Combating User-Behaviour Caused Variations with Robustness in Building Design

Robustness analysis of Two Existing German Office Buildings

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Abstract

Motivation: In the current design practice, the Building Performance Simulations (BPS) makes generalisations about building operation to estimate energy demand. 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 user-behaviour can be to design robust buildings. This, in turn, can reduce Performance Gap. Evaluating the robustness of a constructed building provides insights about the practical implications of its design and how it is operated; and support the theoretical studies of building performance robustness and robust optimization.

Methodology: Two in-use office buildings in South Germany were studied for three summer months for a two-part analysis of: *user-behaviour* and *performance robustness*. The user-behaviour was studied by monitoring, interviews and surveys to derive a general behaviour pattern and compare it to the conventional BPS assumptions. Robustness was assessed by an uncertainty analysis which parametrically simulates hundreds of different behaviour patterns. Parameters were analysed to find the ones which cause high energy consumption and bad comfort. These can be highlighted as the most critical and must be taken care of while making design decisions.

Conclusions: Occupant behaviour was found to be inconsistent and unpredictable and does not match the conventional BPS inputs. For example, the measured CO2 levels, just before a window is opened, ranged from 400-2000 ppm while BP simulations assumes 800 ppm; Automatic shading were manually overridden by 80% of the sample group, either every day or at least once a week; Decentralized mechanical ventilation systems were under-used due to lack of widespread operational knowledge. This highlights the inaccuracy in BP simulation predictions which is one of the design-side reasons for performance gap.

The uncertainty analysis found that the building which had *smaller windows, higher thermal mass, automated shading systems and slightly higher room volume,* showed a lower deviation in energy demand and thermal comfort. It also had a lower overall range. However, the daylight quality was unsatisfactory in this building. The parameters that have the highest influence on energy demand (amongst those than can be altered by an occupant) are: thermostat set point temperatures, shading, CO_2 threshold preference and number of occupants. An interesting find was that an increase in heating setpoint by just two degrees could even double the heating energy demand under other behaviour variations.

Keywords: Building performance robustness, user behaviour, occupant behaviour, uncertainty analysis, sensitivity analysis, post occupancy evaluation, performance gap.

Background

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 (Biswas, 2014). 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). Reducing carbon emissions of the building industry is the need of the hour.

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. Accurate performance predictions are important for success of zero carbon as well as near-zero carbon buildings (Kotireddy, Hoes & Henson 2017). This, consequently, can facilitate carbon emission reduction goals. Performance gap in buildings is a widely researched and established topic because it has far more magnitude and common occurrence than it should. For example, the 'Property data survey programme' (PDSP) assessed *59,967* school buildings and reported that only 5% (*3,039 blocks*) of the surveyed schools performed as intended (PDSP report 2015).

What is robustness?

Robustness in building performance is a building's ability to withstand external variations without significant deviations in its energy consumption or thermal comfort. In simpler terms, robustness is the stability and reliability of a building's performance. The concept of robust optimization or robustness is well established in many fields, for example, structural engineering and aeronautical engineering (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 (Maderspracher 2017).

Why is robustness needed?

There are many uncertainties that cause variations/fluctuations in the boundary conditions that can result in performance gap and cannot be accurately predicted. Some examples are User behaviour, automated system malfunctioning, climate change. An effort to automate systems to reduce dependency on humans, also adds to the uncertainty due to malfunction, incorrect control due to insufficient sensors, incorrect/incomplete programming and also manual override. 'if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' (Fabi et Al. 2013).

These variations are rarely considered during the design process. One of the most common fluctuation in boundary conditions is caused by occupants because humans have individual preferences and thresholds which are dynamic. User behaviour has a great impact on the energy consumption of a building. A 'wasteful' usage pattern can easily double the consumption. (Doda 2017).

A holistic solution to tackle the issue of uncertainty and, in turn, performance gap is to design buildings to withstand these variations instead of solving design deficiencies with complicated systems whose controls are designed using BP simulations which are affected by uncertainties in boundary conditions and hence cannot be completely accurate. Performance robustness assessments which take uncertainties into account, should be an integral part of the design decision-making process in order to design robust buildings (Kotireddy, Hoes, Henson 2017).

Buildings' overview

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, two in-use office buildings in South Germany were studied for three summer-months for a two-part analysis of: *user-behaviour* and *performance robustness*.

The two buildings chosen were administrative office buildings or Rathaus (Deutsch) in South Germany. They were selected for their similarity in usage, climate, mechanical systems and differences in architectural features like window sizes, thermal mass etc. Both offices have individual office rooms and they receive a considerable number of visitors during the day.

Building 1: Figure 2

Townhall of **Ravensburg**, Baden-Württemberg.

Architect: Kohlmayer Oberst Architekten
Climadesign: Transsolar Klima Engineering
Total Occupants: 76
Year of construction: 2017

Climate concept: Figure 5
Floor heating & cooling
Only natural ventialtion
Automated Fabric shading
Smaller windows
Larger room volume

Building 2: Figure 3

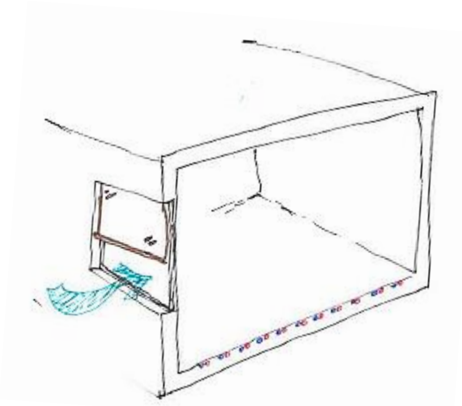
Town hall of **Kolbermoor**, Bayern, Germany.

Architect: Behnisch Architekten
Climadesign: Transsolar Klima Engineering
Total Occupants: 46
Year of construction: 2013

Climate concept: Figure 4
Floor heating & cooling
Extra ceiling cooling
Natural + decentralized mech. ventilation with 70% heat recovery
Manually operated Lamella shading (only wind controled)
Larger windows
Carpeted floor

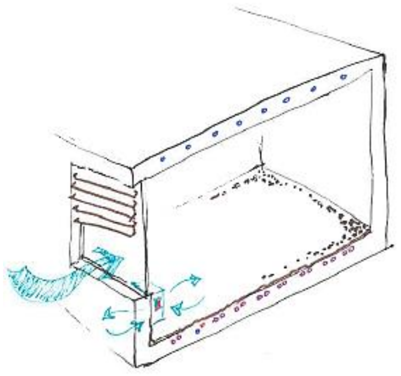
Figure 2 Town hall of Ravensburg.

Figure 3 Townhall of Kolbermoor



-Floor heating & cooling
-Only natural ventialtion
-Automated Fabric shading
-Smaller windows
-Larger room volume

Figure 5 Climate concept illustration of Ravensburg's townhall.



-Floor heating & cooling
-Extra ceiling cooling
-Natural + Decentralized mech ventilation with heat recovery
-manual Lamella shading
-Larger windows
-Carpeted floor

Figure 4 Climate concept illustration of Kolbermoor's townhall.

Methodology

User 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.

Performance robustness analysis: An uncertainty analysis was conducted where the two buildings were parametrically simulated to check the building performance under various scenarios created by different realistic behaviour patterns. These patterns were defined based on the survey and monitoring findings. 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. 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 hundreds of results of both building simulations were analysed using a box plot to compare their sensitivity. The methodology is based on guidelines provided in Kotireddy et al. 2017.

Performance indicators: used for analysing energy performance were annual heating and cooling energy demand. For thermal comfort were Weighted overheating Hours (WOH) and Under-heating Hours (WUH). Lower this number, better is the building's performance. Three types of WOH and WUH were developed in this study:

a. *Adaptive standard WOH/WUH:* Tmax & Tmin are based on the German standards of DIN EN15251 NA as shown in Figure 3. This method of comparison also identifies overheating in winters and over cooling in summers. (Fraunhofer IBP, 2014).

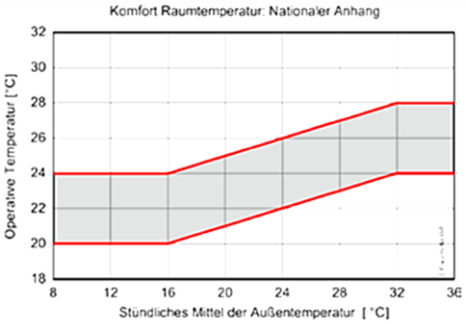


Figure 3 Adaptive standard DIN 15251 temperature limit recommendations

b. *Individual setpoints WOH/WUH:* Tmax and Tmin are the cooling and heating setpoints considered 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 shows the building's capability of meeting the temperature demands of individuals when is it better than that stated by the standards.

c. *Basic WOH/WUH:* Tmax & Tmin are assumed to be 28°C & 20°, corresponding to Class D temperature summer limits in actively cooled buildings. Shows the Buildings ability to provide basic thermal comfort.

A larger value of the Adaptive WOH/WUH as compared to the absolute WOH/WUH, indicates incorrect operation by overheating in winter or overcooling in summer. These hours outside comfort range can also occur during the shoulder seasons when the outdoor temperatures are between 24° to 28°.

Uncertainty analysis simulation details

The parameters, which an occupant has access to change are the windows, shading, thermostat and number of occupants. The boundary conditions of these parameters are varied, which in combination form 288 & 216 behaviour patterns. The values of the boundary conditions are based on the findings from the occupant behaviour study and are listed in the tables.

Parameter	**Control strategy**	**Boundary conditions**		**Notes**
		Ravensburg	Kolbermoor	
Window operation	Window opened by a CO2 threshold [ppm] Window opened by Outdoor temp. [°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 temp. in zone. [°C]	20, 22	20, 22	Heating starts 0.5° before the given threshold is crossed.
Cooling	Setpoint for max allowed temp. in zone. [°C]	24,26 (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.

Unit	Specifications	Kolbermoor	Ravensburg
	Window		
W/m²K	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
%	Transmittance	70	70
%	G-value	44	49
%	Frame portion	20	20
%	shading Fc	25	25
	Building components U value		
W/m²K	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	-	0.19

Findings: Behaviour analysis

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:

Thermostat operation: It was found that 82-85% of the sample group in Kolbermoor and Ravensburg respectively answered on the survey that they feel comfortable above the temperature of 22°C, out of which 49- 50% comfortable above 20°C. While 70% of the sample group in both buildings find it comfortable below 24°C; out of which 33-40% are comfortable below 26°C.

Window operation: There was no consistent CO2 threshold found. It differed between people as well as in the behaviour of the same person. The CO2 level at which occupants opened the windows was derived from the monitored CO2 sensors and it ranged between 400-2000 ppm. However, some general trends are seen. The CO2 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.

The number of visitors received affects the overall performance and so must be considered during the design stage. For example, in Ravensburg, it was recommended to forego mechanical ventilation systems. Frequent visitors fluctuate the CO2 production making it difficult to predict the volume of fresh air required. When visitor traffic is high, the mechanically supplied air becomes insufficient and the window needs to be opened manually leaded to heat losses. Further heat is lost due to the movement of people through the doors.

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.

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, noise, draughts, or simply personal preference. These systems were also not connected to central BMS nor have time controlled automatic operation. It was not possible to assess how and if the mechanical ventilation is used.

The comparison of observed behaviour and the assumptions in conventional BP simulations shows large inconsistencies. This can result in inaccurate predictions of a building's performance. The differences are illustrated in Table 1,Table 2 Table 3. In reality, the windows are opened more often and also kept open during summers; The shading is kept open more often; Different temperatures are preferred by people which can affect the energy consumption; There are visitors which can affect CO2 and internal gains. Other factors such as smells, outdoor noises, memory, preference, wind draughts affect the window operation; and these cannot be quantified or predicted.

Findings: Robustness Analysis

From literature studies it was found that lower the sensitivity of the building towards changes, smaller the box and higher is the robustness. Refer Figure 7, Figure 8 & Figure 6. The red dot represents the actual consumption of the building and the blue box, the simulated prediction during design phase.

Table 1 Thermostat control comparison of surveyed and conventional BPS

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

Table 2 window operation comparison of observed and conventional BPS

	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.	90-74% open windows even outside is warmer than inside.
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

Table 3 Shading operation comparison of observed and conventional BPS

	Conv. Simulation method	Observed behaviour
Solar radiation	Close at 150 W/m², open again at 200 W/m²	75% override it; 55% 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

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

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 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.

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.

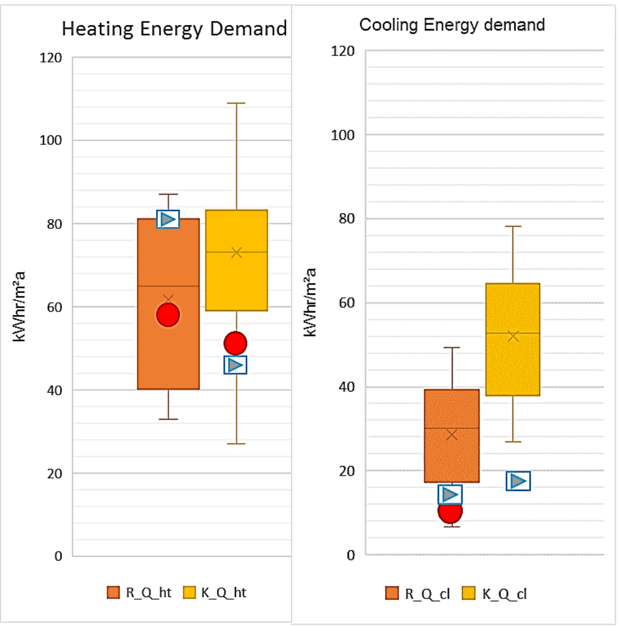


Figure 8 Heating and cooling energy demand

Mechanical ventilation: refer Figure 9 There were 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

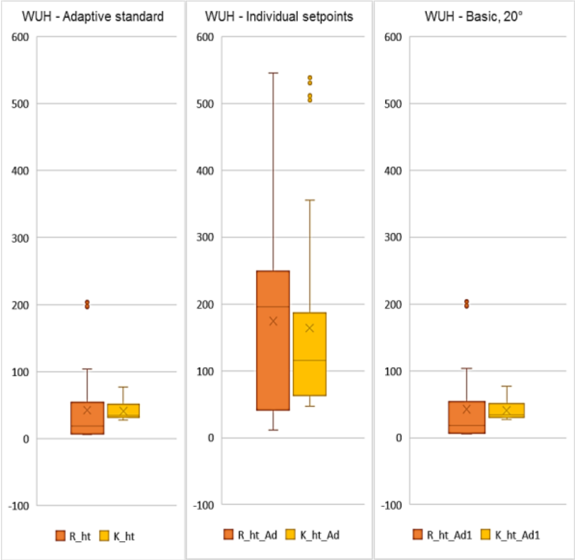


Figure 7 WUH for winter comfort analysis.

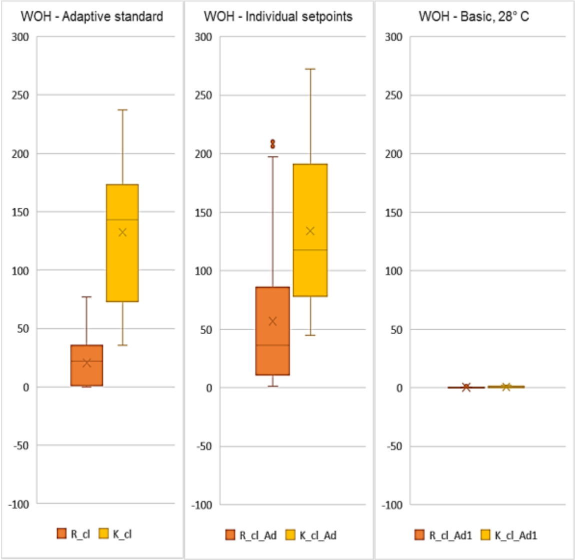


Figure 6 WOH for Summer comfort analysis

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.

Passive design performance: Refer Figure 10. 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

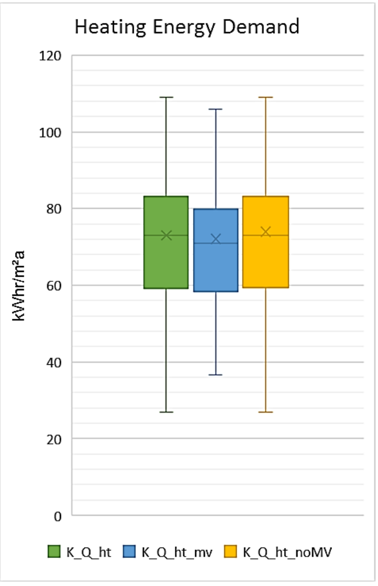


Figure 9 Heating energy demand comparison without mechanical ventilation.

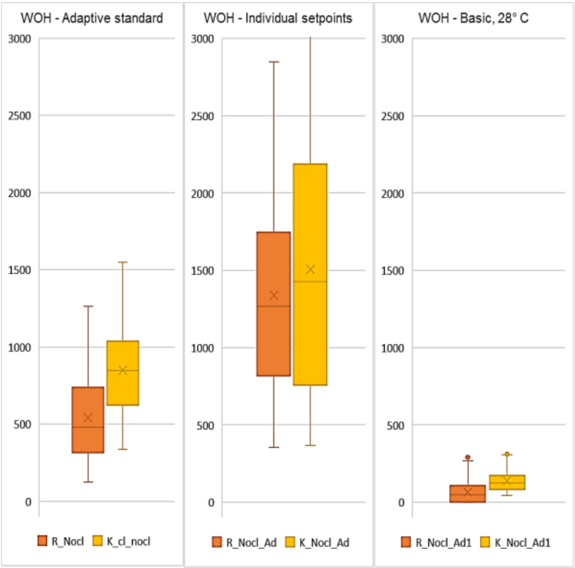


Figure 10 WOH for passive summer comfort.

Findings: Critical Parameter Influence

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. 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. 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. The analysis of these graphs led to the following findings:

Setpoint: A change in the setpoint can significantly increase the heating and cooling energy demand. Refer Figure 11.

A conservative ***window operation*** behaviour can lead to better winter comfort. This is dictated by the CO2 threshold and indoor temperature.

A low ***CO2 threshold*** increases the frequency of window opening and, so, the heat losses, increases discomfort and heating energy demand. Refer Figure 12.

Higher occupancy can accelerate the CO2 production as well as increase internal heat gains and this would cause discomfort in both summer and winter. Refer Figure 13.

Shading operation: Refer Figure 14. A low solar radiation 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 but with higher cooling energy demand.

The ***mechanical ventilation***, as seen in Figure 15 & Figure16, was found to have no significant improvement in winter comfort as it did not provide enough fresh air to suffice the 800 ppm CO2 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

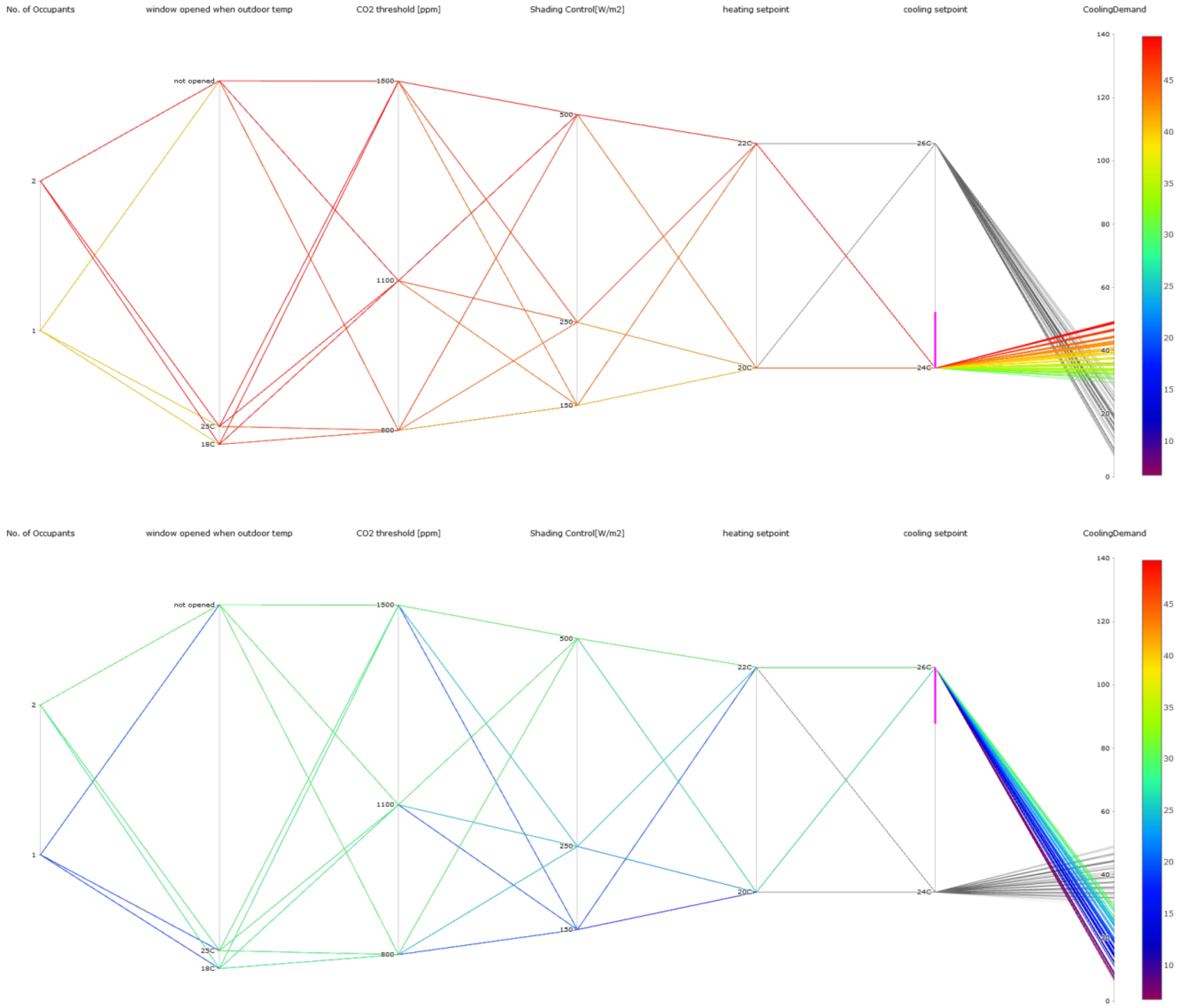


Figure 11 Effects of cooling setpoint temperature on cooling energy demand, Ravensburg.

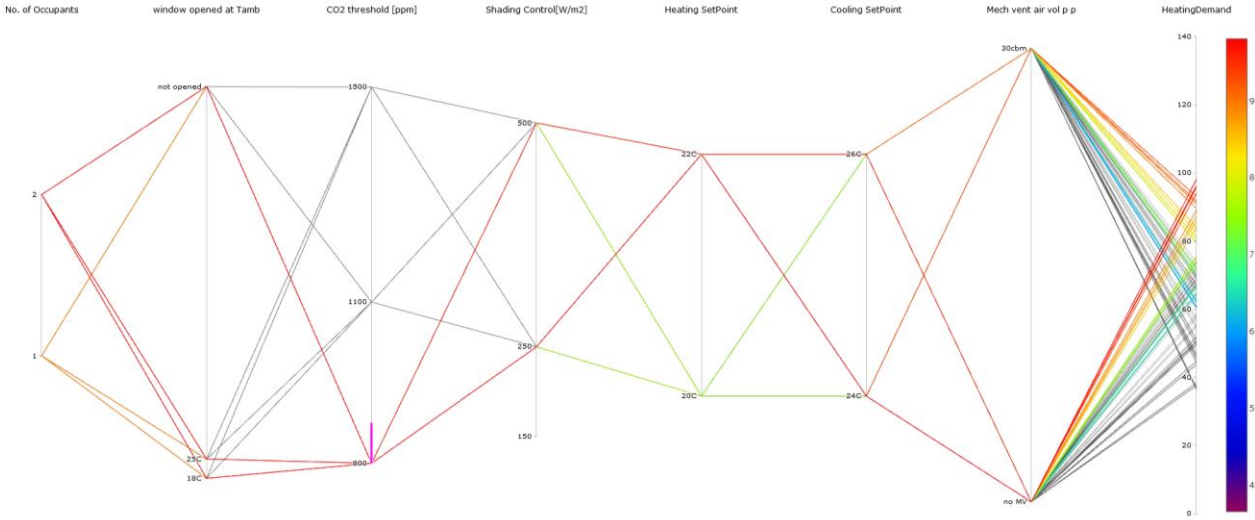


Figure 12 Effects of CO2 threshold on heating demand in Kolbermoor.

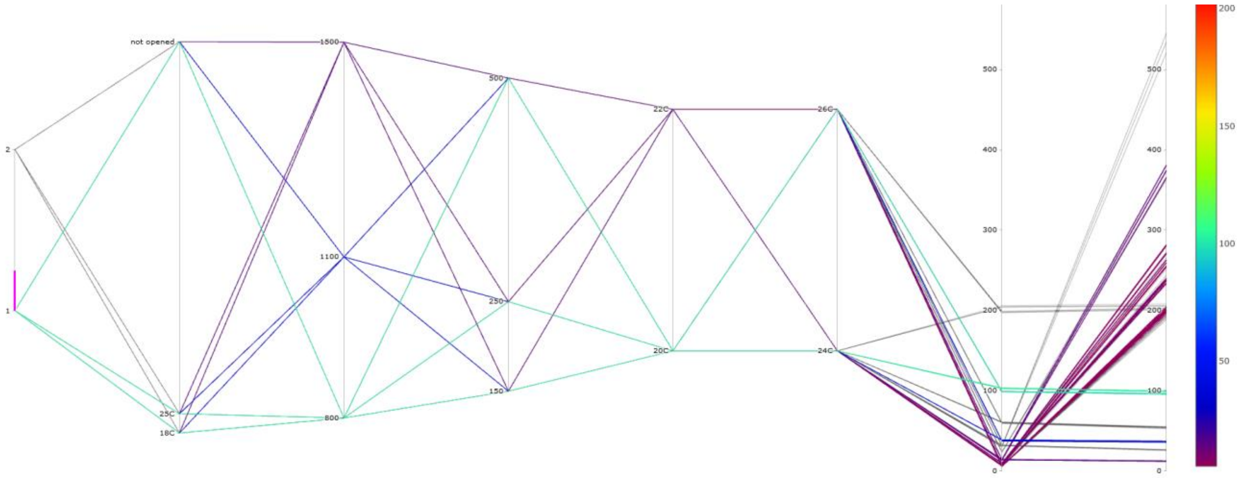


Figure 13 Effects of 'number of occupants' on winter comfort in Ravensburg's building.

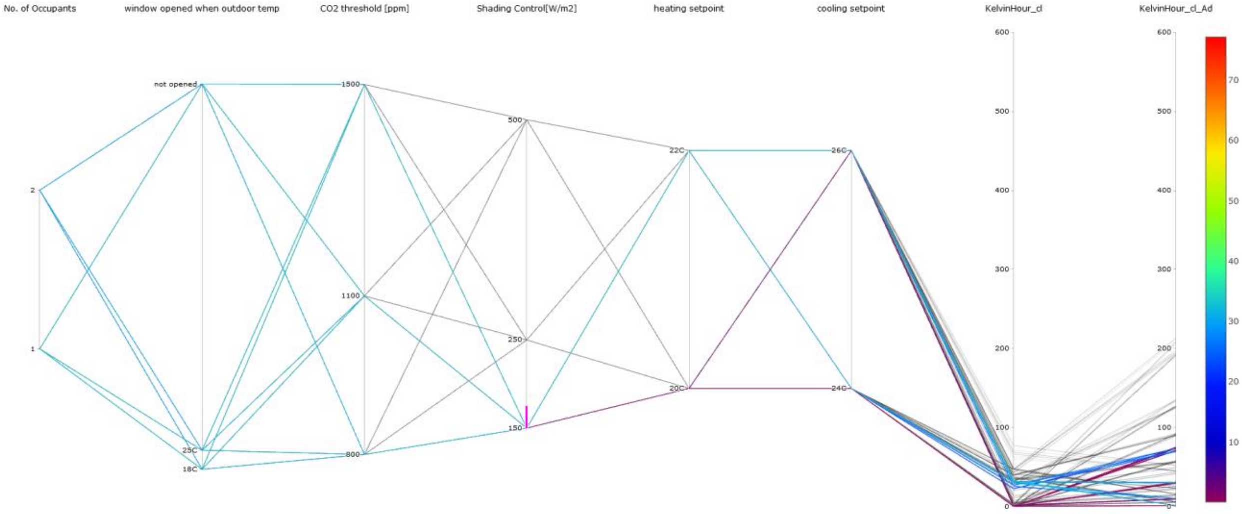


Figure 14 Effects of Shading on WOH. Lower shading threshold, lower overheating.

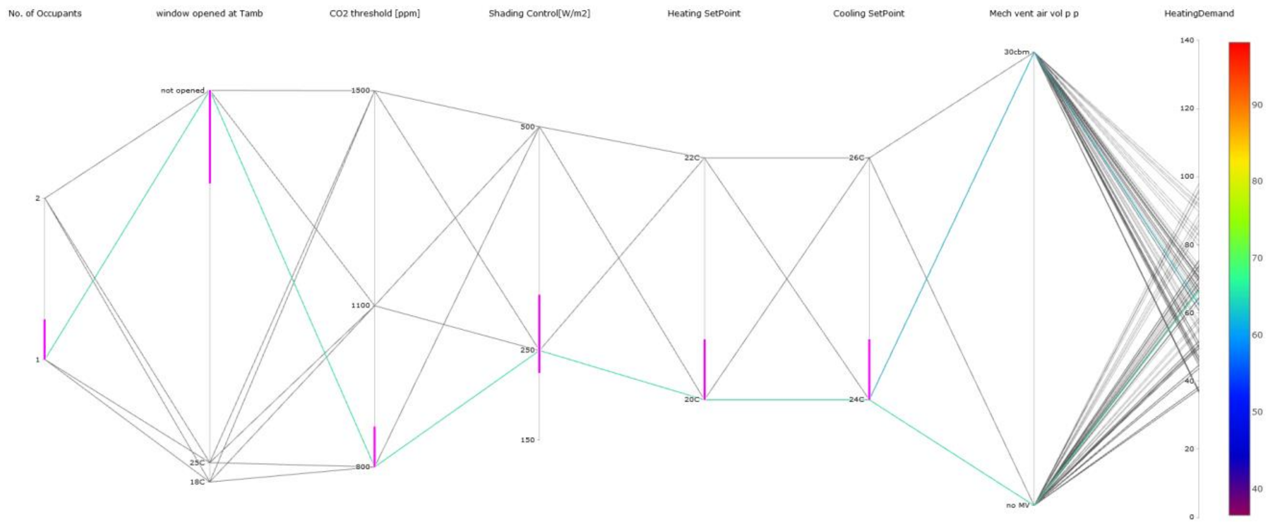


Figure 15 heating energy demand affected by Mechanical ventilation in Kolbermoor

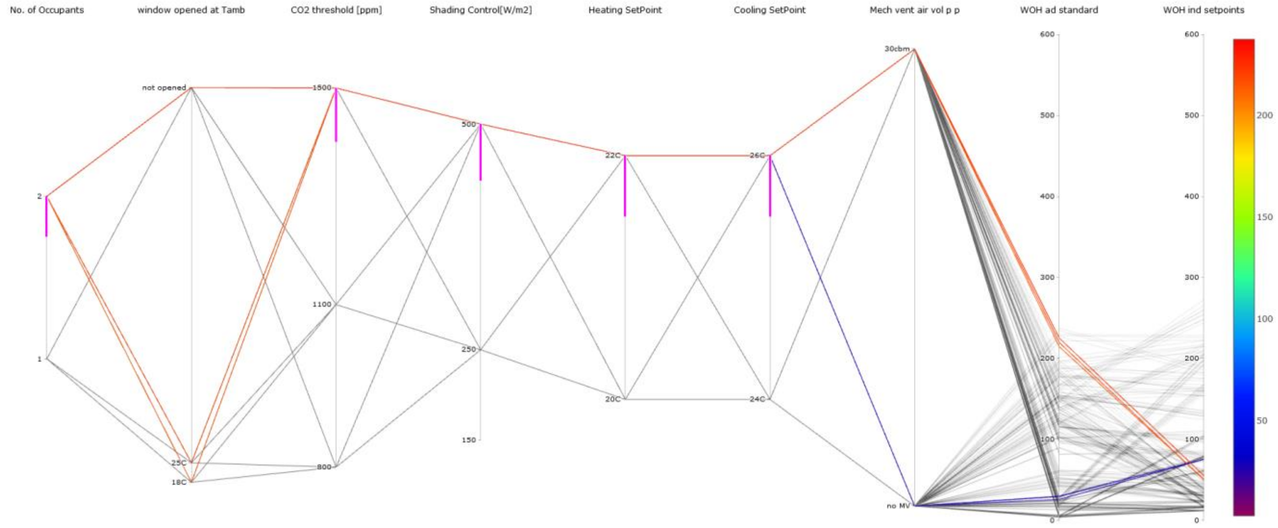


Figure16 Effect of Mechanical ventilation on Summer comfort in Kolbermoor.

windows, in the case of CO2 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.

Robustness: 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.

Recommendations

The factors that affect a building's performance are solar heat gains, ventilation losses and internal gains. Since building operation is unpredictable, it is easier to combat this variation with early passive design strategies. Movable solutions pose a risk of wrong usage and therefore, passive optimization strategies are more robust. Designers should optimize 'robustly' and not just for the ideal scenario. The most critical parameters for optimization are:

1. Optimizing the window to wall ratio instead of relying on manual or automatic operation of shadings. Balancing the size of windows for sufficient daylight and minimum heat gains combined with good sun protection and fixed shading is a robust solution for cooling energy demand reduction;
2. Triple glazing with low U-value increases robustness for winter, especially critical in case of big windows;
3. Materials with high VO emissions should be avoided as they worsen the perceptive air quality and increase the frequency of opening windows, increasing ventilation heat losses.
4. Larger rooms with high ceilings have lower internal heat gains and so, lower cooling demand. Smaller rooms theoretically have a smaller volume to heat, have a higher frequency of opening windows and so higher heat losses. Therefore, larger room volumes are more robust;
5. individual control possibility for systems.

For Building operation:

Raising awareness among the occupants about the correct operation of the building systems and about the effects of their actions in quantifiable terms can help improve user behaviour. 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. A sensor that indicates that the CO2 level in a room is too high already exists. Implementing a second reminder to close the windows when CO2 levels have reached acceptable levels can reduce unnecessary ventilation heat losses.
ii. Shading operation is very important for summer comfort and cooling demand. The south and East facing rooms should keep them closed overnight to avoid overheating in the early unoccupied hours. The programming of the automated shading is critical and should be reviewed by the designers
v. 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.

For Designers:

Some findings from this thesis that designers should consider when designing are:

i. 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 which is theoretically right, however, this office is self-shaded by the building and a big tree. The shading closes regardless of these conditions since it is controlled by a single sensor on the roof of the building.

ii. The number of occupants has a high influence on comfort and energy consumption and should be considered during the comfort-concept design as it affects decisions such as choosing various systems. For example, having mechanical ventilation loses its benefits when there is variable CO2 production rate and when people move in and outside the building/ room frequently.

ii. Designing mechanical ventilation must be considered critically. Not providing all the required air mechanically, instead, combining it with natural ventilation loses the benefits of the energy and comfort. It should be considered based on the usage of the space. It is not recommended when many visitors are received.

v. Decentralized mechanical ventilation is an unfamiliar system in many places. Therefore, for correct usage it is better for them to have central control or a pre-programmed schedule which can be customised and manually overridden.

v. Fabric external shading blocks free air movement, especially required in summer, and is not recommended to be used in buildings with natural ventilation.

/i. All users of the building should be oriented on the correct usage of the systems in their control and also of correct building operation.

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.

In structural engineering, for example, the design value is calculated 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 accurate due to uncertainties, they should be incorporated in prediction process by conducting an uncertainty analysis simulating a variety of scenarios. 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.

It is better to predict the energy consumption with larger, realistic margins than have a higher energy consumption. The regularisation of robust optimization in design would improve prediction accuracy and can greatly reduce Performance Gap. Statistical concepts from other fields of engineering can help to develop a suitable verification concept for the building performance field.

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