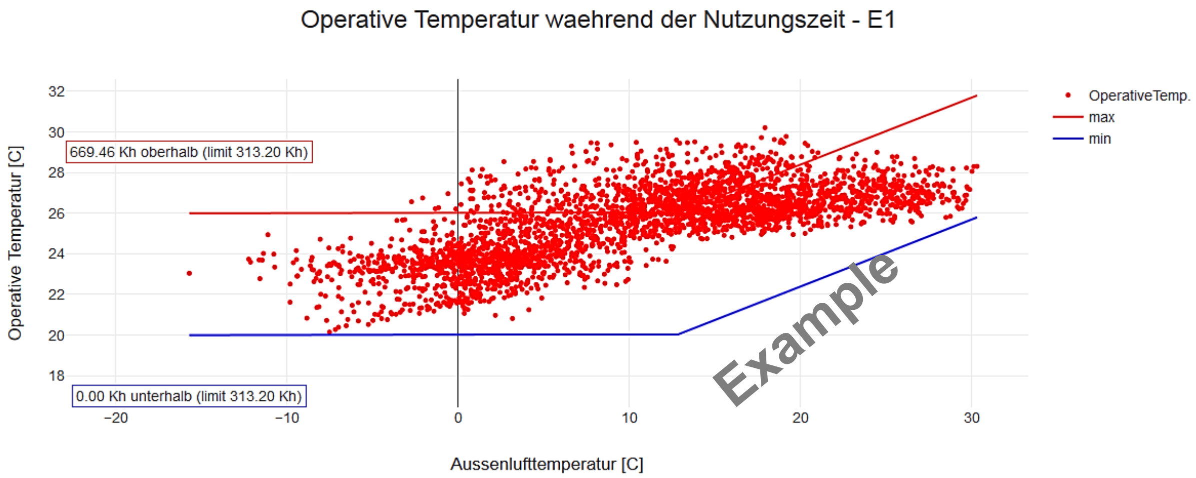


Fig 5.2.2.1 Example graph: Indoor temperature is plotted against outdoor temperature of a random variant showing overheating hours during Winter/shoulder periods.

4.2.4 How to read the performance indicators

Sensitivity studies usually employ this box and whiskers graph way of comparison and the same is used for this study as well. The 288 and 216 variants' results of both buildings are represented as a dot, as shown in the example figure below, and a box encases 50% of the dots/results to help understand and compare the probable outcomes of all the cases in both (or many) buildings. The box is well explained by the following Figure 4.3. The imaginary box represents the range in which 50% of results lie. The 'whiskers' represent the greatest and least value of the result excluding the 'outliers'. The 'outliers' are data points representing the results whose values are too high or low when compared to the rest of the data and are usually more than 1.5 times the interquartile range above the upper quartile and below the lower quartile.

The main take away from these graphs is that the probability of results lying within the box are high as it contains 50% of the variant results. In other words, half of the tested cases' energy demand results lie within this box. However, there is also a 25% possibility of a result lying in either the upper or the lower quartile.

The longer the box, the larger is the output range, indicating that the building has a larger reaction to external changes and so, is more sensitive. Shorter the box, less sensitive is the building and hence, more robust. In the above example diagram, building B is the most robust amongst the three as it has the shortest box, even if the median lies above that of building A.

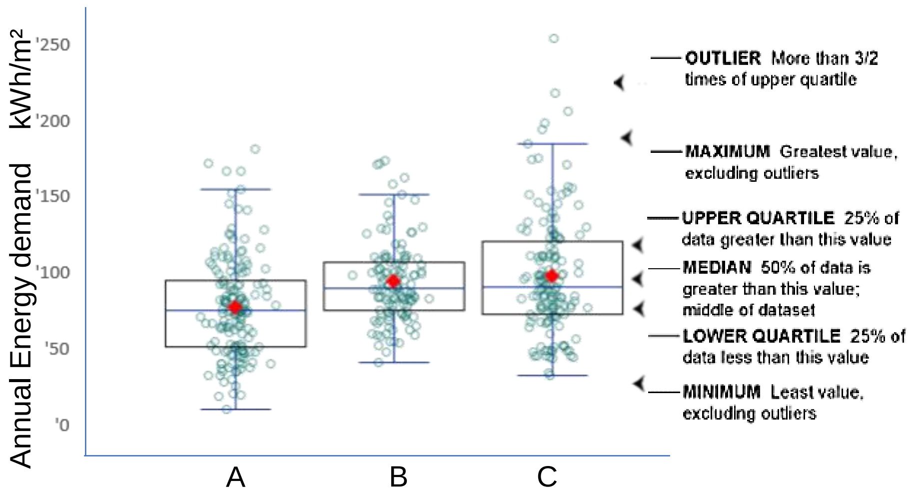


Figure 4.3 Explanation of a box and whiskers graph with an example.

4.3 Energy Simulation Model Validation

Validation is done to check the accuracy or correctness of the computer model simulations with reality. The measured indoor air temperature was used to match simulation result's temperature curves. The measured CO2 level helps in understanding the window operation and the controls were similarly matched in the model. Although measurements for illuminance was recorded, the absence of the information of the exact solar radiation on this occupant's façade makes it difficult to assess individual thresholds. However, interviews provided the information about their general preferences.

The two energy simulation models were first constructed according to the details of the previously simulated model by the climate designers for energy prediction before construction. The user behaviour was then adapted to mimic a real user whose office was being monitored and simulated. The temperatures from the computer simulation results and the measured air temperature and/ CO2 concentrations are compared to check for the correctness of the model. The same duration of one week, from 2nd and 8th July 2018, was considered for both buildings. This period was chosen carefully based on uniformity in user behaviour for accurate and simpler programming of the controls. The Simulations for both buildings were run for one extra day, viz. 1st - 8th July, to compensate for the start-up heating calculations as a default of 0°C room temperature is assumed which gives warped results and should be excluded from considerations. The weather data from the closest weather station was used for the simulation.

Ravensburg

The absence of one of the occupants being monitored, which is indicated by the flat CO2 level, make programming the controls very simple (refer fig.5.3.1). There was no occupant, therefore, occupancy schedule, internal gains, window operations, or shading overrides, etc. The model results show a close similarity in the indoor air temperature trends. The green line in Figure 4.5 shows the measured indoor air temperature, blue the ambient outdoor temperature and yellow the CO2 level. The indoor temperature varies between 22-24°C and between 24-25°C for a few hours on 3 days. Fig 5.3.2. shows that the temperature range matches the measured range closely.

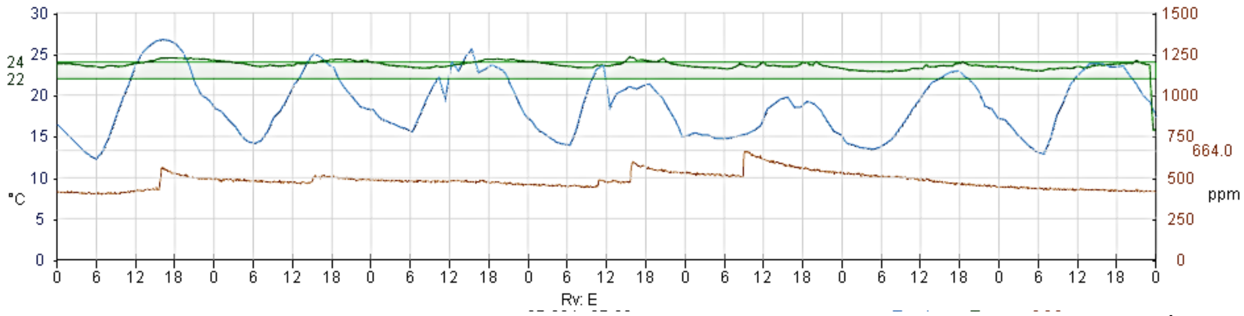


Figure 4.5 Monitored data of East oriented office in Ravensburg for one week (2nd to 8th July 2018) showing indoor & outdoor temperature and CO2 concentrations.

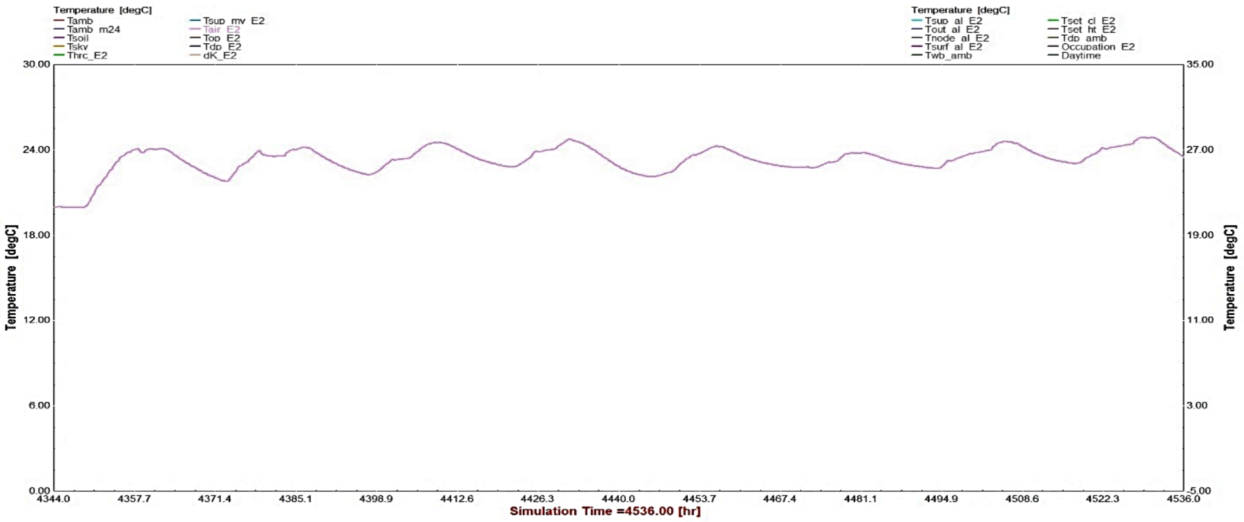


Figure 4.5 screen capture of computer simulation model result of Ravensburg, showing indoor air temperature for 1st- 8th July 2018.

Kolbermoor

There were no periods where an occupant was absent for an entire week, and so a fairly uniform behaviour was chosen to be mimicked as closely as possible. As seen in Fig 5.3.3, the measured CO2 concentration starts to increase at 7.00 and decrease uniformly after 17.00, indicating that the occupant works between 7.00-17.00. The absence of a sharp increase in CO2 level and the jagged feature of the CO2 line indicates that they do not keep the window shut and probably slightly open.

To imitate this behaviour, the CO2 level threshold of 800 along with a 30 m³ unconditioned air supply by the mechanical ventilation, an occupancy schedule between 7.00-17.00 was simulated and the resulting temperatures match closely to the measured values which lie between 22 & 24°C as shown in Figure 4.7.

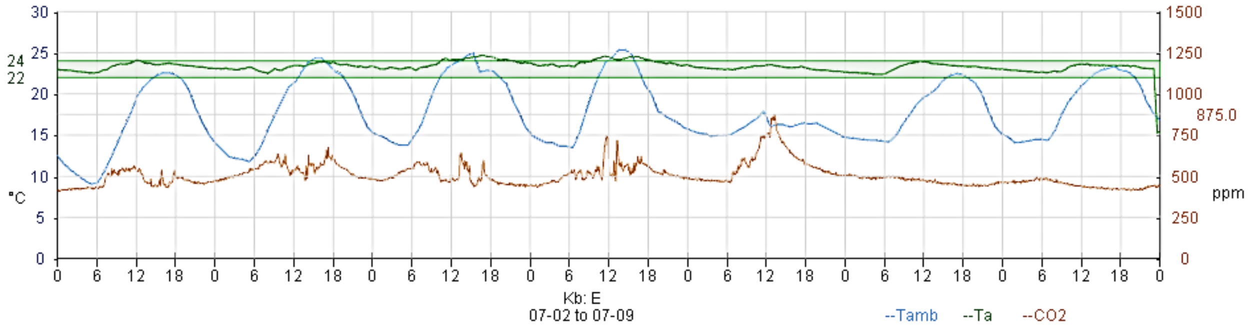


Figure 4.7 Monitored data of East oriented office in Kolbermoor for one week (2nd to 8th July 2018) showing indoor & outdoor temperature and CO2 concentrations.

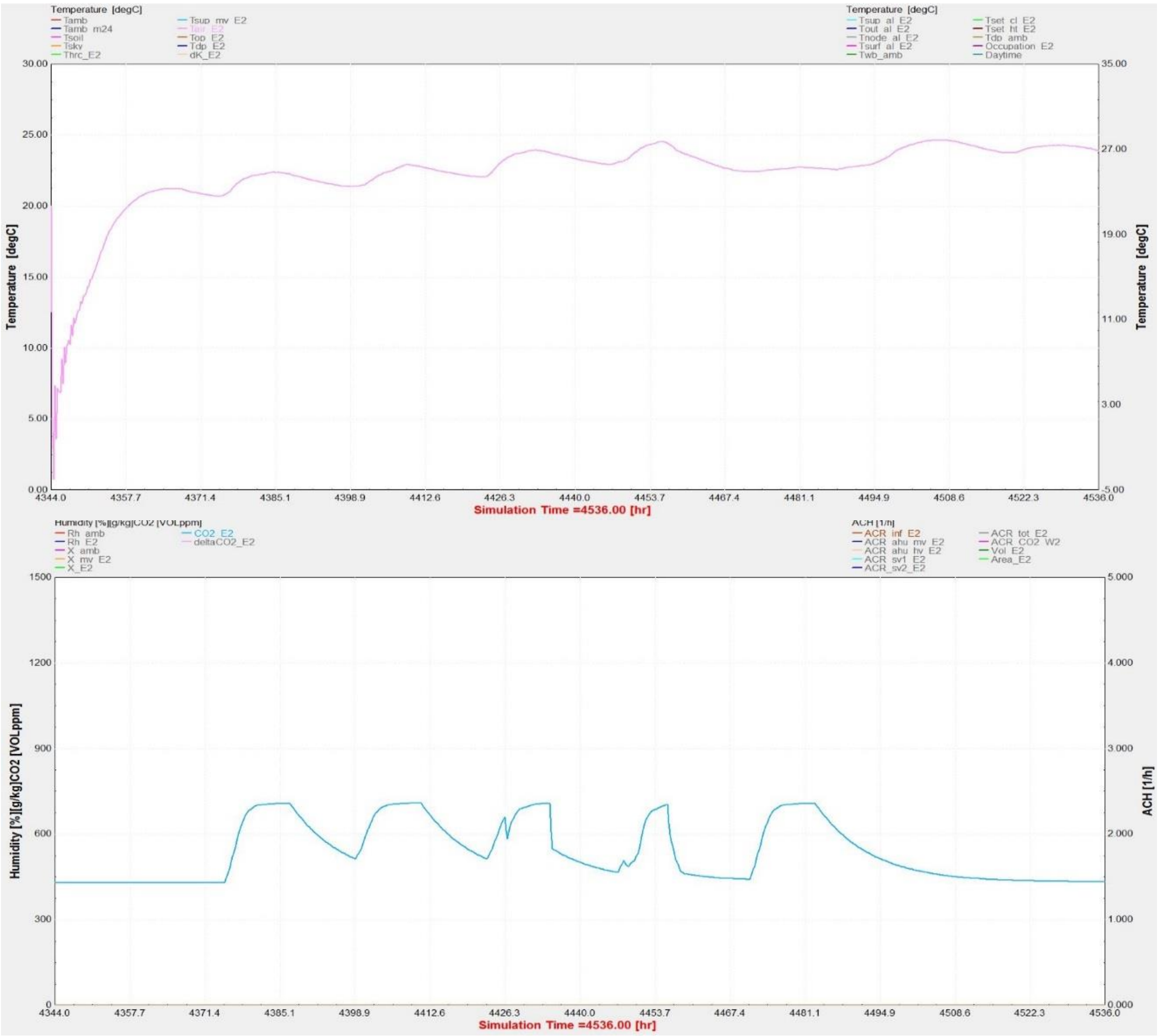


Figure 4.7 Screen capture of computer simulation model result of Kolbermoor, showing indoor air temperature and CO2 for 1st- 8th July 2018.

4.4 Results: Energetic robustness

4.4.1 Robustness in Heating energy:

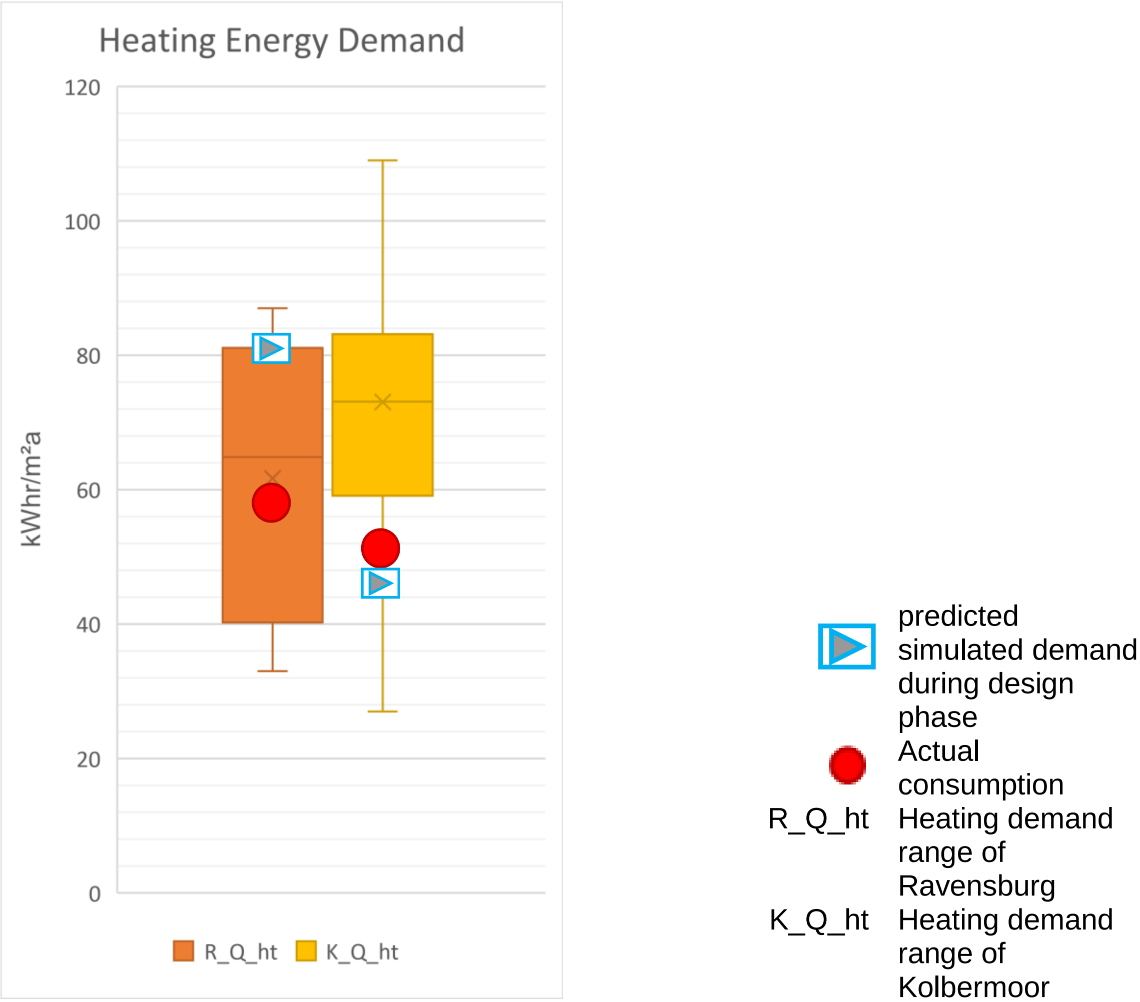


Figure 4.8 Net Heating energy demand comparison for Uncertainty analysis.

Uncertainty analysis observations

The length of the box, in Figure 4.8, represents the robustness. The shorter the box, the less sensitive and hence more robust. The box + whiskers represents the results for all the scenarios considered, excluding some possible outliers. But the box alone represents 50% of scenarios and the whiskers, the rest. From the various scenarios of user behaviour patterns simulated in this study, Ravensburg, has an overall slightly smaller range than Kolbermoor when both the box <u>and</u> the whiskers are considered. While Kolbermoor's box is shorter but whiskers longer.

The median of Ravensburg is at 65 kWh/m²a while Kolbermoor is at 72 kWh/m², meaning that half of the simulation results lie above and the other half below this value. In Ravensburg, the higher end of behaviour scenarios could result in a consumption of between 65 and 85 kWh/m²a; while that of Kolbermoor, lies between 72 and 110 kWh/m², having a slightly larger range and with a higher value. Statistically, Kolbermoor would be considered as more robust due to the higher concentration of the results in a smaller range. However, this also means that statistically the resulting energy consumption would also have a higher value than of Ravensburg.

Reasoning

Logic suggests that the higher energy demand in Kolbermoor can be due to the higher glazing ratio. The considerably high U-value of glass allows larger heat losses to occur as compared to walls. This would naturally increase the need for more active heating. Another contributor can be the carpeted floors which are not as efficient in conducting heat and would hinder the floor heating. The glazing used in Kolbermoor is a double-paned sun protection having a higher U value of 1.11 W/m²K as compared to a lower 0.7 of the triple-paned heat protections glazing in Ravensburg. Higher U-value results in a higher heat conduction, in this case, unwanted heat losses through the large windows, while the sun protection blocks solar radiation which is important for avoiding overheating during the summer. The higher thermal mass and smaller window sizes in Ravensburg is more suitable for a glazing which protects the heat from escaping, hence the triple-pane.

Kolbermoor should have a slightly higher heating demand which is not seen in the results because the offices on the top floor which lose most heat were not considered in the simulations. These, in fact, were considered in Ravensburg because they were considered in the simulations done for prediction and also, two of the monitored offices were on the topmost floor.

Table 7 Comparison of actual consumption and predicted demand

Net Heating energy demand [kWh/m²a]	Ravensburg	Kolbermoor
Prediction	82	50
Actual	61.2 (90% of site energy = 68)	56.7 (90% of site energy = 63)

The red dots, in Figure 4.8, represent the current measured energy consumption while the blue box, the simulated prediction during the design stage as shown in the Figure

4.8. The measured site heating energy consumption of Ravensburg from July 2017 to June 2018, as received from the facility manager, is 68 kWh/m²a which is slightly higher than the 63 kWh/m²a of Kolbermoor. To convert the site energy to net energy for comparability,10% transmission losses are considered.

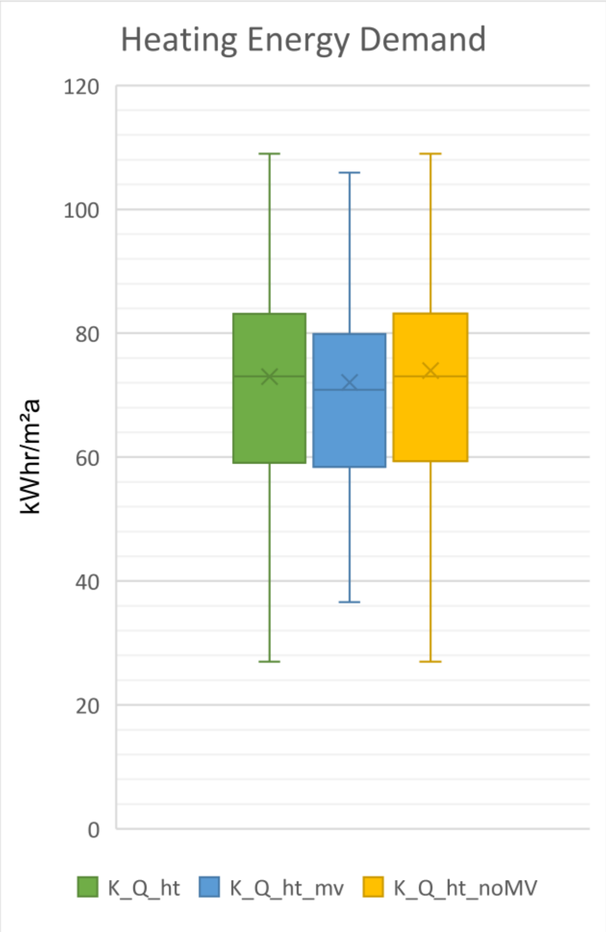
Reasoning

The performance gap of around 7 kWh/m² seen in Kolbermoor is not very significant and is normally expected. The actual consumption at Ravensburg is much lower than predicted and this is because a very pessimistic prediction was made. The energy simulations had only considered the zones of the top floor which lose considerably more heat being in direct contact with the outside air, unlike the middle floors.

The energy consumption may not be accurate as the value is for the entire building which also includes larger areas like halls, library, school, some of which have different heating concepts. A separate energy consumption value for the office areas was not possible to obtain.

There is a possibility of a reduction in the energy consumption in Ravensburg a few years after fine-tuning the systems as it has only seen one year of usage at the time of this study. However, this is not guaranteed as it also highly depends on user behaviour. The simulation prediction was pessimistic, showing a higher demand because all the zones were simulated with an external roof which loses more heat.

4.4.2 Heating energy without mechanical ventilation



K_Q_ht	Heating demand range of Ravensburg
K_Q_ht_MV	Heating demand of Kolbermoor with mechanical ventilation & heat recovery (70%)
K_Q_ht_NoMV	Heating demand of Kolbermoor with ONLY natural ventilation

Figure 4.9 Net heating energy demand of Kolbermoor, with & without mechanical ventilation

Uncertainty analysis observations

The buildings were simulated with their energy and comfort concepts to get a realistic and holistic understanding of their performance, which means that mechanical ventilation was modelled in Kolbermoor even though it was not in Ravensburg. However, to test the benefits seen by the mechanical ventilation under various behaviour scenarios, the parametric simulations were run without any mechanical ventilation. The results are illustrated in the graph above, refer Figure 4.9

The yellow box on the right end, in Figure 4.9, represents the heating demand range for the Kolbermoor building without mechanical ventilation. It is only slightly longer and ranges between 26 and 110 kWh/m² while the range with mechanical ventilation is between 36 and 106 kWh/m².

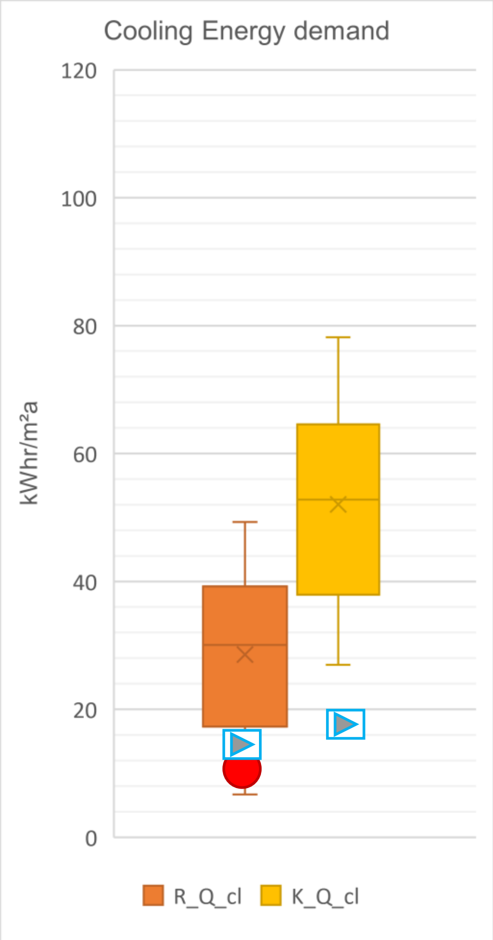
Reasoning

The benefits of mechanical ventilation or its heat recovery is not seen because the windows are also operated alongside when the CO2 level is above a threshold or if the space over heats. The reason for the windows to be opened in the simulations can be because of two main reasons: if the designed air supply of $30m^3$ per person was insufficient or if the inefficient shading operation caused overheating which also would make the controls open the windows. Lower energy demands can be obtained in the simulations by increasing the volume flow however, this is not tested as the designed vol flow rate for Kolbermoor was $30m^3/p$. The electrical energy for the mechanical ventilation should be considered as a cost, which is not done for this study.

The user behaviour study found that a 100% of the sample group would like to open the windows manually regardless of the existence of a mechanical ventilation system for many reasons such as the preference to natural fresh air, indoor smells, health etc. It is also suspected that a considerable number of people did not know how the ventilation system works and since it is not connected to the BMS and there is also no automatic schedule, it is hard to know how the people use the system. It was also mentioned that when it on the lowest mode supplying 15 m^3, it does not make any noise, making it hard to identify if it is running. This could even mean that it is permanently on or off, if the occupants do not know how to control it or forget to switch it off.

In conclusion, the improper/ inefficient operation of the windows and the mechanical ventilation could result in high deviations in the energy consumption which, when not considered, can result in unexpected high energy costs for a building.

1.1.1. Robustness in cooling energy:



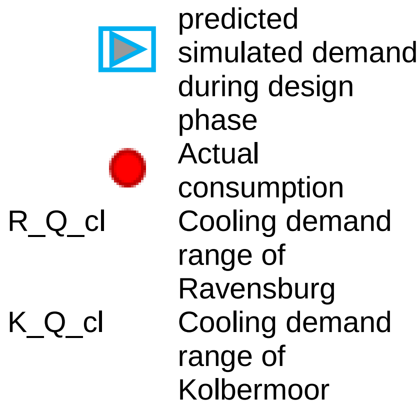


Figure 4.10 Net Cooling demand results from the uncertainty study

Uncertainty analysis observations

The yellow box, in Figure 4.10 ,representing Kolbermoor is longer representing a larger reaction range to changes in occupant behaviour. The median line (56 kWh/m²) of the yellow box lies above the end of the whiskers of the orange box (50 kWh/m²). This means that in Kolbermoor, 50% of the scenarios can have cooling energy demands higher than the that all the scenarios in Ravensburg. However, the lengths of the boxes are similar, suggesting that the amount of deviation caused by user behaviour is similar relative to the individual buildings. Therefore, both buildings are equally robust as they are equally reactive, even though the overall cooling energy consumption for the same behaviour can be lower in Ravensburg.

Reasoning

The higher cooling energy values in Kolbermoor complies to the expectation that a building with larger windows would have higher solar heat gains and thus, a higher cooling demand. Kolbermoor also has a double cooling system, floor and ceiling cooling, this also is a reason for the higher cooling energy consumption. The volume of the offices in Kolbermoor is lesser leading to faster overheating potential which needs more cooling.

The external shading in Kolbermoor is manually operated and this was simulated in the model by setting which only closes it during work hours allowing possible overheating during the mornings and weekends. A higher solar radiation threshold of 250 W/m² is set as the closing signal while in Ravensburg, the shades would be signalled to close at 150 W/m². This is done to mimic human inefficiency in the reaction to close the shades to prevent overheating.

Table 8 Comparison of actual consumption and predicted demand:

Cooling energy demand [kWh/m²a]	Ravensburg	Kolbermoor
Prediction	13	18
Actual	14	Undetermined

The measured cooling consumption and estimated prediction are quite close 13 and 14 kWh/m²a and is the lower than the average and the median in the case of Ravensburg. It is unclear whether the real consumption matches the simulation in the case of Kolbermoor because the correct COP value of the pumps could not be obtained. This is needed to calculate the cooling demand because the only value received was the electrical energy for the pumps that pump the groundwater which is the cooling source.

Kolbermoor's predicted cooling energy value is lower than the all the results of the uncertainty analysis and it can be because of the difference in shading controls. The initial concept by the designers of the energy concept recommended automated shading and so the for the energy prediction also simulated the shading closing at a solar radiation of 150W/m². The uncertainty analysis considers a higher threshold of 250W/m² thus allowing more solar heat gains. The absence of controls outside the work hours also significantly increase the cooling energy demand.

4.5 Results: Thermal Comfort Robustness

4.5.1 Winter thermal comfort:

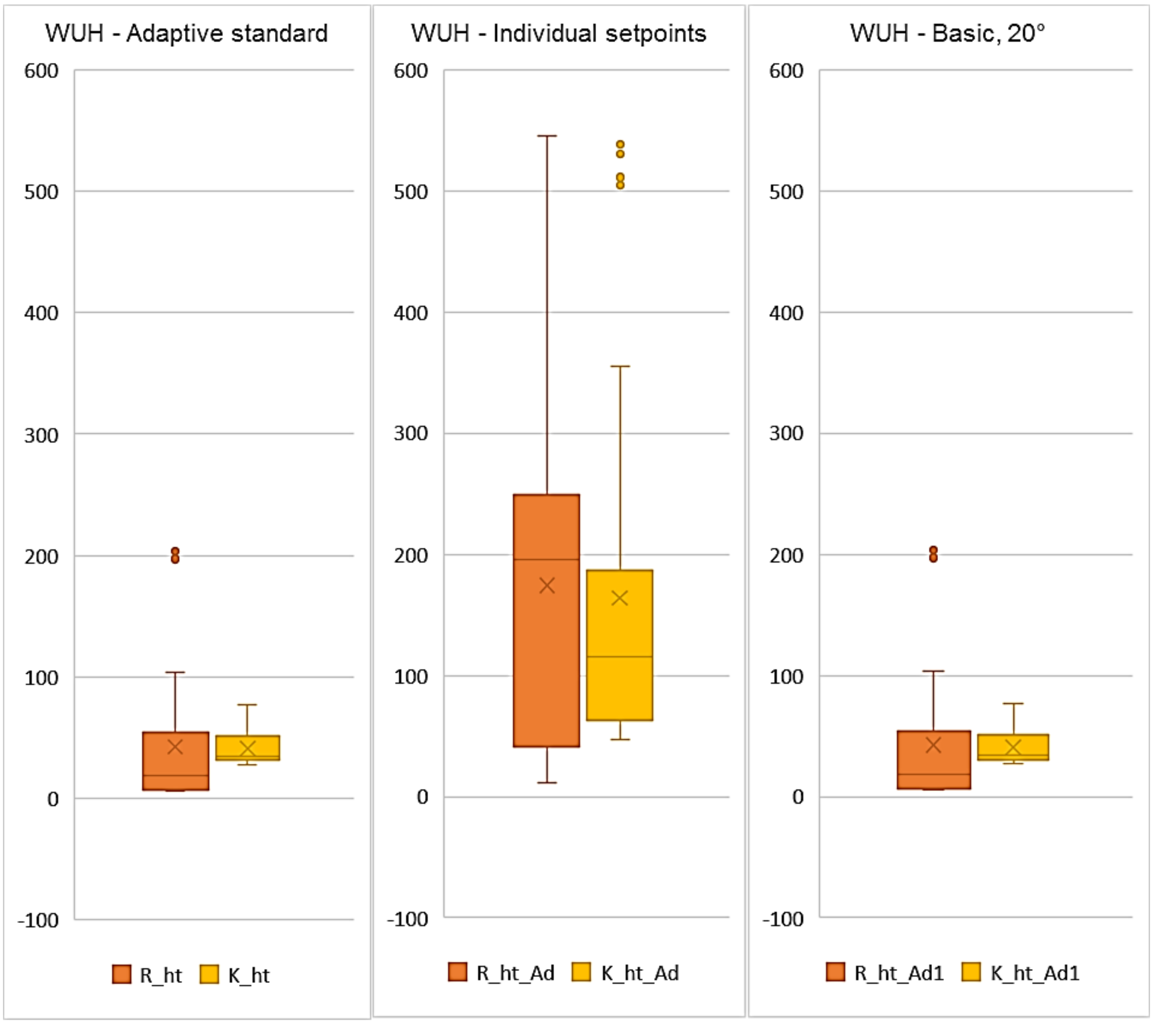


Figure 4.11 WUH or underheating hours results from the uncertainty study

Weighted Under-heating Hours (WUH) are shown in the graphs in Figure 4.11. As explained in detail in the chapter 4.2.2**,** WUH is the number of hours and degrees by which the indoor operative temperature is below a target temperature, in simpler terms, the hours when it is too cold. Three target temperatures used for calculations are:

- Adaptive standard: The min temp. recommended by the German standard: DIN 15251 NA, which is 20°C in winter and 24°C in Summer.
- Individual setpoints: The individual setpoints which can be 20° or 22°C.
- Basic: 20°C in all the seasons.

As mentioned earlier in chapter 4.2.4, the shorter box indicates that the range of reaction is smaller. In other words, this building would be more stable in providing thermal comfort, less sensitive to changes and can be called more ‘Robust’. In all the three graphs, Kolbermoor performs better, as the yellow boxes are shorter and have a lower average and maximum values, hence, can be called more ‘Robust’.

As mentioned in the previous chapter 4.2.2, three performance indicators are used when normally just one is because: (1) good performance in the first graph shows that the building provides good adaptive thermal comfort as recommended by the German and European standards. (2) The second graph can provide insights into how well the building can provide the comfort demanded by individual users which may be more than the basic comfort ensured by the German standards. (3) A comparison between the first and third graph can confirm that the overheating & underheating hours occur only at the ‘extreme’ limits of under 20°C or over 28°C. If the values are higher in the first graph, then it indicates that those hours are occurring in during the shoulder periods and these are solvable by the correct operation. Overheating solved by natural ventilation and or underheating by either reducing cooling or closing the window before it gets too cold.

Adaptive standard:

In the first graph, where the target temperature is defined by the German adaptive standards, all the cases result in WUH values between 0 and 100-kelvin hours. Both buildings provide good thermal comfort in winter but Kolbermoor is clearly more robust without much fluctuations in the thermal comfort.

Individual setpoints:

In the second graph, the target temperature can be either 20° or 22°C depending on the heating setpoints assigned for that case. Ravensburg performs worse with a maximum of 550 Kelvin hours (Kh) while only about 200 in Kolbermoor. The size of just the box is much smaller as well. With the median at around 60 Kh, half of the scenarios have underheating hours between only 40-60 Kh. Kolbermoor is more stable in providing winter thermal comfort to the satisfaction of the occupants.

Basic:

In the third graph, shows that both buildings provide robust winter thermal comfort since both the boxes are compact and do not exceed 100 Kh even in the worse scenario tested. Interestingly, these results are identical to those calculated by the DIN Standards.

This suggests that most of the overheating hours are occurring between a temperature of 22° and 20° in Ravensburg, which may be totally unacceptable by only a few.

Reasoning

The better comfort provided by Kolbermoor can be due to the higher percentage of floor covered in active heating considered in the zone, lower ventilation heat losses through the windows because of the mechanical ventilation

4.5.2 Summer thermal comfort

The Weighted Overheating Hours (WOH) is shown in the graph Figure 4.12. The windows opening signal in the case of overheating was implemented in the simulation models, as already mentioned earlier. This avoids preventable overheat significantly. This efficient behaviour cannot be guaranteed, especially when there is no occupant present to operate

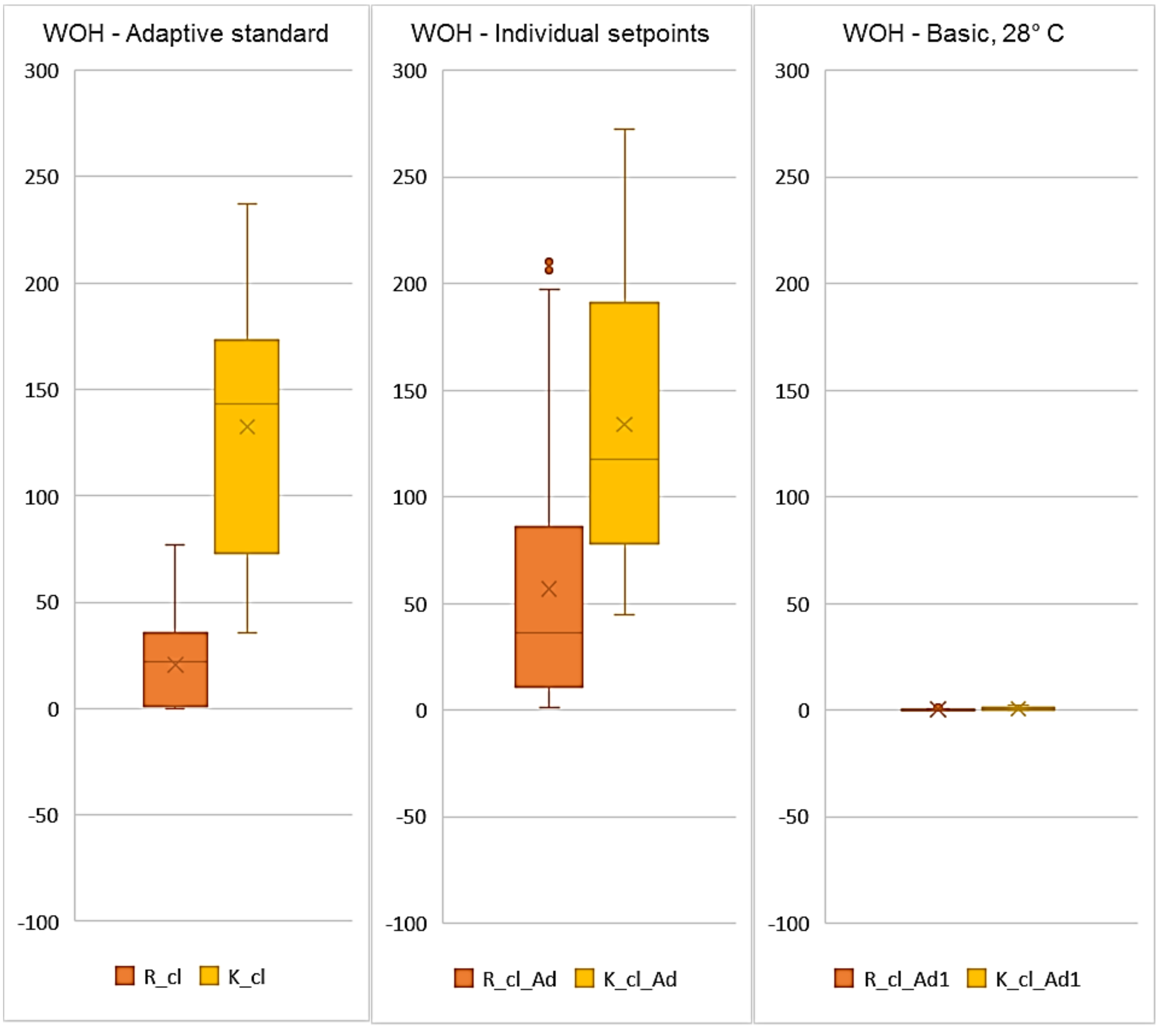


Figure 4.12 WOH or overheating hours results from the uncertainty analysis.

the window. For example, an occupant in Kolbermoor complained that the heavily glazed corridor was overheating simply because no one was continually present to manually close the shading or open the windows.

Adaptive standard:

The Orange boxes clearly much smaller than the yellows ones, indicating that Ravensburg is more robust can provide reliable summer thermal comfort. Even with the controls to open the windows to avoid overheating, Kolbermoor's building ends up with a much high number of overheating hours. Three quarters of the same scenarios have a much higher WOH than that of the same scenarios in Ravensburg.

Individual setpoints:

The second graph calculates the overheating hours by individual cooling setpoints for each case. The performance of Kolbermoor remains similar but Kolbermoor shows a higher range. This indicates that Ravensburg, although provides good adaptive comfort, has some difficulty in providing enough cooling to reach 24°C or 26°C and overheating hours occur with temperatures between 26 and 28°C.

Basic:

Both buildings are excellently robust in providing the basic summer comfort of 28°C regardless of any behaviour patterns tested. The difference of performance between adaptive and basic indicates that the overheating hours occur during the shoulder period despite the measures taken to get rid of the heat by having a window control.

Reasoning

The reasons for overheating would be the same as the reasons for high cooling demand as mentioned earlier. Bigger windows in Kolbermoor, paired with manual shading operation without sun protection during the non-working hours and weekends can result in high temperatures in the zone. Although both buildings provide good basic comfort, Kolbermoor overheats during the shoulder seasons and natural ventilation does not seem to be sufficient to disperse the accumulated heat. Never the less, since most of the overheating occur between temperatures of 24 and 28°C, it may still be satisfactory to many.

4.5.3 Passive summer comfort robustness

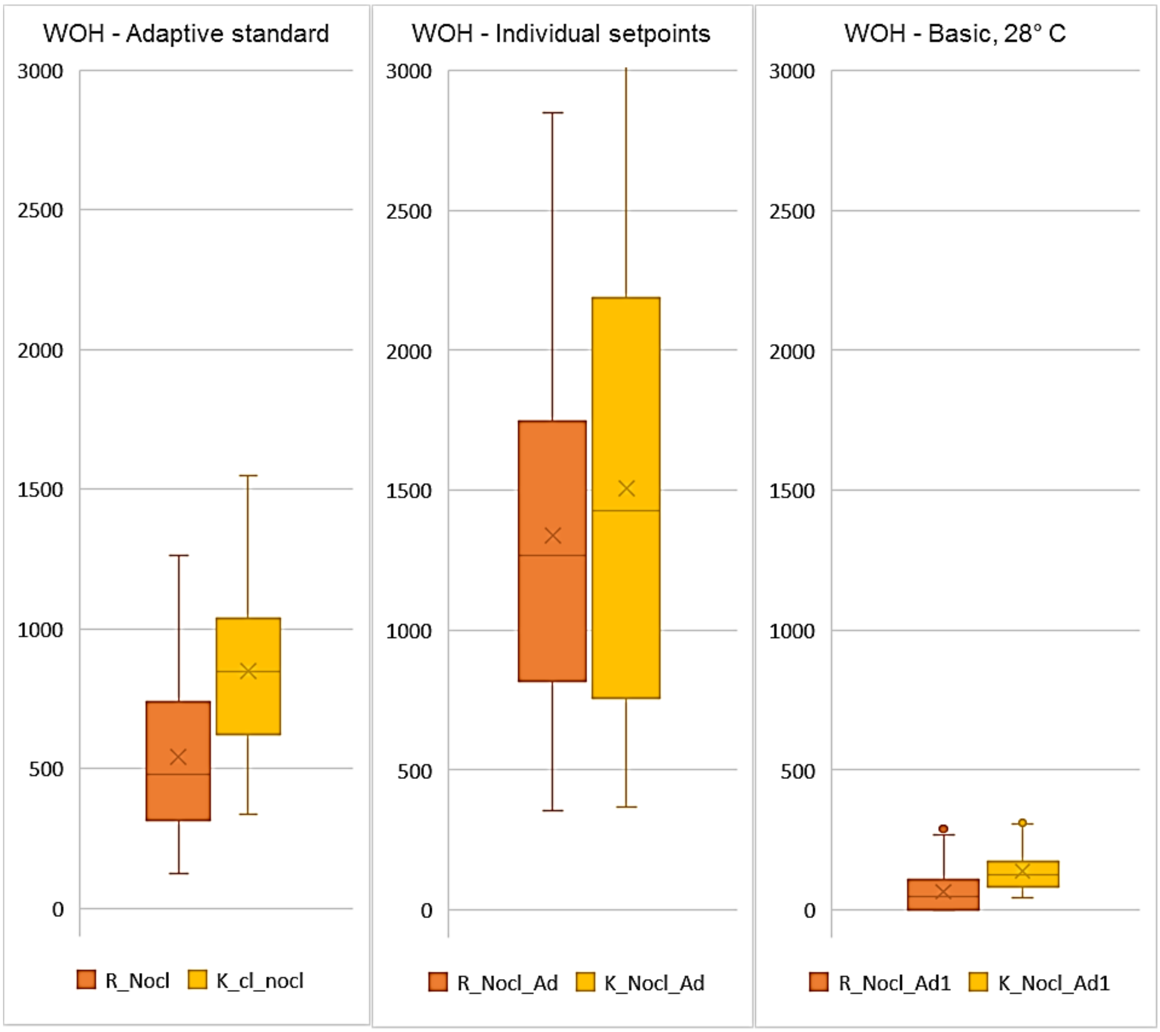


Figure 4.13 WOH or overheating hours results from the uncertainty analysis testing passive robustness without active cooling.

To understand how the buildings, perform passively in the summer, they were simulated with all the cases but without any active cooling. The results, as illustrated in Figure 4.13, show that Ravensburg performs much better in providing thermal comfort in the summer with 50% of the cases having less than 500 Kh and 75% of cases below the median of Kolbermoor. The high glazing ratio is probably the reason for Kolbermoor being highly sensitive. In Kolbermoor, 75% of the behaviour patterns, the overheating hours are between 600 to 1550 Kh. Never the less, both buildings are still able to provide temperatures below 28°C.

4.6 Conclusions

4.6.1 Energetic robustness

Ravensburg, has an overall slightly smaller range than Kolbermoor when both the box and the whiskers are considered. While Kolbermoor's box is shorter but whiskers are longer. Statistically, Kolbermoor would be considered as more robust due to the higher concentration of the results in a smaller range. However, this also means that statistically the resulting energy consumption would also have a higher value than of Ravensburg.

Both boxes have similar sizes indicating that they have similar robustness but Kolbermoor has a higher cooling energy demand. The higher window to wall ratio, two-paned sun-protection glazing, and manual shading operation in Kolbermoor which allow unwanted heat gains and escape of heat are indicated to be the combining reasons for the higher heating and well as cooling demands for many scenarios tested.

The behaviour analysis in chapter 4, clearly showed that shading is not operated as recommended in most of the cases and the automated operation is also overridden for better view or daylight. This increases the importance of having a robust shading system or a robustly optimized glazing ratio which allows sufficient daylight and view, and which does not need to rely on the responsibility of the users to behave correctly or on the non-failure or malfunction of the automated systems. This would lead to an energy performance which is more consistent and does not greatly deviate from the predicted consumption.

There are no significant benefits seen from the mechanical ventilation when it is used in combination with natural window ventilation since the energy & comfort benefits from the heat recovery is negated by the ventilation losses when the windows are opened due to insufficient fresh air or overheating. Neither the energy heating energy consumption nor the under-heating hours rise much without any mechanical ventilation. It was also found that the users of the building do not widely use it due to noise/ draught/ lack of know-how/ personal preference. If in this case, the results of scenarios run without the mechanical ventilation would be applicable.

4.6.2 Thermal comfort robustness

Kolbermoor's building is more robust in providing winter comfort owing to larger floor activated area, Solar heat gains during non-working hours, and the slightly smaller room volume leading to higher internal gains per m². However, it may not be so robust in terms of heating energy consumption as the variation seen has a wide range.

Most of the underheating hours (WUH) occur between temperatures of 20°C and 22°C in both buildings, however, in Ravensburg, the number of hours is much higher for many scenarios.

Ravensburg's building is more robust in summer comfort performance due to its smaller windows and automatic shading blocking unwanted solar radiation. Most of the weighted overheating hours (WOH) are between temperatures of 24-28°C in both buildings. Bigger windows in Kolbermoor, paired with manual shading operation without sun protection during the non-working hours and weekends can result in high temperatures in the zone. Although both buildings provide good basic comfort, Kolbermoor overheats during the shoulder seasons and natural ventilation does not seem to be sufficient to disperse the accumulated heat. Never the less, since most of the overheating occur between temperatures of 24 and 28°C, it may still be satisfactory to many.

The scenarios were simulated without any active cooling as a test for comparing their passive design performance and to mimic cooling malfunction. Ravensburg's building clearly performs better than Kolbermoor without any active cooling systems because of the same reasons it has a lower weighted overheating hours and lower cooling.

In summary, Ravensburg's buildings with smaller windows, better shading control, slightly larger room volumes, uncarpeted floor, and higher thermal mass was indicated to be more robust, stable/ reliable in cooling energy consumption and summer & winter thermal comfort. Whereas, Kolbermoor's building, with larger windows, mechanical ventilation, double paned sun protection glass, with slightly smaller volumes, carpeted floors and manual shading was found to be more robust in in winter thermal comfort and statistically more robust heating energy demand but with an overall higher value.

5 Parameters influence performance

5.1 Parameter testing

The results of the Uncertainty analysis are represented in a para-plot graph for each performance indicator. This graph provides a comprehensive overview of exact inputs in boundary conditions and its resulting output. The last column on the right shows the output and the rest of the columns show the values of the inputs. The legend on the top mentions the parameter that was changed. This graph is useful because it allows one to select a certain value set for a parameter, 800 ppm CO2 threshold for example, and the results of the cases that have 800 ppm in combination with the other inputs are shown in colour and the rest of the results are greyed out. This would be helpful, for example, to know the energy consumption value range when the CO2 threshold is 800ppm. It is also possible to work backwards, meaning that if an output range is selected, the coloured lines left would connect the values causing those outputs. This would be helpful to know boundary conditions that are causing, for instance, the highest or lowest energy consumption. The results narrow down as multiple values are selected. If one value for each of the parameters is selected, then there would be a single coloured line showing one output value.

This method helps identify the parameters that result in bad performance. These would be the ones that are required to be careful during building operation.

5.1.1 Energy consumption

Heating energy demand

The Figure 5.2 & Figure 5.1 show that a two-degree difference in the heating setpoint temperature can even double the heating demand, regardless of any behaviour pattern considered in this study. Increasing the setpoint from 20 to 22° can double the energy demand in most of the scenarios.

The highest energy demand is caused by scenarios that have combinations which include one occupant and heating setpoint of 22°C, as seen in Figure 5.1. The Effect of a lower CO2 threshold can also lead to a higher heating demand because lower the threshold, the more frequently the window is opened, and heat lost. The Figure 5.5 shows

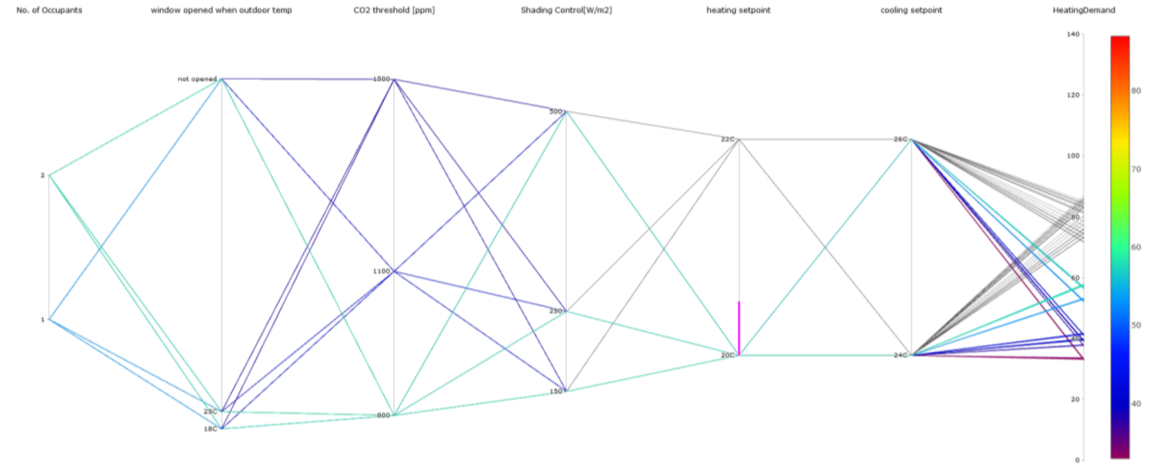


Figure 5.2 Para-plot showing heating energy demand, Ravensburg.
Comparing the effect of heating setpoint on energy demand.

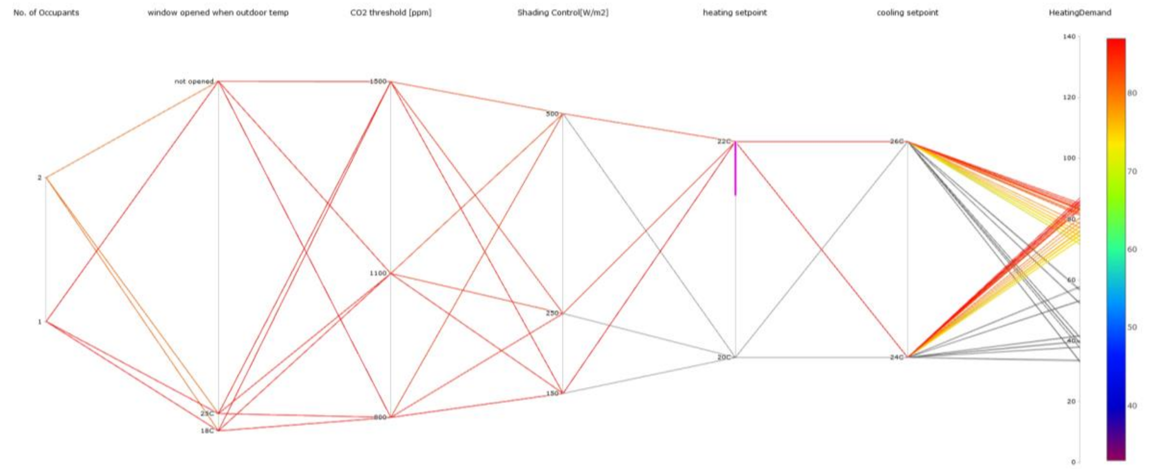


Figure 5.1 Paraplot showing heating energy demand, Ravensburg
Comparing the effect of heating set point and no. of occupants on heating energy demand.

the outputs of the scenarios that have 800 ppm as the CO2 threshold. The resulting heating energy demands are on the higher end, never the less, with combinations of the other inputs, perhaps having two occupants or having higher solar gains, can result in a lower heating demand.

A similar trend can be seen in both buildings as seen in Figure 5.5 and Figure 5.5, the lower CO2 threshold leads to higher energy demand values.

In Kolbermoor, the difference in heating demand energy with and without mechanical ventilation is not very significant, As seen in Figure 5.5., When the same boundary conditions are selected the difference in energy between having mechanical ventilation and having only natural is only around 5 kW/m². This difference is also affected by the CO2 threshold, lower the threshold, higher is the difference, meaning that when the occupants prefer good air quality of 800 ppm , then the provision of fresh air being supplied by the mechanical ventilation helps in reducing the frequency of the window being opened, however, when naturally ventilated, and when the occupants do not open the window until the ppm levels reach 1100 or 1500 ppm, then the heat losses are also minimized in a similar manner and the resulting heating energy demand is also similar. More studies would be required to learn the complexities of having a mixed ventilation system, i.e. having constant mechanical air supply and also window ventilation, to conclude about its benefits. In conclusion, the biggest influence on heating demand is by the heating setpoint and having a single occupant or a lower CO2 threshold can also result in higher energy demands.

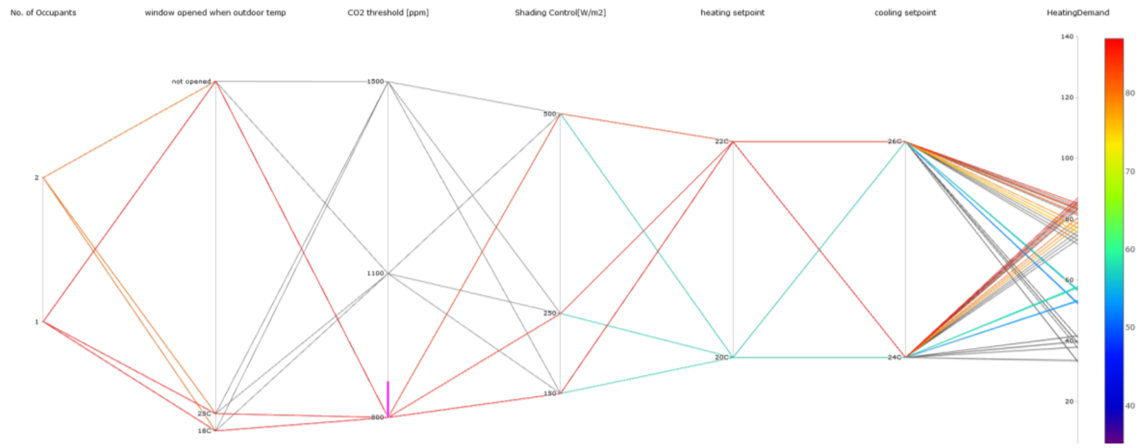


Figure 5.5 Paraplot showing heating energy demand in Ravensburg

Studying the effects of CO2 threshold on heating demand.

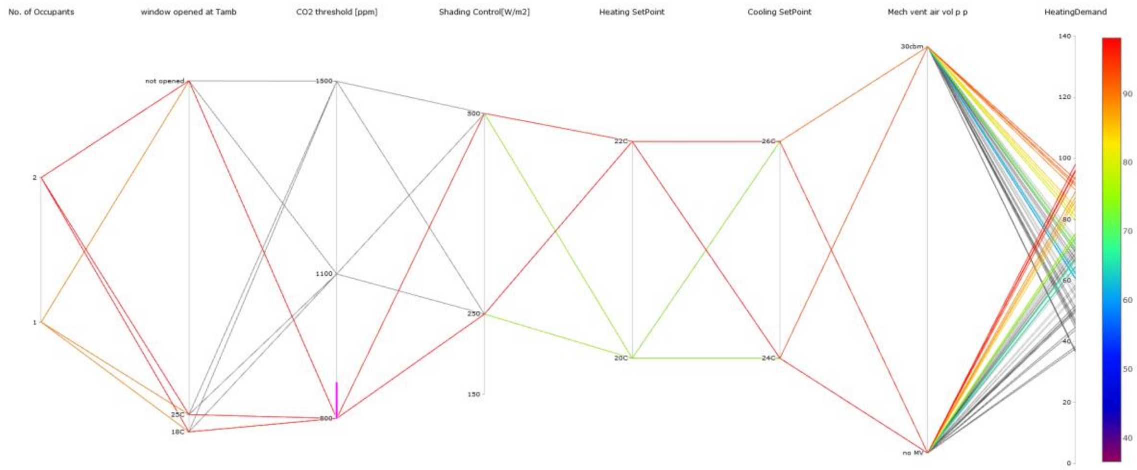


Figure 5.5 Paraplot showing heating energy demand in Kolbermoor

Studying the effects of CO2 threshold on heating demand.

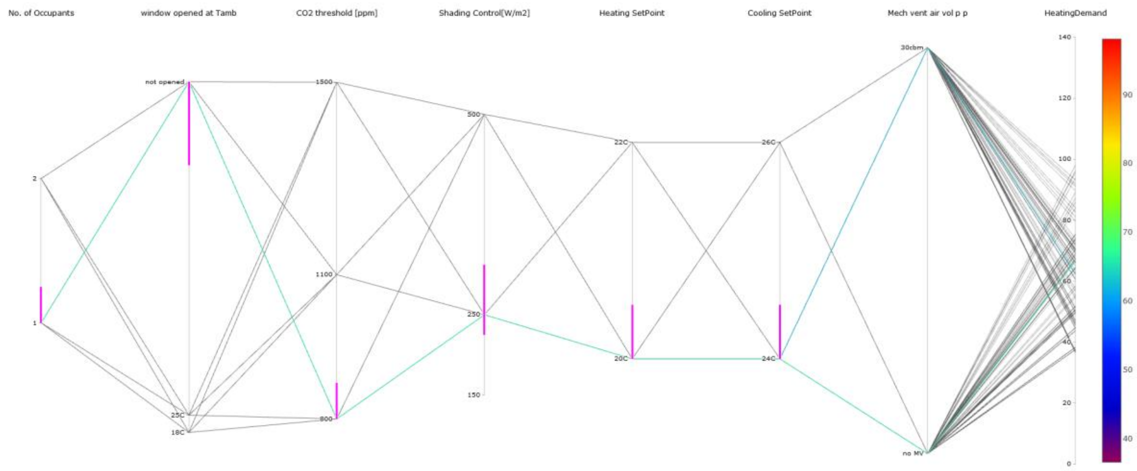


Figure 5.5 heating energy demand affected by Mechanical ventilation in Kolbermoor

Cooling energy demand

A similar observation can be made about the cooling energy demand as well. The temperature of the cooling setpoint has a certain and big influence on the resulting energy demand. Deceasing the maximum temperature allowed in the room from 26°C to 24°C can easily double the energy demand, as seen in Figure 5.6

The other parameters which result in higher energy demands are shading threshold. When the shading is closed after the solar radiation on the façade is 500 W/m², the solar heat gains are much higher as the shading does not close early enough and would require more cooling energy, as can be seen in Figure 5.7. The Highest energy demands are caused by a combination of cooling setpoint temperature being 24°C, high shading threshold of 500 w/m² and a higher occupancy of 2 occupants. This can be clearly seen in Figure 5.8.

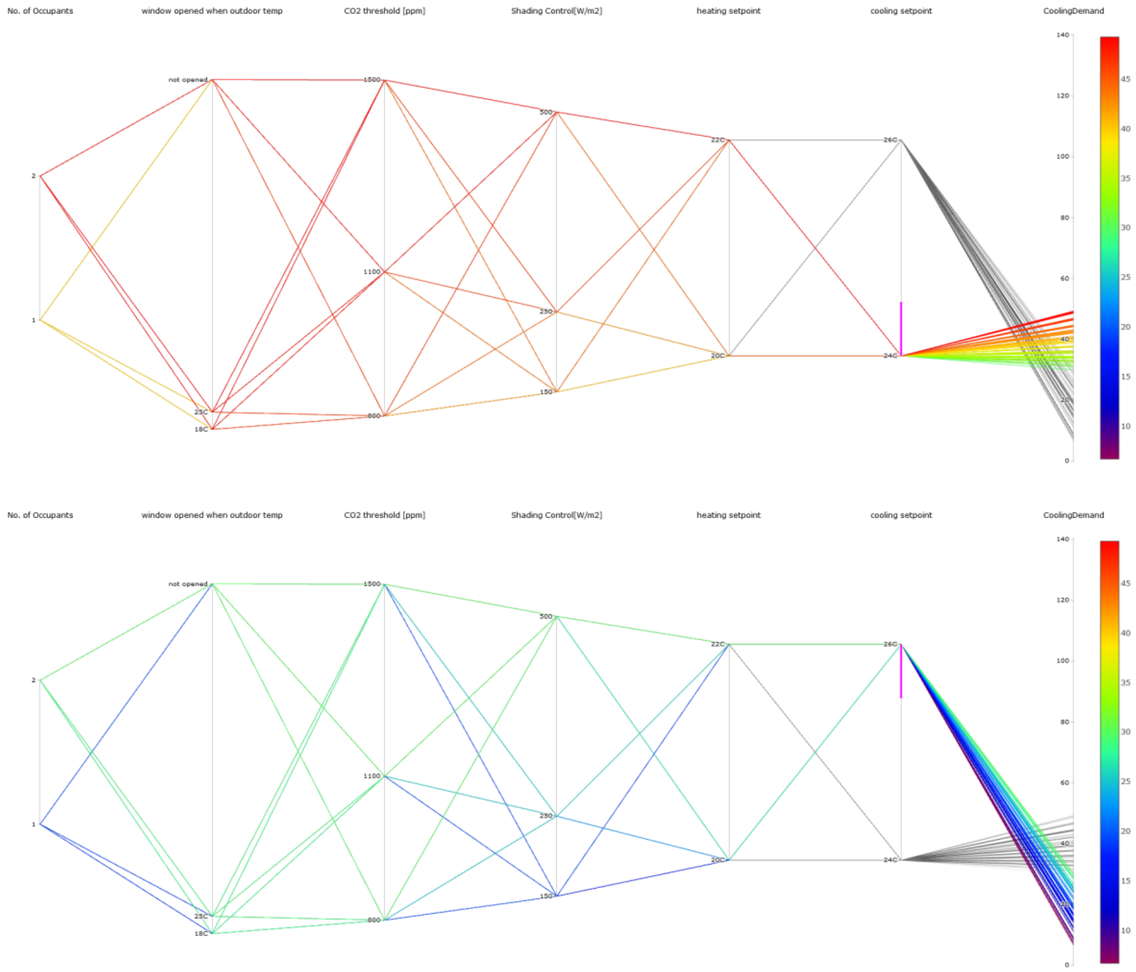


Figure 5.6 Para-plot showing cooling energy demand, Ravensburg.
Comparing the effect of cooling setpoint on energy demand.

As seen in Figure 5.8, the resulting energy demands are within a small range. However, In Kolbermoor, the output range is much wider for the same boundary conditions and can be observed from Figure 5.9. This is an indicator that the reaction shown by the building towards ‘similar’ behaviour is large and that small changing in other boundary conditions also greatly affect the final output, in other words, sensitive or not so robust.

In conclusion, a lower set point leads to higher energy consumption, sometimes double with a decrease of just 2°C. A higher shading threshold and higher number of occupants add to overheating due to solar heat gains and higher internal gains and therefore, a higher energy required to cool. Mechanical ventilation has no effect on cooling energy, also seen in Figure 5.9., since it only supplied outdoor air directly without conditioning it.

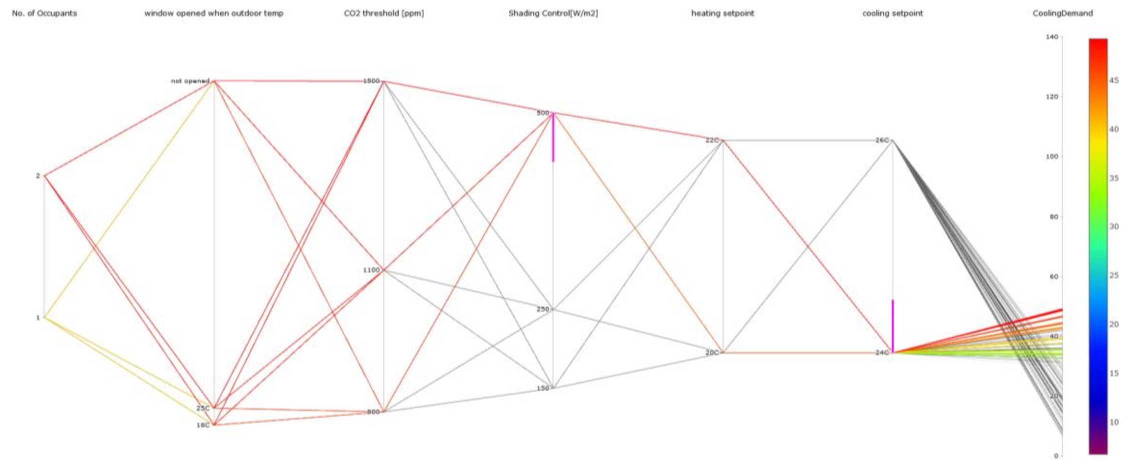


Figure 5.7 Effects of <u>shading, cooling setpoint</u> on cooling energy demand, Ravensburg

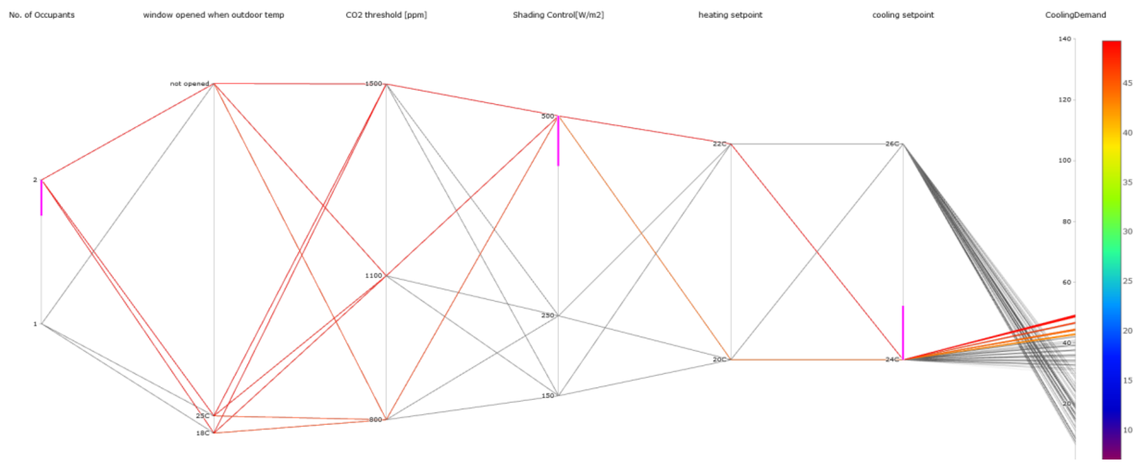


Figure 5.8 Effects of <u>shading, cooling setpoint & occupants</u> on cooling energy demand, Ravensburg

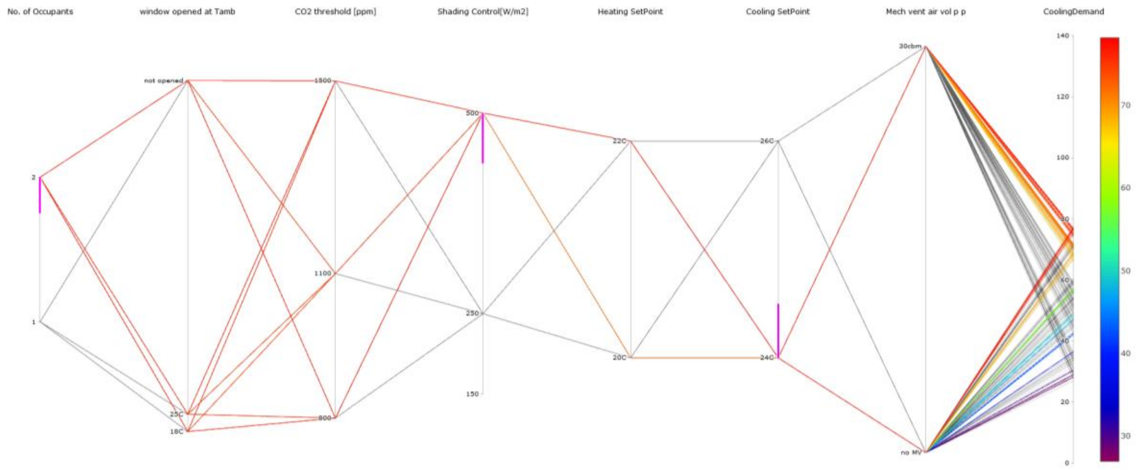


Figure 5.9 The effects of shading, occupants and cooling setpoint on cooling energy demand in Kolbermoor.

5.1.2 Comfort

The WUH/WOH or Weighted Under-heating or Overheating hours are analysed to understand the comfort capabilities of the building. The Para-plot, this time, has two columns of outputs on the far-right side of the graph. The very last column represents the individual setpoint WUH/WOH and the column left of it represents the WUH/WOH according to the standards. The calculation of WUH/WOH and how to read them is explain in section 4.2.2 & 4.2.4 on page 63 - 66.

Even though the building provides good summer and winter comfort in general and the adaptive standard WOH/WUH never exceeds 500Kh for any case in either of the buildings, the purpose of this exercise to understand the influence of parameters. It is also Important to note that this need not accurately represent all possible behaviour scenarios because one of the automatic settings used opens the window as soon as the temperature exceeds a certain limit in winter or summer. This would not represent scenarios where occupants do not do this, or absent.

Winter comfort

Winter comfort is studied by reading the weighted Under-heating hours. The reasons for high WUH are similar to the reasons for high heating energy demand. higher. However, it is interesting to note that even though one occupant leads to a higher heating energy demand, it leads to lower Underheating hours and better winter comfort. This is because, the rate of CO_2 production is lower reducing the need for opening windows and thus, minimising ventilation heat losses. Shown in Figure 5.10.

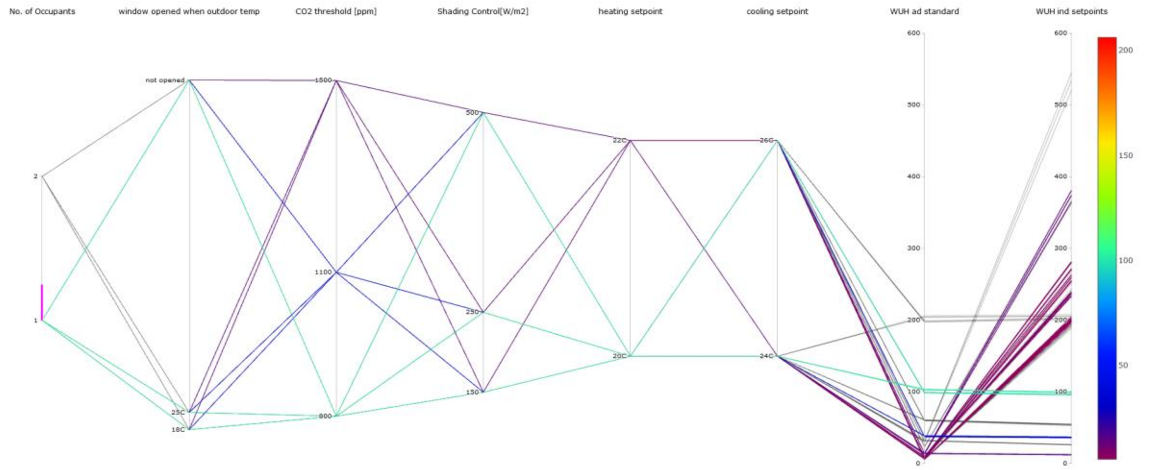


Figure 5.10 The effects of 'number of occupants' on winter comfort in Ravensburg's building.

The scale in the graph for the adaptive standard WUH in Kolbermoor has been increased for better visual clarity and it is important to keep in mind that the WUH values are all below 80Kh which is very low.

A lower heating setpoint, of 20°C seems to have higher number of hours below the recommended temperature by the German adaptive standards. When the heating set point is the same as the lower limit of the standards, there is less buffer room for the system to react and ensure 20°C in the room because the heating only starts when the temperature reaches 21.5°C, whereas, with a heating set point of 22°C, it begins at 23.5°C. Therefore, there is a lesser chance of underheating when the system is actively trying to maintain a higher temperature.

The Figure 5.11 clearly shows that there are higher WUH when the heating setpoint is 20°C as compared to 22°C in Ravensburg, However, at 22°C the resulting WUH has a much larger range in Kolbermoor, refer Figure 5.14. This suggests that the Kolbermoor building is more sensitive to other parameters as well, making it less robust. It is important to note that the low CO2 threshold of 800 ppm, combined with the low heating setpoint of 20°C, always result in a high WUH, as seen in Figure 5.12

The effect of a single parameter in Kolbermoor, is not as clear cut as it is in Ravensburg. Figure 5.14 shows the results of a heating setpoint of 22°C are quite scattered but in Ravensburg the effect of the same boundary condition is very clear, as seen in Figure 5.11. This shows that other parameters also have an influence on the result, indicating that it is more sensitive to boundary conditions. Never the less, the same parameters influence both buildings similarly, namely, CO2 threshold which is accelerated by the number of occupants.

Mechanical ventilation is seen to have some effect on the winter comfort but not a considerable amount. In the scenario chosen in Figure 5.14, the difference between the adaptive standard WUH is about 20 Kh. It is interesting to note that although mechanical ventilation may provide slightly better comfort according to the German standards, it does not manage to perform as well to provide the comfort according to the individual setpoint.

In conclusion, the most influential causes that lead to higher discomfort in winter are ventilation heat losses caused by opening the window. Therefore, lower CO2 threshold and a higher number of occupants leads to higher underheating hours. Another leading reason is the lower heating setpoint, however, it should be noted that the WUH is quite low for both building and they provide good winter thermal comfort. The difference between the adaptive comfort WUH and Individual setpoint WUH, are the cases when the temperature is between 20°C and 22°C which may not be a highly unacceptable temperature for many

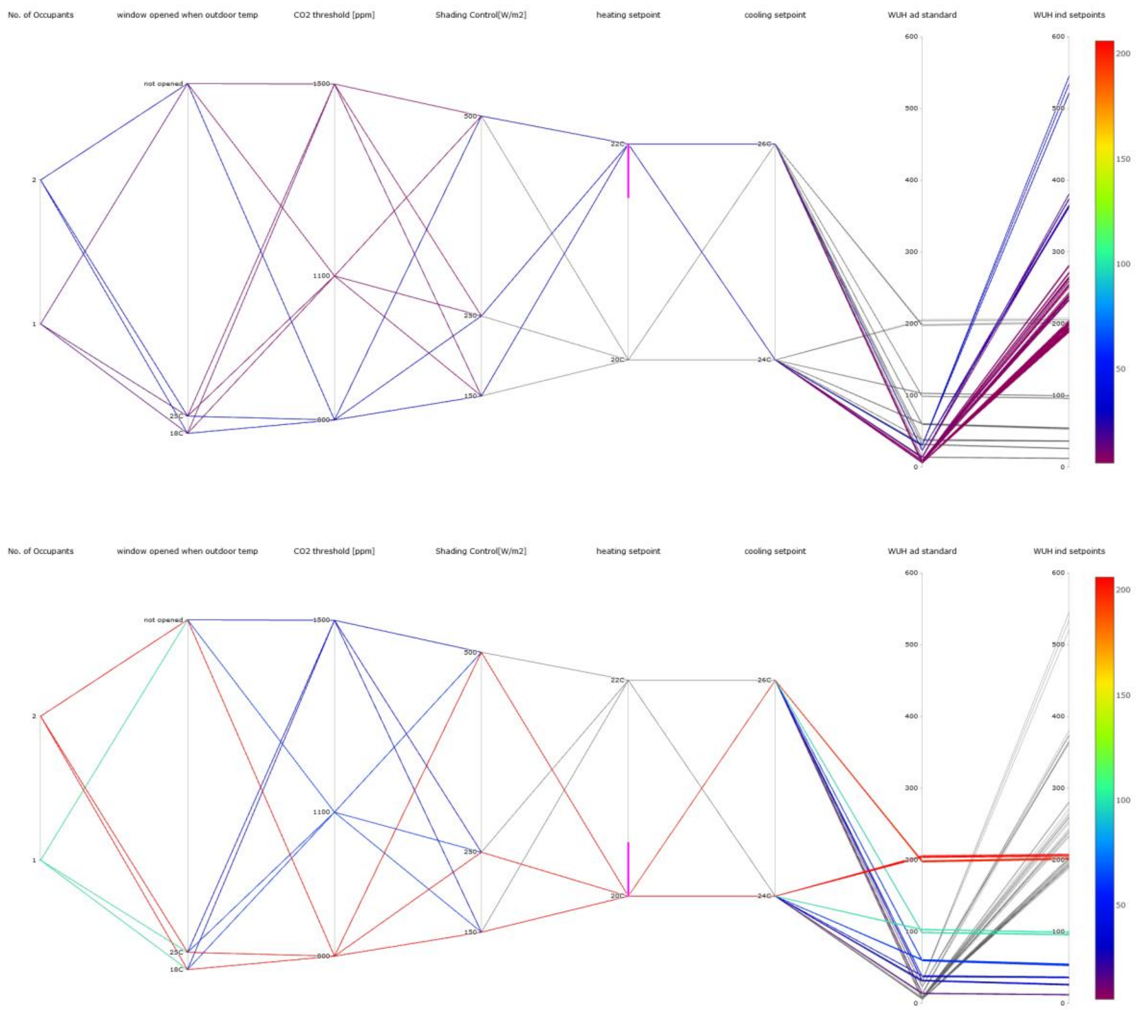


Figure 5.11 Effects of different heating setpoint on winter comfort in Ravensburg.

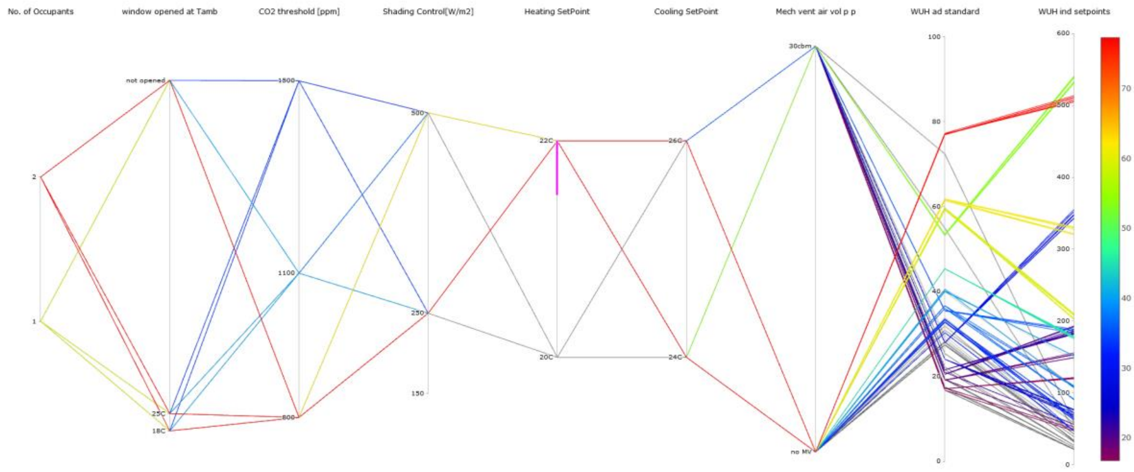


Figure 5.14 Effects of heating setpoint on winter comfort in Kolbermoor.

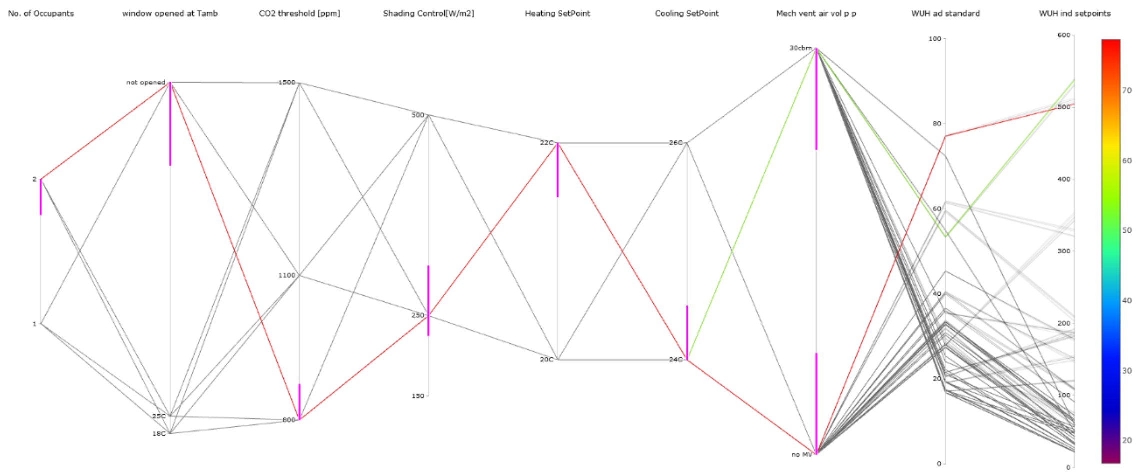


Figure 5.14 Effects of mechanical ventilation on winter comfort in Kolbermoor's building.

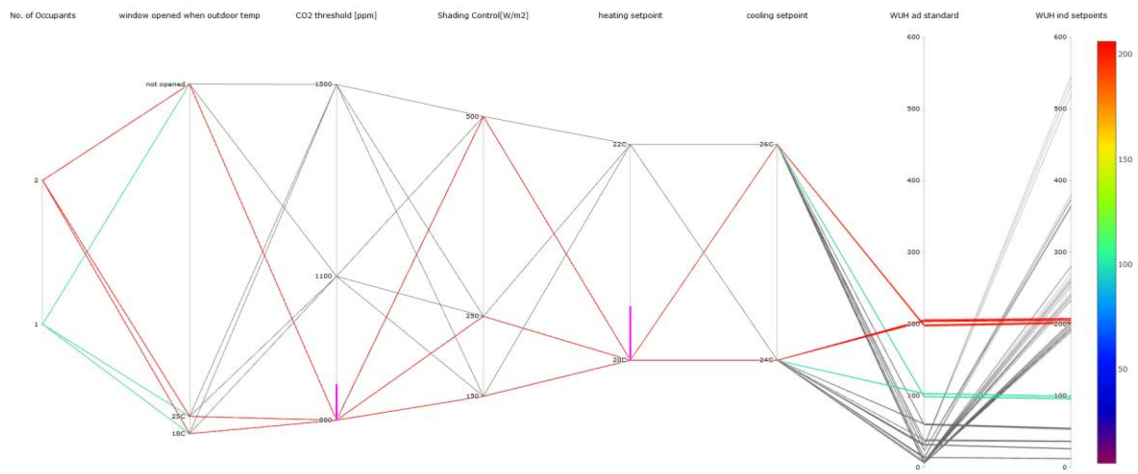


Figure 5.12 Effects of <u>CO2 threshold and heating setpoint</u> on winter comfort in Ravensburg's building.

Summer comfort

The main parameters are were found to influence summer comfort are shading and the number of occupants in Ravensburg. In combination, these two parameters can lead to high WOH and this can be seen in Figure 5.16. However, the same boundary conditions for Kolbermoor still has a wide range of outputs indicating its non-robustness as seen in Figure 5.15.

It is interesting to note that in Ravensburg, a lower shading threshold of 150 W/m², results in a lower WOH but a higher threshold of 500 W/m², does not always result in a higher WOH. Meaning that preventing solar gains by closing the shading can ensure good summer comfort but not doing it can still be compensated by other factors and behaviours to ensure good comfort. This would normally mean a higher cooling energy required to maintain the same amount of comfort. refer Figure 5.18 and Figure 5.18 for the comparison. Shading control or window size would matter more in buildings without active cooling.

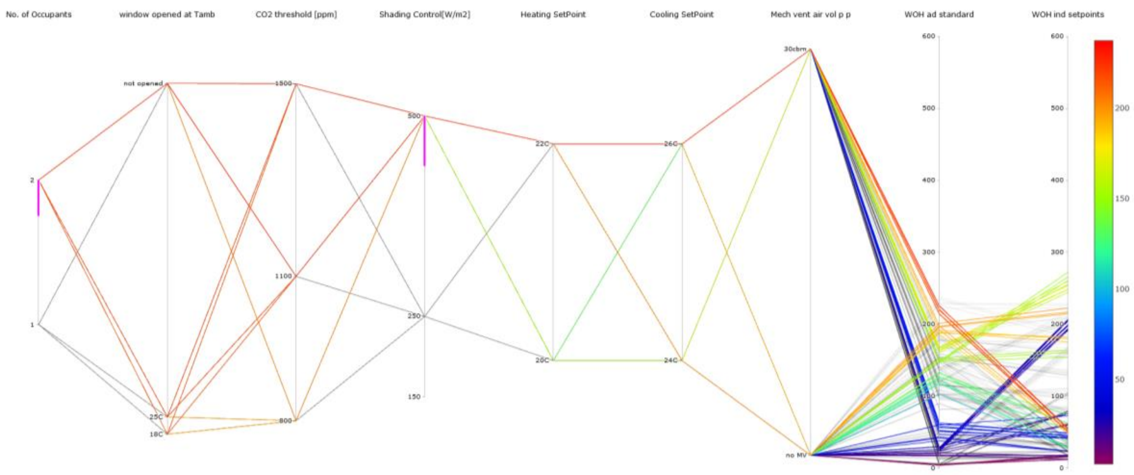


Figure 5.15 Effects of shading and occupants on summer comfort in Kolbermoor

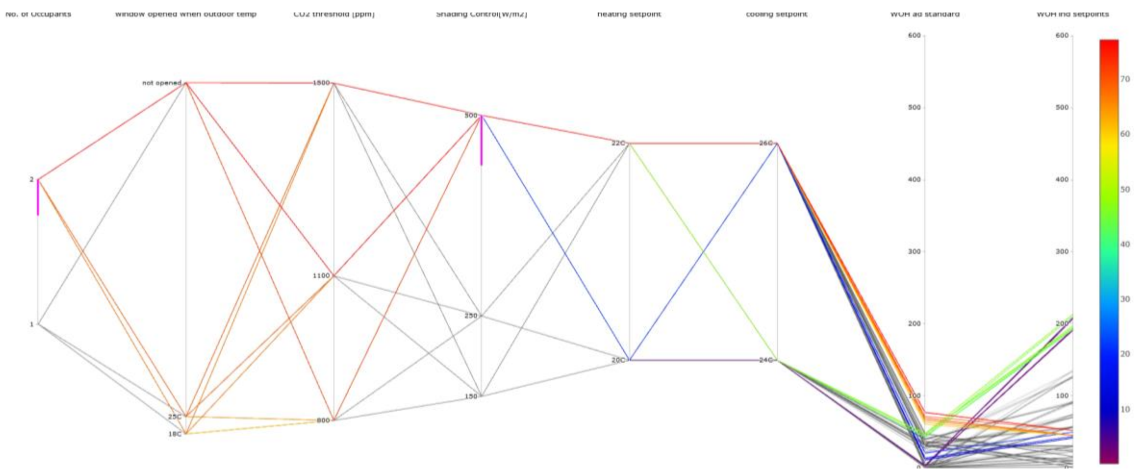


Figure 5.16 Effects of <u>shading control and occupancy</u> on summer comfort in Ravensburg's building.

Furthermore, it was found that mechanical ventilation can even have a negative effect on comfort with certain combinations of behaviour. For example, when the CO2 threshold is 1500 ppm, the difference between the WOH as a result of mechanical ventilation and natural ventilation is stark as seen in Figure 5.19., however the difference disappears when the threshold is 800 ppm. The reason for this could be that, the need for

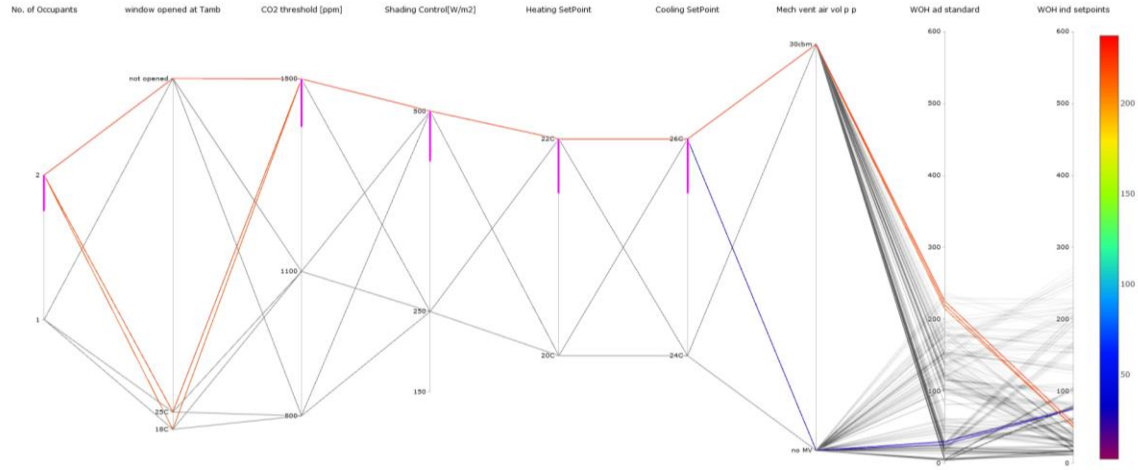


Figure 5.19 Effect of Mechanical ventilation on Summer comfort in Kolbermoor

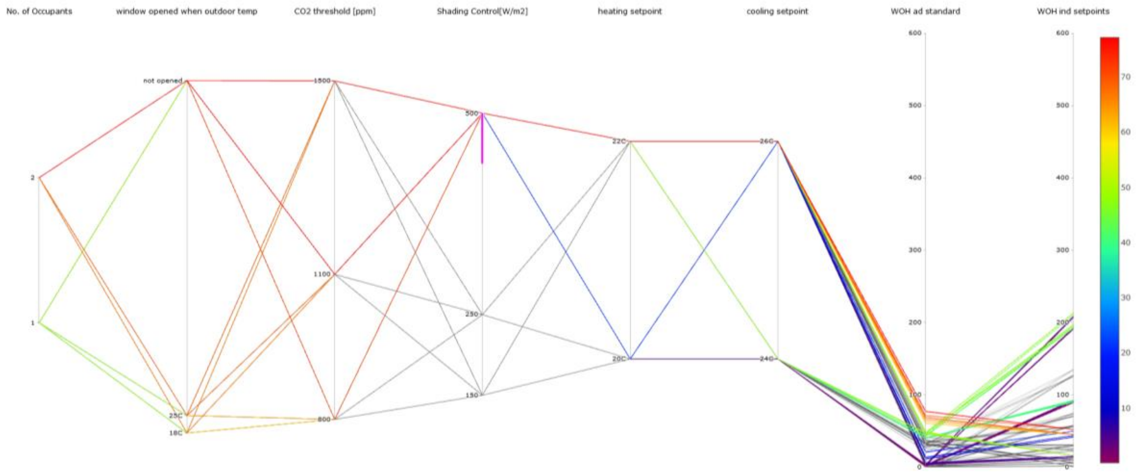


Figure 5.18 Effects of shading on summer comfort in Ravensburg's building.

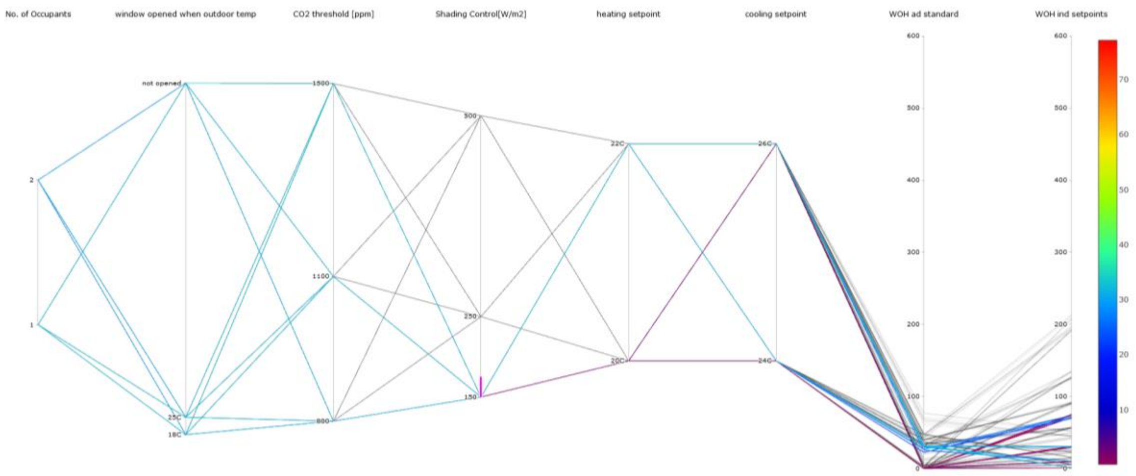


Figure 5.18 Effects of shading on summer comfort in Ravensburg's building.

opening the window when the mechanical ventilation supplies air is low and the need is practically non-existent if the window is only opened at 1500 ppm. This case has a significantly higher over heating hours, indicating that higher volume flows due to the natural ventilation might be dispersing the indoor heat, which the mechanical ventilation does not with its fixed low volume flow rate. However, the confirmation of this theory needs further study to be confirmed.

In conclusion, the biggest reason for discomfort in summers can be attributed primarily to the shading controls and secondarily to internal gains due to occupancy. It is important to note that the simulations for the uncertainty analysis in this thesis assumes a control which opens the window when the indoor temperature exceeds a certain value. Thus, naturally ventilating it, which may not occur in reality due to many factors.

5.2 Conclusions of parameter analysis

By assessing the results from the uncertainty analysis done for assessing robustness using the para-plots, it is possible to better understand the influence of various parameters. Although reading these graphs is easier to assess on the computer because one can select different boundary conditions dynamically, the interesting findings were explained in this chapter.

The main findings show that a conservative window operation behaviour can lead to better window comfort and shading operation to good summer thermal comfort. A higher occupancy level usually contributes to both summer as well as winter discomfort because of the increased internal gains in summer and accelerated CO2 production, in turn, increasing the frequency of window-opening operation allowing heat losses. The CO2 threshold set for signalling the window opening also plays a role, lower thresholds mean that windows have to be opened more frequently and again losing heat. A combination these boundary conditions leads to high WOH /WUH and thus discomfort.

The benefits of mechanical ventilation are not significant in the winter, either in terms of energy saving or winter thermal comfort. This can be due the ‘low’ designed volume flow of 30 m^3, which may be insufficient for many and would prefer to also open the windows to have enough fresh air. This combined system for window operation and a basic air supply by the mechanical ventilation may be the reason for the lack of benefits seen. The benefits of the 70% heat recovery get negated when the windows are opened. This conclusion was also derived in the previous chapter during the robustness analysis.

However, an interesting finding from this analysis is that the over-heating can be higher in the case of mechanical ventilation with just natural ventilation in the cases when the CO” threshold is high (1500ppm). This was attributed to the reasoning that mechanical ventilation reduces the need for opening windows, especially if the CO2 threshold is as high as 1500 ppm, and this might prevent the higher air exchange that happens when the window is opened helping dissipate the indoor heat gains.

6 Conclusions

6.1 Summary of Findings

6.1.1 POE

The Post Occupancy Evaluation was conducted by series of steps to better understand Occupants' interaction with their built environment, their satisfaction with thermal comfort as well as identify the magnitude of the Performance Gap. As a result of the interviews, anonymous survey and monitoring of some private offices, some teething issues surfaced and were solved in Ravensburg. Some learnings from this process were:

i. Good communication protocol should be established between the users and the facility manager so that solvable issues can be quickly sorted. Sometimes a problem simply persists because the right people who can fix it do not know about it. In Ravensburg, the floor cooling system was fixed by increasing the coolant inflow temperature from 18 to 20°C in order to avoid condensation due to the high dew point temperature of that region.

ii. When a building is newly constructed, the designed 'correct' operation should be informed to all its users. Possible training workshops to raise awareness on the magnitude of influence that users have on the total energy consumption and also on their own thermal comfort. For example, the decentralized ventilation units at

Kolbermoor are widely under used and they are to have a short workshop for all the employees for the same.

iii. Gaps in the programming of the controls of automated systems can cause dissatisfaction in the occupants leading them to override the shading control more often. It was found that in the shading controls are not perfectly set as it is controlled based on one sensor on the roof and calculates using the horizontal lux levels rather than the recommended solar radiation on the façade which is the usual simulated method. For example, on the east facing zone, it closes much later than recommended and this not blocking glare or solar gains. This was communicated to the facility manager of the building to be corrected.

iv. In Ravensburg, the 50% of the sample group surveyed think that the shading does not function well. In Kolbermoor, where the shading is only wind controlled for its physical protection, the shading does not return to its original position, sometimes leading to East façade offices overheating in the mornings even when the occupant takes the precaution of closing it the night before.

v. There was dissatisfaction about daylight inside the room as well as the corridor at Ravensburg. Occupants kept the desk lights on most of the day for reading and was the primary reason for manually opening the shading.

vi. The dissatisfaction with air quality in Ravensburg was associated with VOCs and smells rather than CO2 level. The Fabric shading hinders the movement of air in the summer, affecting air quality as well as reducing the cooling capabilities of natural ventilation.

6.1.2 Behaviour analysis

Occupant behaviour was analysed in both buildings by recording indoor climate data, anonymous surveys and personal interviews. The key parameters which an occupant has access to change or override are studied which are the operation of thermostat, windows, and shading. The indoor CO2 concentrations measured were used to understand window operation, Illuminance levels, survey and interviews for shading operation and the survey for understand basic thermal comfort preferences. The Key findings are:

i. The comparison of the observed behaviour and the assumptions of user behaviour in conventional BP simulations shows a large inconsistency between the two and this can result in inaccurate predictions of a building’s performance.

ii. Thermostat operation: It was found that 82-85% of the sample group in Kolbermoor and Ravensburg respectively were comfortable above the temperature of 22°C, out of which 49- 50% comfortable above 20°C. 70% of the sample group in both buildings were comfortable below the temperature of 24°C out of which 33- 40% are comfortable below 26°C.

iii. Window operation: There was no consistent CO_2 threshold found. It differed between people as well in the behaviour of the same person. The range of CO_2 concentrations at which the occupants opened the windows found from the monitored data ranged between 400-2000 ppm. However, some general trends were seen. The CO_2 threshold decreased with the increase on outdoor temperature above 18°C, in other words, the windows were either more frequently opened or simply kept open when the outdoor temperatures are above 18°C.

iv. The number of visitors received is an important factor which affects the overall performance of the building as well as the climate design. For example, in Ravensburg, it was recommended to forego mechanical ventilation systems. Frequent visitors fluctuate the CO_2 production and make the mechanically supplied air insufficient and would need additional ventilation though the windows and the movement of people in and out of the building also results in heat losses.

v. Shading operation: Even when the shading controls are completely automatic, controlled by solar radiation and protected for winds, is overridden by 75% of the sample group for reasons such as glare protection, more natural daylight, view to the outside, wrong functioning of the automatic control. The wind-controlled shading is also overridden by 55% of the sample group.

vi. The decentralized mechanical ventilation was not widely used by the occupants the systems were not widely used by the occupants probably due to the lack of know-how of operation, the noise, draughts, or simply personal preference. These particular systems are also not connected to central BMS nor have time controlled automatic operation. It was not possible to assess if and how the mechanical ventilation is used.

6.1.3 Robustness analysis

From literature studies it was found that lower the sensitivity of the building towards changes, higher is the robustness. Therefore, to check for sensitivity, an Uncertainty analysis was conducted where the two buildings were simulated in an energy modelling software to check for building performance under various scenarios created by different realistic behaviour patterns. These patterns were defined based on the survey and monitoring findings. The hundreds of results of both building simulations were analysed separately for energy and thermal comfort in summer and winter, using a box plot to compare their sensitivity.

The findings from the uncertainty analysis were:

i. Ravensburg's buildings with smaller windows, better shading control, slightly larger room volumes, uncarpeted floor, and higher thermal mass was indicated to be more robust, stable/ reliable in cooling energy consumption and summer & winter thermal comfort. Also, with a similar overall range of heating energy demand as Kolbermoor

ii. Kolbermoor's building, with larger windows, mechanical ventilation, double paned sun protection glass, with slightly smaller volumes, carpeted floors and manual shading was found to be more robust in in winter thermal comfort and statistically more robust heating energy demand but with an overall higher value. This maybe because of the higher heat losses through the large two-paned glazing area.

iii. Kolbermoor's resulting box for heating energy demand was shorter but whiskers longer in the box plot. Statistically, Kolbermoor would be considered as more robust due to the higher concentration of the results in a smaller range close to the median. However, since this range lies near the higher end of the results on Ravensburg, it also means that statistically the resulting energy consumption would also have a higher value than of Ravensburg.

iv. There are no significant benefits seen from the mechanical ventilation when it is used in combination with natural window ventilation since the energy & comfort benefits from the heat recovery is negated by the ventilation losses when the windows are opened due to insufficient fresh air or overheating. Neither the energy heating energy consumption nor the under-heating hours rise much without any mechanical ventilation. It was also found that the users of the building do not widely use it due to noise/ draught/ lack of know-how/ personal preference.

v. Ravensburg's building clearly performs better than Kolbermoor without any active cooling systems because of the same reasons it has a lower weighted overheating hours and lower cooling.

6.1.4 Parameter influence on robust performance

The results from the uncertainty analysis were analysed using a para-plot graph which gives a visual overview of all the boundary conditions varied and the resulting output. This was done to identify critical parameters and better understand the magnitude of influence that the parameters and their boundary conditions have on the building performance. The main findings from this study were:

i. A conservative window operation behaviour can lead to better winter comfort. This is dictated by the CO_2 threshold and indoor temperature. A low CO_2
ii. threshold increases the frequency of window opening and, so, the heat losses, increases discomfort and heating energy demand.
iii. Higher occupancy can accelerate the CO_2 production as well as increase internal heat gains and this would cause discomfort in both summer and winter.
iv. A low shading operation threshold was found to be the most effective and robust solution that ensures good summer thermal comfort. A higher threshold, however, can also result in good comfort with an increased cooling energy demand.
v. The mechanical ventilation was found to have no significant improvement in winter comfort as it did not provide enough fresh air to suffice the 800 ppm CO_2 threshold, especially with two occupants, and so the windows has to be opened losing the heat. It even worsened summer comfort because it supplied enough air to reduce the need to open windows, in the case of CO_2 threshold of 1500 ppm, thus, preventing the larger volume flows from the windows which would dissipate the indoor heat. It can, therefore, be questioned whether such a combine system of mechanical and natural ventilation can have any significant benefits.
vi. In Kolbermoor, single parameters did not have a clear large individual influence on the outputs unlike in Ravensburg. For example, this suggests that many other parameters also have higher influences on the result, in other words, the building reacts sensitively to many parameters and thus, less robust.

6.2 Discussion

It was established by existing literature that occupant behaviour can greatly affect the performance of a building in terms of energy consumption as well as comfort, it was also established in the literature study that a difference between predicted or designed energy demand and the actual energy consumed exists widely, with a mere 5% of the schools that were assessed were performing as expected. “*Of the 59,967 blocks surveyed, 3,039 blocks have all survey records graded A*” (PDSP report 2015).

The thesis studies two constructed buildings to assess their as-built performance, study the behaviour of its occupants and theoretically analyse and compare their robustness in withstanding variations in boundary conditions caused by the changes in occupant behaviour.

The Post occupancy evaluation showed the various minor malfunctions that can cause user dissatisfaction. The occupant behaviour study concludes that behaviour is complicated and varied. It was not possible to derive a conclusive general behaviour for the operation of windows or shading as it is dependent on a number of other factors such as preference of quality of air, temperature, view, daylight, etc. Individuals have different preferences for each of these boundary conditions. The measured CO2 thresholds that triggers window opening varied between 400-2000 ppm amongst just the eight occupants who were observed Some behaviours cannot be predicted or quantified at all, such as smells, noises, preferences, memory, absence due to vacations, visitors etc. This conclusion from the chapter 3.7 and page 56, confirms the need for addressing the problem of varying boundary conditions.

From the study done for this thesis, it can be concluded with certainty that occupant behaviour is inconsistent, unpredictable and cannot be accurately generalized. But the current Simulation methods do not consider these variations, instead assume an ideal or static behaviour pattern. The problem of Performance Gap is not only due the inaccuracy of computer simulations, but also, the actual performance of a building after its construction. A sensitive building is more likely to react strongly to the changes that a building faces, and in turn, have larger deviations in its actual energy consumption from its predicted. If a 'robust' building is one which is less sensitive, or more stable/reliable in simple terms, then it means that it would have a smaller Performance Gap than that of a sensitive building even if not simulated accurately.

The Robustness of both buildings was assessed by conducting an uncertainty analysis, where the buildings were simulated with hundreds of different behaviour pattern scenarios and their energy demand and comfort was analysed. The building with the higher thermal mass, smaller triple-paned windows, automated shading and slightly larger office volumes was found to be more robust overall, in terms of summer and winter comfort and heating and cooling energy demand as it showed a smaller reaction and the boundary conditions had a predictable influence on the performance.

High tech vs low tech:

Low energy building design has been focusing of innovative sophisticated technical systems to optimize the operations and combat 'inefficiencies' of human operation.

Automating aspects with-in the reach of a user's operation, such as having mechanical ventilation, solar radiation-controlled shading, motion sensor-controlled lighting, centralized heating/cooling systems, has been an attempt to maintain the energy balance and not rely on the occupant for the correct operation of the building. This approach could work in an ideal world where there are no malfunctions in the operating systems; with an expert facility manager a good working knowledge of the software and mechanical systems; continuous monitoring of the operations; and with a working system of communication between the users and the facility manager which is usually entirely missing, but this can also lead to the impossible task of satisfying everybody's requests. As seen in the behaviour study, people override automated systems extensively, sometimes nullifying the energy, cost and comfort benefits of the concept.

Some designers take it a step further do not have any option of overriding, i.e. no openable windows, automated shaded which do not stay in the manually overridden position for very long etc. However, this can quickly lead to unhappy occupants. The user behaviour study found that a 100% of the sample group would like to open the windows manually regardless of the existence of a mechanical ventilation system for many reasons such as the preference to natural fresh air, indoor smells, health etc.

If occupant behaviour cannot be controlled and is going to fluctuate, then the built environment must adapt to this. It should be capable of handling these variations, it should be insensitive to change and stable in performance. Good passive design which is adapted to the climate, along with robust and necessary mechanical systems can be the key to the reliable performance of a building throughout its 50 or 100-year lifespan. 'Robust optimization' is the concept which does exact this. It helps optimize building design, not to the least energy possible but, with a 'safety factor' as used in other fields such as structural engineering. However, it is trickier to find the 'robust optimum' design of a parameter as it may not be not a linear relationship, such as increasing the load-bearing capacity for the robust structural performance of a column for example. Finding the balance between 'too small' a window which does not provide enough daylight and 'too large' a window that overheats the space is the approach of robust optimization. To prevent the overheating problem and not solve it by designing sophisticated automated systems which might often fail, malfunction or get overridden.

6.3 Recommendations & Further Research

Operation side:

The most obvious and simple, but nonetheless very effective approach in improving a buildings performance is to raise awareness among the occupants about the correct operation of the building systems and about the critical parameters that influence their performance. The Occupants may not be widely aware of the influence their behaviour can have on building performance or may not be aware of the intended way of operation at all. Simple tips like turning the light off or switching the water off when brushing might seem obvious but have to be made actively widespread in an effort to reduce consumption.

Some of the findings from this thesis that can be taken as recommendations for a more efficient occupant behaviour are:

i. Lowering the heating setpoint by just 2 degrees can result in reducing the overall energy consumption by up to 50%.
ii. Opening the windows for too long or too frequently can result in a high variation in comfort as well as energy consumption. There is a sensor that beeps to remind occupants to open the window when the CO2 level is too high. But what should also be implemented is a second beep to make sure that the windows are not open longer than required which results in an unnecessary loss of heat.
iii. Shading operation is very important for summer comfort and cooling demand. The south and East facing rooms should close them early enough to avoid overheating. The programming of the automated shading is critical and should be reviewed by the designers
iv. Using mechanical ventilation that only supplies outside air is not recommended during the summer if it constantly supplies air regardless of whether the outdoor temperature is higher than the indoor temperature.

Design side:

Some findings from this thesis that designers should more aware of or critical about are:

i. It is advisable to optimize the window to wall ratio and high glazing quality than rely on the manual or automatic operation of shading.
ii. Room sizes and number of occupants also influence the overall performance. But it may not be planned with the energy performance perspective and rather with spatial and economic factors. Never the less, it is usually underestimated; but it could be used as a tool to compensate for other design decisions taken, such as large windows. Larger the volume, lower is the overheating and cooling loads, smaller the volume lower is the heating load.

iii. The programming of the automated shading is very critical. The settings programmed by the shading manufacturers should not only be reviewed by the climate designers but also monitored after it is in use. The occupants should have the possibility of requesting a custom operation in special cases. For example, it was found that the south facing office was designed with the smallest window to wall ratio, however, this office is self-shaded by the other part of the building as well as a big leafy tree. The shading closes regardless of these conditions since it is controlled by a single sensor and needs to be opened every time to have some daylight and heat gains. Another example is glare from the reflection of other buildings that cannot be predicted. This is quite a common occurrence which calls for individual programming for shading control.

iv. It is advisable to optimize the window to wall ratio rather than relying on the manual or automatic operation of shading.

v. The Number of people can result in both a high or low energy consumption depending on how the other parameters are controlled. However, this parameter should be considered during the climate design as it affects the systems to be used. For example, having mechanical ventilation which does not have a central control when the occupants do not know how to operate it.

vi. Designing mechanical ventilation must be considered critically. Combining it with natural ventilation loses the benefits of the energy and comfort provided by it. It is also to be carefully considered based on the usage of the space. It is not recommended when the building receives too many visitors.

vii. Recommending decentralized ventilation systems must be done carefully and critically. As found in this case study, the systems were not widely used by the occupants probably due to the lack of know-how of operation, the noise, draughts, or simply personal preference. They are also not connected to central BMS nor have time controlled automatic operation. When a system that is not commonly used or known by the people of that region and it is also completely dependent on their operation, it is important to educate them on the correct usage.

viii. Fabric shading, while providing good glare protection, blocks the air movement and so should not be used with natural ventilation, especially if natural ventilation is also used for cooling.

Testing the parameters for robustness and the information about the critical parameter can be very useful for the design of a robustly-performing building and can be a topic worthy of further research.

There is currently no standard accepted scale for measuring robustness of building performance. Since it is relative and climate specific, it can only be compared to itself or other buildings in a similar climate. According to the definition of robustness, which is 'less sensitivity or reaction to external changes', only refers to its reaction range and not to the actual energy consumption. For example, a building can be robust and yet have a high energy consumption if it does not react much to changes but inherently has a higher consumption. Hence, comparing robustness is complicated and further research can help create a reference value to measure the robustness so that it can be comparable. This, for example, could be a factor of its own consumption as a reference which can be represented as a percentage or a 'robustness factor'.

In structural engineering, for example, the design value used is calculated as by a similar method to tackle uncertainties in the boundary conditions relevant to structural performance both on the effect of actions side (loads such as wind, traffic, weight etc) as well as the resistance side (material strength). The recommended design value, which can be the value for designing the thickness of a loadbearing material for instance, is the 5th percentile of the material strength which is calculated by subtracting 1.96 times the standard deviation from the mean value. In simpler words, in 95% of the scenarios the actual material strength is higher than the assumed value. This way, the standard deviation as well as the mean value of any parameter are always considered in the design.

This method could be borrowed and adapted for the prediction of energy consumption at the building design stage. Since predicting building performance cannot be absolutely accurate due to uncertainties and variations, they should be incorporated in prediction process. Further research can be conducted for outlining a simpler or faster method for analysing uncertainty which can be regularly employed by designers as a norm. This can be done by defining this 'factor of safety' to deal with uncertainty, with a further study on the uncertainties themselves. The boundary conditions that should be tested for the analysis needs be to be defined as a guideline. The 'factor of safety' in this case need not be as high as it is for structural engineering since they absolutely cannot afford any failure in design. Further studies on the uncertainties themselves and deriving a 'probability of occurrence' of a certain behaviour and their influence on the energy performance can form the basis for defining this factor.

It is better to predict the energy consumption more conservatively and have a lower actual consumption than the other way around. If this method becomes a norm, it would promote more robust building designs which could even eliminate Performance Gap altogether. Statistical concepts from other fields of engineering could help to develop a suitable verification concept for the building performance field.

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