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Assessment of a cloud-based heating controller: Impact on user behaviour, comfort, and perceived control

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ABSTRACT

This study investigates user behaviour, thermal comfort and perceived control in two office buildings, a part of the Living Lab Energy Campus project at Forschungszentrum Jülich, Germany. A questionnaire-based assessment was conducted at the end of the heating season in March 2024, with 91 responses. From January to March 2024, monitored data were collected on indoor and outdoor environmental parameters, occupant-related data, and heating consumption. The findings reveal that distinct heating consumption profiles and indoor environmental conditions may arise from variations in heating system supply, building age, offices orientations, and user preferences. Adaptive opportunities through web-based interfaces (e.g., JuControl) and Thermostat Radiators Valves (TRVs) were associated with reduced thermostat interventions and increased user satisfaction. Contextual factors, including office orientation and desk type (fixed or shared)—significantly influenced thermostat adjustments. The majority of respondents (74%) felt within the thermal comfort range and 64% preferred to maintain same conditions, reflecting the efficiency of the heating controller. While thermal discomfort was infrequent, occupants typically adjusted clothing or thermostats to maintain comfort, often opening windows for fresh air. Additionally, 82% of respondents consider themselves savvy regarding energy-saving practices, with common measures including shock ventilation and thermostat adjustments if needed. Regression results showed that hybrid control systems—by combining thermostat automation and manual window control—may enhance occupant comfort and perceived control in office environments. These insights inform designers and researchers how to enhance the design and implementation of cloud-based controller to ensure occupant-centric building automation while reducing energy use.

1. Introduction

In the European Union (EU), the building sector consumes about 40% of the total primary energy consumption and contributes to one-third of greenhouse gas (GHG) emissions [1,2]. The urgency to address the environmental impacts of this sector, particularly emissions from building operations, requires immediate and informed actions [3]. The deployment of Internet-of-Things (IoT) technologies presents a promising solution for mitigating and optimizing energy demand based on real-time occupancy patterns—aiming for net-zero operational emissions [4]. For instance, the improvement in building equipment, deployment of sensors, actuators and controllers, can achieve more than 30% of aggregated annual energy saving [5]. However, ensuring occupants' comfort as well as energy savings have become essential in optimal building design and operation, as comfort plays a crucial role in human well-being and productivity [6].

Building automation can lead to unintended behavioural effects such as changes in occupants' comfort expectations, conflicts between automated controls and occupants' needs, or negative effects such as reduced satisfaction [4,7]. Thus, neglecting occupants in building control systems may lead to system overrides, reduced comfort and increased energy consumption [8]. Therefore, the success of such systems depends on the effectiveness of automation technologies and the choice of control algorithms in achieving energy efficiency and raising user comfort and acceptance [9,10].

In office environments, thermal comfort is crucial for occupant health, happiness and productivity [11]. According to ASHRAE, thermal comfort is defined as "that condition of mind that expresses satisfaction with the thermal environment". Adaptive behaviours such as adjusting clothes, opening a window or adjusting the thermostat, play a significant role in achieving this comfort [12]. These adaptive

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Acronyms

EBC	Energy in Buildings and Communities
EU	European Union
FZJ	Forschungszentrum Jülich
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICT	Information and Communication Technology
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IoT	Internet-of-Things
LLEC	Living Lab Energy Campus
MPC	Model Predictive Control
NFA	Net Floor Area
OCC	Occupant-Centric Control
PICO	Personalization-Integrated Co-Optimization
PMV	Predicted Mean Vote
TRVs	Thermostat Radiator Valves
TSV	Thermal Sensation Votes
ORs	Odd Ratios

behaviours—in particular window opening and temperature setpoints adjustments—are major drivers of energy use in buildings [13–15]. Several studies [10,16–21] suggested that the perceived control (i.e., individuals perception of their personal control) and thermal satisfaction with workplace environments are closely connected. Therefore, without a degree of personal control, occupants can be dissatisfied with indoor thermal conditions. In a large-scale study, Karjalainen and Koistinen [22] found that both thermal comfort and perceived control of heating and cooling systems are lower in office buildings, compared to residential settings. If perceived control of thermostat adjustments is low, users may turn to space heaters or open windows, often leading to excessive energy consumption [23].

Considering these challenges in understanding the impact of building automation on occupant comfort and perceived control, this study presents a comprehensive assessment of the performance and effectiveness of a cloud-based heating controller on heating consumption and indoor thermal conditions. The controller is deployed in two office buildings, as part of the Living Lab Energy Campus (LLEC) project at Forschungszentrum Jülich (FZJ). The controller is designed to easily incorporate user setpoint preferences from different sources, provide reliable fallback solutions, and be scalable across multiple buildings [24]. This study then examines the controller's impact on thermostat and window interactions, as well as its effect on user thermal comfort and perceived control under real-world conditions, aiming to optimize controller operation for occupant comfort and satisfaction, whilst maximizing the energy efficiency.

2. State-of-the-art

In recent years, a significant amount of research has focused on bridging the gap between human comfort studies and building control systems, particularly in line with IEA EBC Annex 79 activities [25] and other related studies [9,10]. Occupant-centric control (OCC) seeks to balance energy savings with occupant comfort and prioritize user well-being and satisfaction. While several studies addressed the main challenges and opportunities to implement OCC in real-world settings [4,6,26–28], a comprehensive assessment of such implementations in terms of occupant comfort and acceptance remains limited. This study evaluates a heating controller, that integrates user wishes of temperature setpoints via a web-based interface or physically through thermostat radiator valve (TRVs), while maintaining comfort and energy efficiency. The controller gives the highest priority to manual user setpoints, followed by scheduled preferences, and finally a fallback schedule [24].

2.1. Thermostat control: Impact on comfort, perceived control, and energy use

According to Fanger [29], there is no single thermal environment that makes everybody satisfied. Accordingly, providing personal control over the thermal environment is important for improving occupant satisfaction [17,30] and productivity [31]. An experimental study [18] showed that perceived control can improve the thermal comfort of the occupants in winter. They suggested to provide users different ways to effectively control the thermal environment (i.e., through windows and thermostat). In similar study, Karjalainen [16] investigated the impact of thermostat use on thermal comfort and perceived control over room temperature. A quantitative survey was conducted with a sample of 3094 participants in homes and offices in Finland, during winter and summer seasons. The findings revealed that the thermal comfort levels were significantly higher in homes than offices, and the perceived control was notably lower in offices, since occupants had fewer adaptive opportunities to control their thermal environment.

Several studies further explored how building automation and control strategies enhance user satisfaction and perceived control [9,19,32]. For instance, Tamas et al. [10] explored the impact of building automation on perceived comfort and control among 170 workspaces in 23 institutional buildings at a Canadian University campus. The study employs a mixed-methods approach, including interviews and surveys. A general preference for manual control was noted, with higher satisfaction in private offices. The results showed that the availability of adaptive control options significantly enhanced perceived comfort. To enhance user satisfaction, some studies recommended providing occupant training on buildings systems and controls, along with well-designed interfaces that increase system transparency and provide users with information to effectively use their systems [21,33].

With a focus on thermostat control in office buildings, an earlier study by karjalainen et al. [22,34] aimed to assess and improve the usability of thermostat controls by developing guidelines that address common user challenges, to improve user thermal comfort, satisfaction and productivity. The study conducted contextual interviews with 27 office occupants in 13 buildings in Finland. Participants were mostly working in private offices, with access to local temperature controls (e.g., thermostat valves and room thermostats). The study found that effective thermostat controls should be simple, accessible, and provide clear feedback to users, allowing for specific temperature adjustments. Key recommendations include enhancing control visibility, using intuitive symbols, offering immediate feedback, are suggested to improve user satisfaction and comfort in office settings.

In another study, with the aim to improve perceived control in offices by addressing usability issues of thermostat interface, Brackley et al. [21] employed a three-phase approach study in 25 offices within an institutional building in Ottawa, Canada. The offices were identical, each with a single window facing the northeast facade, except two corner offices. The authors assessed existing controls, developed new features to improve the functionality of the user interface, and feedback was gathered from the users. The results suggested considering human factors principles like clear feedback, and emphasizing the need to incorporate human factors research to improve perceived control. Due to the small sample size (4 participants), the study focused only on qualitative responses, making it impossible to draw broad conclusions.

In the study by Liu et al. [35], the authors developed and evaluated a user-interactive thermal environment control system that enhances energy efficiency and occupant satisfaction in office buildings. A prototype system, integrated with a model-predictive HVAC controller, was tested in a three identical south-facing offices located in West Lafayette, Indiana. The occupants were allowed to adjust the thermostat settings via a web interface displaying real-time energy feedback. The results showed that occupant overrides contributed up to 55% of additional energy use, but providing real-time energy information reduced this by 36%, as users selected setpoints closer to energy-efficient recommendations without compromising comfort. An utility-based decision model was developed and validated, demonstrating that occupants balance comfort and energy considerations when adjusting thermostats. The study recommends implementing interactive thermostat interfaces with real-time energy feedback to promote energy-efficient behaviour while maintaining comfort. Finally, the authors point out that a more longitudinal study across different office layouts should be carried out to enhance the generalizability of the findings.

Belazi et al. [14] investigated the impact of thermostat settings on building energy demands during the heating and transition seasons in residential buildings in France. The study combined experimental monitoring and numerical modelling in 18 apartments to analyse occupant behaviour and its effects on energy consumption. The study found high variability in heating consumption, ranging from 441 kWh to 3157 kWh across apartments, largely driven by stochastic occupant behaviour. A probabilistic model was developed based on environmental factors such as outdoor temperature, indoor humidity and CO_2 levels to improve energy consumption predictions over traditional deterministic models. However, the study did not examine the impact of thermostat settings on indoor thermal comfort conditions.

Stopps and Touchie [36] examined occupant thermal comfort and HVAC operation in two high-rise residential buildings located in Toronto, Canada. Both buildings were constructed after 2012 and have highly-glazed envelops. Occupants have control of their in-suite temperature setpoint through a thermostat which controls the HVAC system. The research utilized field data collection methods, including surveys, and connected thermostat data, to infer occupant comfort and identify opportunities for improved energy efficiency and comfort. Despite the presence of in-suite controls, the research revealed prevalent thermal discomfort, with the Predicted Mean Vote (PMV) model and setpoint deviation not consistently aligning with occupant-reported thermal sensation. This study demonstrates the potential of smart thermostat data as a tool to detect ways to save energy in buildings.

Personalized control strategies was developed to improve energy-efficiency and user experience in HVAC systems. For example, Meimand and Jazizadeh [37] introduced a novel occupant-centric framework called PICO (Personalization-Integrated Co-Optimization) for HVAC systems to enhance energy efficiency and peak reduction while considering occupant preferences and sensitivities to indoor thermal environments. Through a comprehensive uncertainty quantification analysis, the framework was evaluated against three common control strategies, showing increased efficiency and peak time productivity. The results demonstrated up to an 18.3% increase in peak time productivity and a significant reduction in standard deviations for thermal comfort experience. The evaluation was conducted in a simulation environment, highlighted the potential of personalized control strategies in achieving energy savings and enhancing user comfort in buildings. Future research is directed towards real-world testing to validate these results in practical settings.

2.2. Research gaps and contributions of the study

Most existing literature focused on thermostat controller's evaluation from a single perspective, particularly energy demand, neglecting occupant thermal comfort, which is a critical factor for user satisfaction and system effectiveness. Additionally, several studies were limited to single-occupancy offices or specific building types (e.g., residential, office, or institutional), limiting the generalizability of their findings. Many previous studies rely on short-term field studies—often based on small sample size—or simulations, leaving a significant gap in conducting long-term and real-world evaluations. To this end, this study aims to fill in several of these gaps by addressing the following objectives:

- Provide a **comprehensive real-world assessment** of a cloud-based heating controller, evaluating its impact on heating consumption, user behaviour, thermal comfort, and perceived control.
- Examine the **combined impact** on thermostat interventions and window openings, considering both as adaptive behaviours response to indoor thermal conditions, extending beyond previous studies that focused only on thermostat adjustments.
- Conduct a **comparative study** across two office buildings with varying construction ages, comprising different offices layouts (e.g., orientation and floor level), occupancy level (e.g., single, shared and open-plan offices), and desk-sharing types (e.g., fixed or shared) to understand how building design and envelope characteristics influence controller effectiveness.

To achieve the aforementioned goals, this paper used a mixed-methods approach including a web-based questionnaire with monitored datasets in two pilot studies to assess how the controller influences occupant behaviour (i.e., thermostat interventions and window opening), thermal comfort, satisfaction and perceived control. This paper contributes to the field by offering empirical insights into how heating automation can be optimized considering different office layouts, types, and different building typologies and structure. These insights inform designers and researchers how to enhance the design and implementation of a cloud-based controllers for more occupant-centric building automation, while reducing energy use.

The remainder of this work is structured as follows: In Section 3, we introduced the case studies characteristics and the methodology employed in this work, including the questionnaire design, monitored datasets and statistical analysis. Afterwards, Section 4 presents an overview of the heating controller's impact on indoor climate and heating consumption, then details and discusses the main results of the questionnaire, including its impact on thermostat and window use patterns, thermal comfort, and perceived control, followed by a clarification of user engagement and energy-savvy measures. Finally, Sections 5 and 6 summarize the main conclusions, recommendations, and limitations of this study.

3. Methods

The cloud-based heating controller was evaluated using a mixed-methods approach. A web-based questionnaire was distributed on March 5th, 2024, and remained open for one week across two buildings. In addition, real-world measurements were collected from a local server database during the heating season, spanning from January to March 2024.

3.1. Buildings and climate

The assessment analysis covers 77 offices across two institutional research buildings, namely Building A and B (see Fig. 1), being part of the Living Lab Energy Campus (LLEC) project at Forschungszentrum Jülich (FZJ), Germany. LLEC is a comprehensive living lab comprising 16 buildings equipped with sensors and actuators to test novel monitoring and model-based control approaches at room, building, and district levels [38]. An advanced ICT platform was developed as part of the project to manage decentralized energy sources and facilitate occupant-centric room automation and building controls [39].

An overview of the key characteristics of the buildings is provided in Table 1. Building B represents a contemporary construction—completed in 2021, while Building A is an older, non-retrofitted building—constructed in 1976. Building A is a two-storey, L-shape structure oriented towards southeast (SE) and northwest (NW), while Building B is a three-storey, rectangular structure oriented towards northeast (NE) and southwest (SW).

Table 1
Buildings A and B key characteristics.

	Building A	Building B
Construction year	1976	2021
Number of floors	2	3
NFA (m^2)	999	2003
Building orientation	NW, SE	NE, SW
Number of monitored offices	32	45

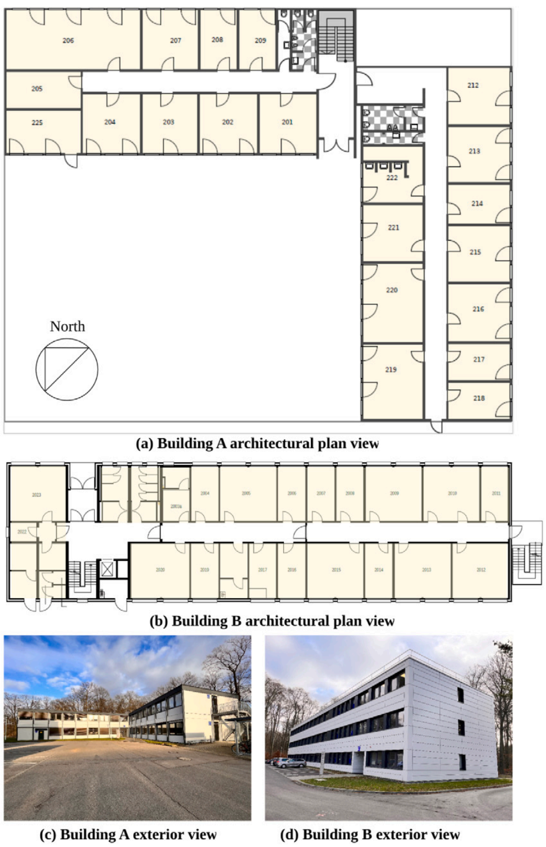


Fig. 1. Architectural plan and exterior views of Building A (a,c) and Building B (b,d).

The questionnaire was released between the 5th and 11th of March, 2024. Some questions evaluated the participants' momentary feelings (i.e., thermal sensation and preferences), while others assessed their experiences during the heating season. From the 26th of February to 11th of March, 2024, the week preceding and the week including the distribution time of the questionnaire, the average outdoor temperature was 6.9 °C, and average relative humidity was 77.6%. The study period from January to March 2024 experienced generally cold weather, with a mean daily average outdoor temperature of 5.7 °C. The temperature fluctuated significantly, with extreme values ranging from −11.8 °C to 19.4 °C. Fig. 2 shows the daily mean, min and max of the floating average ambient temperature (calculated using a 10-sample window) during the study period, highlighting the week of the questionnaire distribution. The daily average relative humidity ranged from 33.3% to 100%, with a mean of 82.1%. These conditions highlight the importance and the need of an effective heating controller, and provide a relevant context to assess thermostat use and thermal comfort, as users experienced substantial variations in weather conditions.

3.2. Monitored offices and observed data

The evaluation of the heating controller was performed on 32 offices in Building A and 45 in Building B. The offices varied in terms of orientation, size, occupancy, desk-sharing and floor level. Each office is equipped with one or more operable windows. Offices in both buildings are equipped with indoor air quality (IAQ) multi-sensors, thermostat radiator valves (TRVs), and "smart" window handles which report the window states (i.e., open, tilted, or closed). More details about the devices and communication protocols can be found in [38]. The monitored datasets were extracted from a cloud-based database server. Data fetching, preprocessing, cleaning, filtering and visualizing were performed in Visual Studio Code (v1.100.0) and OriginPro 2024. The monitored datasets are as follows:

- Outdoor environment-related data such as outdoor temperature (°C) and relative humidity (%). Weather data was collected from the meteorological weather station tower located at FZJ, recorded every 10 min.
- Indoor environment-related data such as indoor temperature (°C), relative humidity (%), and CO_2 concentration (ppm), measured by IAQ multi-sensor, recorded every 15 min.
- Occupant behaviour-related data such as window state (0: closed, 1: tilted position, 2: partially to fully open), temperature setpoint triggered by controller, temperature setpoints triggered by users, radiator valve opening (0%–100%), all are recorded as event-based measurements.

3.3. Heating controller

The TRVs, installed at the radiators in both considered buildings, are controlled by a dedicated automation application allowing the integration of user wishes in different ways. As a result, users can indicate their setpoint preferences and anticipated presence through a web-based interface, named JuControl [40], as well as setting a manual setpoint temperature at the TRVs, disabling the automatic mode for 8 h. JuControl is a web application with graphical interface, provide access to room level real-time and historical data (e.g., indoor conditions and the state of window and door), as shown in Fig. 3. For more details about JuControl's design including interactive logic and feedback mechanisms, please refer to Ubachukwu et al. [41]. Currently, access to JuControl is granted only when all users assigned to an office consent to the data policy agreement. Once access is granted, the heating controller is automatically activated based on the calendar inserted in JuControl.

During unoccupied times, a night-setback is applied. In case no setpoint wish was provided by a user, a fallback setpoint of 19 °C during working time and 17 °C during night time is applied. The current configuration of the automation generates a setpoint trajectory based on the input data provided by the occupants. One variant of a rule-based control approach applied to the TRVs involves shifting any increase in the temperature setpoint by a timespan (Δt) in advance to achieve the desired temperature on time, as shown in Fig. 4. Δt is assumed based on an engineering guess to mimic MPC. Further details about the design and architecture of the controller can be found in [24].

3.4. Questionnaire

A web-based questionnaire was conducted in LimeSurvey, an online survey tool (https://www.limesurvey.org/). The survey was conducted to understand user behaviour with thermostat automation and window opening, and evaluate their thermal comfort and perceived control. The design of the questionnaire was based on other questionnaires, used in related previous studies [21,35,36,43]. The questionnaire consists of 38 questions grouped in six sections, see Appendix A.1. The first two parts comprise questions about occupants' demographic data (i.e., age and gender), and contextual and time-related data (i.e., work activity and workplace). The third part involves questions about how often and when the users interact with thermostats and windows. The next two parts focus on thermal comfort assessments (i.e., thermal sensation,

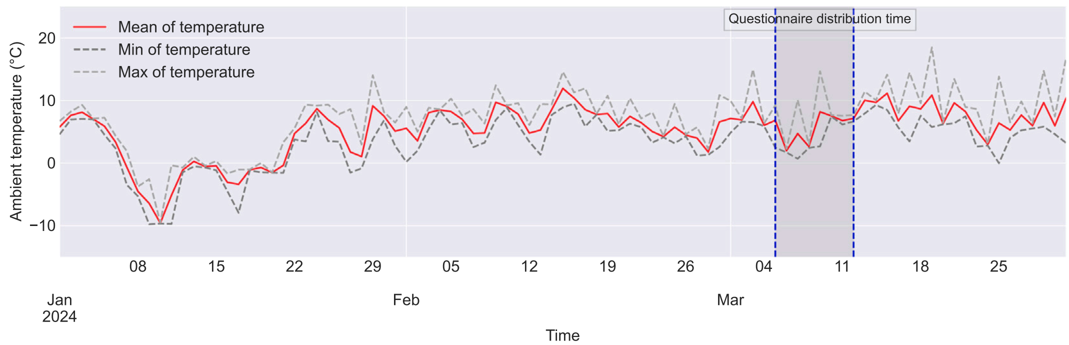


Fig. 2. Daily mean, min and max of floating average ambient temperature during the study period. The highlighted area represents the period when the questionnaire was distributed.

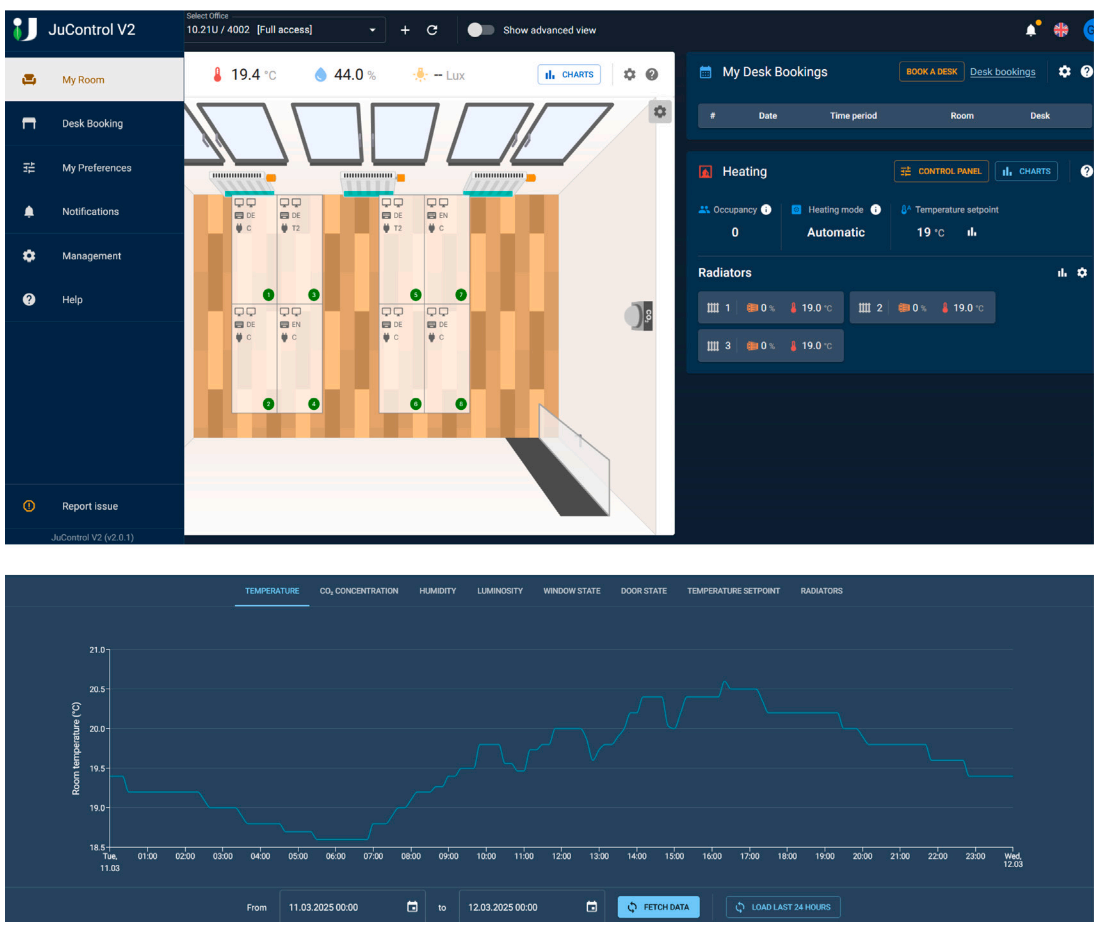


Fig. 3. Screenshot of JuControl, a web-based interface (https://www.fz-juelich.de/de/blogs/llec/2022).

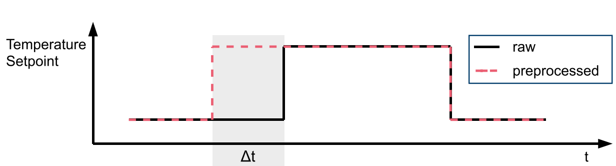
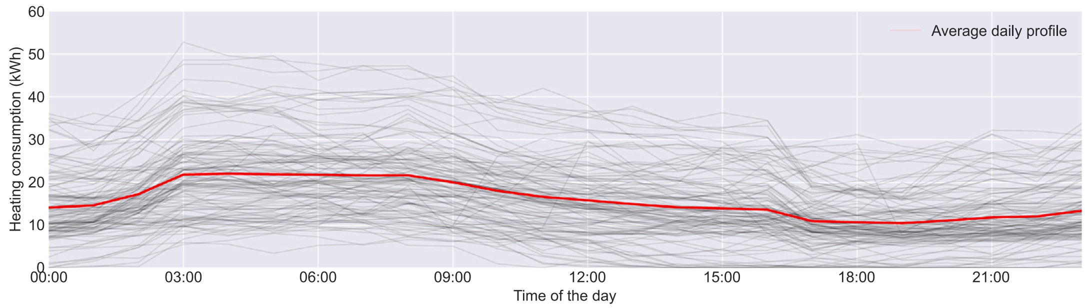


Fig. 4. Schematic on setpoint trajectory preprocessing as introduced in [42].

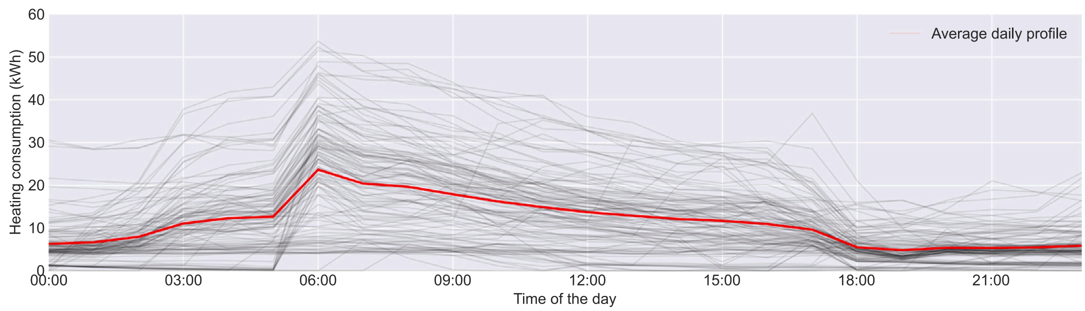
preferences, acceptance and satisfactions), and users' perceived control and satisfaction. Last part includes questions about user engagement of energy-saving measures. The questionnaire was approved by the local ethics of Executive Board Office at FZJ before being conducted.

3.5. Statistical analysis

Statistical analysis was performed using IBM SPSS statistics version 29.0.2.0 (20) software and Visual Studio Code (v1.100.0). Descriptive statistics and cross tabulation were used to analyse the data. To test the normality, Shapiro–Wilk test was conducted on the datasets. Shapiro–Wilk test is commonly used for small samples. Null hypothesis is rejected when p-value is less than 0.05, the data is not normal. If normality is rejected, the Mann–Whitney U test, a non-parametric test, was applied to determine any significant differences between two independent groups. The independent-samples Kruskal–Wallis test was used to find significant differences between three or more independents groups. Both tests are used for continuous or ordinal data (e.g., Likert scale: 1 to 5 or satisfaction votes), while Chi-square test is used for



(a) Building A



(b) Building B

Fig. 5. Daily profile of heating consumption of (a) Building A and (b) Building B. The red line represents the average daily profile of heating consumption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

categorical data to assess the association between the variables. Ordinal logistic regression is used to assess the association between the explanatory variables (i.e., one or more independent variable) and an ordinal outcome (i.e., dependent variable). Odds Ratios (ORs) are used to interpret effect sizes and estimate the strength of association between predictor and outcome variables. An OR value of one means there is no association between the predictor and the outcome.

4. Results and discussion

First, an overview is provided of the heating controller's impact on energy consumption, temperature setpoints and indoor environmental conditions. Following this, the main results of the questionnaire are presented, covering demographic and contextual information, thermostat and window use patterns, thermal comfort assessment, user satisfaction and perceived control, as well as energy-savvy measures. Preliminary results of the questionnaire were presented in [42], covering a different period of study.

4.1. Overview of heating controller performance

This section presents the impact of heating controller on heating consumption daily profile, temperature setpoints and indoor climate conditions such as indoor temperature (°C), CO_2 concentration (ppm) and relative humidity (%).

4.1.1. Impact on heating consumption daily profile

Fig. 5 (a & b) shows the heating consumption daily profiles for Building A and B during the study period. The distinct patterns showed of each day can be explained by differences in heating system's supply, which maintain the indoor temperature based on user preferences and controller setpoints. Fig. 5 (b) demonstrates a notable increase in the average daily profiles in Building B around 5:00 am due to the controller recovery of the night setback, in order to warm up the buildings before occupants' arrival. In the evening, a corresponding decrease around 6:00 pm aligns with the end of typical working hours. In Fig. 5 (a), different average profile is observed in Building A, the peak of heating consumption starts at 3:00 am and decreased around 5:30 pm. These differences can be a result of different building age and envelope structure, discrepancies in occupancy level and occupant setpoints preferences. More details can be found in [44].

4.1.2. Impact on temperature setpoints

The mean daily average temperature setpoints in offices, stemming from all user input interfaces—including JuControl schedules, direct setpoint input, and TRVs—ranged between 16.8 °C to 18.2 °C in Building A, and 16.8 °C to 19.3 °C in Building B. These results reflect different user preferences (uncertainty) in terms of thermal comfort which influence the indoor thermal conditions. As shown in Fig. 6 (a), the highest mean temperature setpoints in Building A were recorded in SE facing offices, while the lowest were in NW facing offices at 17.4 °C, which is below the default heating controller setpoint. Fig. 6 (b) shows the distribution of temperature setpoints derived only from online interfaces, excluding any local interaction, for offices in Buildings A and B, grouped by their orientation. Non-significant differences were observed in the mean of controller setpoints across different orientations with an average ranging between 16.7 °C to 17.1 °C. Regarding valve operation, daily opening averages ranged from 03% to 33.3% in Building A, and from 6% to 28.7% in Building B, as shown in Fig. 6 (c). The low averages of temperature setpoints can be attributed to (1) the low occupancy level during the study period, or (2) few occupant interventions to increase the controller setpoint.

4.1.3. Impact on indoor environmental conditions

The daily average indoor temperature in offices of Building A fluctuated between 17.1 °C and 21 °C, and in Building B between 18.6 °C and 22.1 °C. Higher indoor temperature in Building B can be assigned to the efficient thermal insulation of building envelop compared to Building A. These fluctuations can be explained due to different offices' orientation, occupancy and the capacity of heating radiators. In Building A, the CO_2 concentration daily average ranged from 516 to 1957 (ppm), while in Building B ranged from 863 to 1950 (ppm), attributed to differences in occupancy level and ventilation rates. However, relative humidity

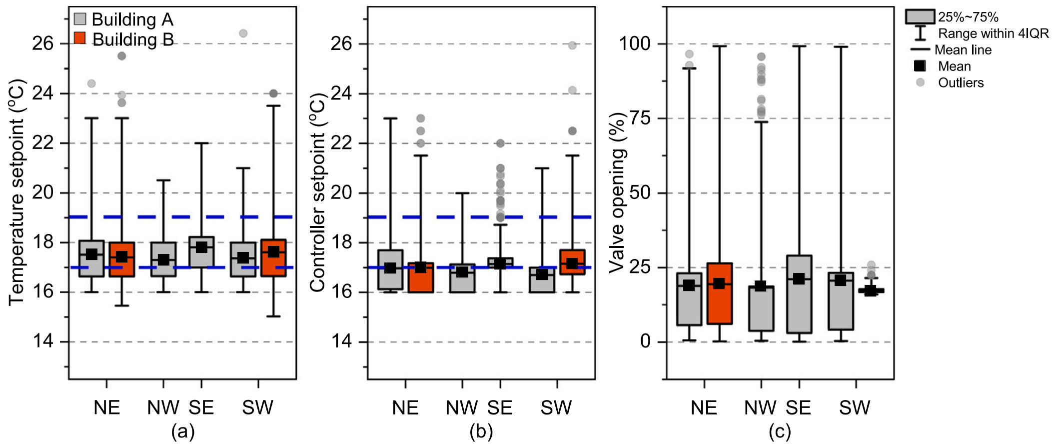


Fig. 6. Distribution of daily average (a) temperature setpoints, (b) controller setpoints, and (c) radiator valve opening per office orientation in Buildings A and B during the study period. The blue dashed line represents the default controller setpoint range (17 °C to 19 °C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

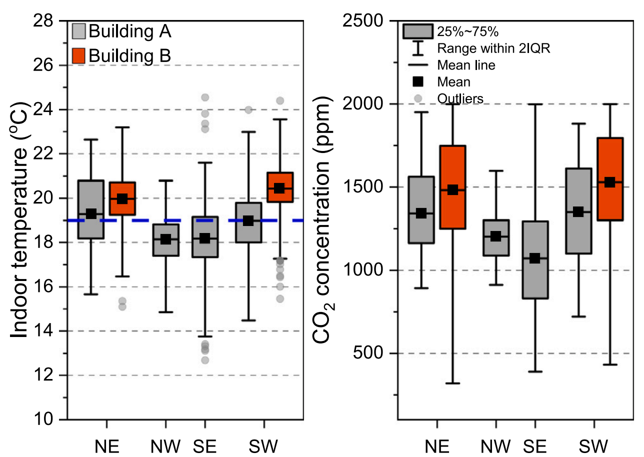


Fig. 7. Boxplot distribution of indoor temperature (°C) and CO_2 concentration per office orientation for Building A and B.

daily averages remained within comfort levels with (37.5%–48.6%) in Building A and (39.8%–52.5%) in Building B.

Fig. 7 illustrates that NE and SW facing offices showing the highest average temperatures (approximately 19 °C), while NW and SE facing offices showing the lowest in Building A (between 18 °C–19 °C). This can be explained due to space orientation or different institutes' employees, as NE and SE wing belongs to one institute, and NW and SE belongs to another institute. Higher indoor temperatures are observed in NE and SW facing offices in Building B (above 19 °C). Additionally, Building B offices showed higher CO_2 levels compared to Building A offices, possibly due to (1) the prevalence of shared and open-plan offices in Building B, contrasting with mainly single offices in Building A, and (2) the significantly higher air tightness in Building B. This result can explain the high frequency of window opening, reported from respondents in Building B compared to Building A, as presented in Fig. 11.

Based on the aforementioned findings, the study suggests that differences in building age and envelope structure, user preferences, and offices orientations, contribute to variations in energy consumption and indoor environmental conditions. This highlight the importance of considering these factors while developing the heating controller to ensure comfort and energy efficiency in the buildings.

4.2. Key findings of the questionnaire

The main results of the questionnaire are presented in the following sections, covering demographic and contextual information, thermostat and window use patterns, thermostat comfort assessments and discomfort actions, user satisfaction and perceived control, and energy-savvy measures.

4.2.1. Demographic and contextual information

A total number of 91 respondents completed the survey (a response rate of 57%), with 25.3% from Building A (N=23, representing 39% of building's occupants), and 74.7% from Building B (N=68, representing 54% of the occupants). The achieved response rate is considered acceptable for behavioural studies in work environments, especially where participation is voluntary. Moreover, the sample yields an acceptable margins of error (6.8%) at a confidence level of 95%, ensuring that the findings reliably reflect the broader population. Among the participants, 56% identified as male, 43% as female, and 1% as other. Regarding age, 37.4% are between (18–29) years old, 33% are in the (30–39) range, and 29.7% are above 40. More than 60.4% of the respondents are working for more than 2 years, 26.4% are in the office for 1–2 years, and 13.2% are working for less than one year. Table 2 summarizes the demographic information of respondents per each building.

Regarding the working time, about 74% of occupants in Building A and 44.1% in Building B reported working from the office for three days or more. Notably, the majority of occupants (76.9%) are working typical work hours, few people work in the morning (8.8%), and 14.3% of occupants do not have a regular time. More than half of the occupants (64.8%) have a fixed desk, while the rest have a shared desk with two or more people. Fig. 8 (a & b) illustrates the frequencies of daily working hours and desk type per each building.

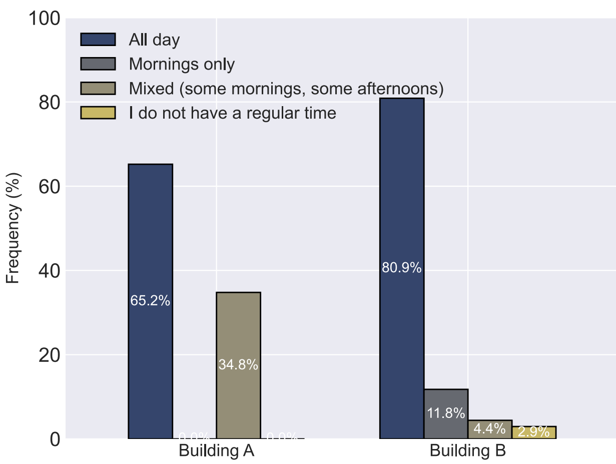
About 56% of the observed offices are open-plan offices (more than 3 people), while 25.3% are shared offices (2–3 people) and only 18.7% are single-occupancy offices. Approximately half of the occupants (53.8%) work in NE facing offices, 35.2% in SW facing offices, and 11% are distributed between SE and NW facing offices in both buildings. The highest percentage of respondents in NE and SW is mainly due to the long axis of Building B facing both directions. The offices are distributed equally between the 1st and 2nd floors (38.5% and 36.3%, respectively), while less participants are located on the ground floor (25.3%). Table 3 summarizes the frequencies of offices' types, orientations and floor levels in Building A and Building B.

Table 2
Demographic information of respondents per building.

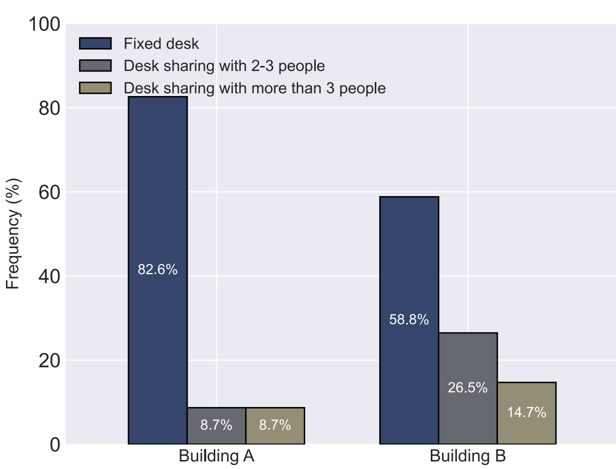
	Gender			Age			Contract duration		
	Male	Female	Other	18–29	30–39	40–49	50–59	>2 years	2 years and less
Building A	65.2%	34.8%	0%	34.8%	39.1%	13%	13%	73.9%	26.1%
Building B	52.9%	45.6%	1.5%	38.2%	30.9%	11.8%	19.1%	55.9%	44.1%

Table 3
Offices description per building.

	Office type			Orientation				Floor level		
	Single	Shared	Open plan	NE	NW	SE	SW	GF	first floor	second floor
Building A	34.8%	39.1%	26.1%	21.7%	17.4%	26.1%	34.8%	47.8%	52.2%	0%
Building B	13.2%	20.6%	66.2%	64.7%	0%	0%	35.3%	17.6%	33.8%	48.5%



(a)



(b)

Fig. 8. Frequencies of (a) Daily working hours and (b) Desk type per building.

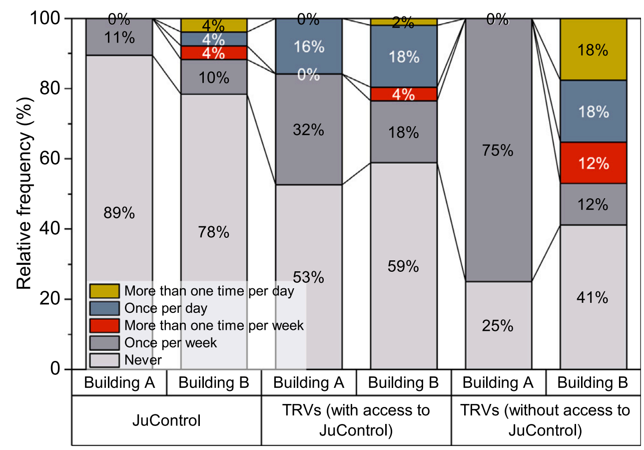


Fig. 9. Relative frequency of thermostat adjustments using JuControl, TRVs with access to JuControl, TRVs without access to JuControl. It was introduced in [42].

4.2.2. *Thermostat and window use patterns*

Participants were asked about how often they adjust the thermostat using JuControl and TRVs, and windows over the past week, using a 5-point Likert scale (1: never, 5: more than one time per day). To gain deeper insights into user behavioural patterns, respondents are categorized into three groups based on their interaction frequency: **passive users** (low group), who adjusted the thermostat either never or only once per week; **normal users** (moderate group), who adjusted it more than once per week; and **active users** (high group), who adjusted it once or more per day.

Frequency of thermostat adjustment

First, participants were asked if they have access to JuControl or not. In Building A, 82.6% of the respondents reported having access to JuControl, compared to 75% in Building B. Occupant who have access to JuControl often did not tend to adjust the temperature setpoint using JuControl, with 89% in Building A and 78% in Building B. Only 8% of respondents adjusted the thermostat setpoint once or more per day, as illustrated in Fig. 9. Interestingly, people tended to override the thermostat via the TRVs more often than JuControl, with 47% did it once or more per week in Building A, and 41% in Building B.

Additionally, user interventions via TRVs were more frequent among those without access to JuControl. A bout 75% of occupants in Building A adjusted the TRVs once per week, while 35% in Building B did so once or more per day. These findings align with previous studies suggesting that increasing the number of adaptive opportunities significantly increases occupant satisfaction, which can limit occupant adaptive actions [10,16,45]. In the following subsection, the analysis of this study focused on user-thermostat interventions frequencies only for those with access to JuControl, as the percentage of respondents without access (23.1%) was too small for meaningful analysis.

Contextual and time constraints impact on thermostat use patterns

As shown in Fig. 10, the relative frequency of thermostat interventions—normalized across contextual and worktime constraints such as building, office orientation, floor level and working hours—was analysed for three user groups (low, moderate, and high). For example, occupants in Building B exhibited a higher frequency of TRVs adjustments compared to those in Building A, with 72% assigned to high and moderate groups. Moreover, occupants in SE and SW facing offices were more likely to adjust the thermostat than those in NE and NW facing offices. Interestingly, occupants on the 2nd floor of Building B

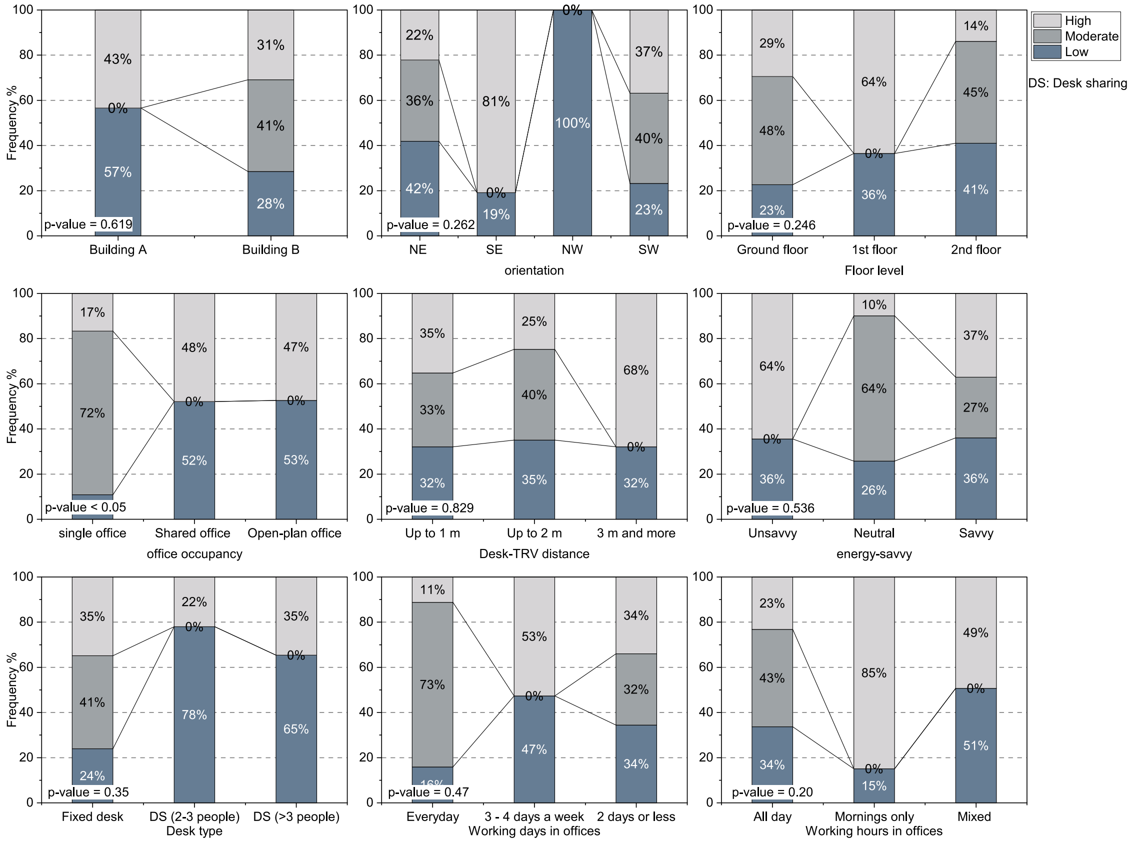


Fig. 10. Thermostat use patterns in terms of building, office orientation, floor level, occupancy level, desk-to-TRV distance, savvy | unsavvy, desk type, working days and hours.

were less often to adjust the thermostat, with 86% were assigned to low and moderate group. This behaviour may be attributed to different reasons: (1) Occupants on this floor were more familiar with JuControl and heating controller automation. This aligns with the findings of Day and Gunderson [33], who reported that occupants who received training or were familiar with building controls were significantly more likely to be satisfied with their workplace environment. (2) The high exposure of the 2nd floor surfaces to sunlight may have increased the operative temperature. However, since the operative temperature was not measured in this study, this explanation cannot be confirmed.

People situated farther from the TRVs showed a greater need to adjust the TRVs compared to closer ones, likely due to feeling colder at a distance. The Chi-square test revealed that office occupancy significantly influenced thermostat use frequency (p-value = 0.04), the single-occupancy offices exhibiting the highest frequency, with 89% were assigned to high and moderate group (active users). Moreover, 64% of unsavvy-energy occupants were assigned to high group, while 37% of savvy and 10% neutral were assigned to the same group. However, none of the aforementioned factors demonstrated a significant association with thermostat interventions (p-values > 0.05). Majority of the occupants who are coming in the mornings only are assigned to high group (active users) with 85%. Interestingly, occupants with fixed desks tended to adjust the thermostat more often (only 24% assigned to low group) compared to those sharing desk with two or more people. One possible explanation is that users with fixed desks may spend more time at their workstations, making them aware of temperature changes and more likely to adjust the temperature setpoints.

Window adjustments and position states

Similarly, the user interaction with window opening was grouped into 3 categories (low, medium, and high) to identify the use patterns frequencies in terms of building, orientation, floor, occupancy, and desk-window distance, energy-saving considerations, as shown in Fig. 11. Contrary to the frequencies of thermostat adjustments, occupants tended to open the window very often during the day. For instance, about 75% of respondents were assigned to high and moderate groups in Building B compared to 51% in Building A. Both office orientation and occupancy were found to statistically significantly influence the window opening frequency based on Chi-square test (p-value < 0.05). The lowest frequency of window-opening behaviour was found in NW facing offices, while the highest occurred in SE and SW facing offices. Similar frequency was assigned to moderate and high group (70%) in single and shared offices, while 60% were assigned to high group in open-plan offices. Non-significant difference was found in terms of desk-to-window distance. Additionally, energy-savvy people tended to open the window more often compared to unsavvy people.

Participants were asked about their preferred window position, considering three options: fully or partially open (i.e., shock ventilation) and tilted position (i.e., trickle ventilation). In Building A, about 50% of the respondents preferred to fully open the window, compared to 67.2% in Building B. Additionally, 86% reported opening the window fully for 0 to 10 mins. However, when the window was partially open or tilted, participants tended to keep it open longer, typically between 5 to 15 mins, as illustrated in Fig. 12(a). This is align with the findings from the monitored datasets in Building A during the study period. For shock ventilation, window opening duration ranged from 0 to 26 mins with an average of 4.1 mins, while trickle ventilation ranged from 0 to 24 mins with an average of 5.8 mins. In Building B offices, the daily window opening duration for shock ventilation ranged from 0 to 19.7 mins with an average of 2.5 mins, while less duration was observed for trickle ventilation — ranged from 0 to 3.16 mins with an average of 0.15 mins.

In Fig. 12(b), 94.2% of the respondents—who preferred the fully open position—tended to open the window one or more per day, while adjustments to partially or tilted positions were less frequent. The primary reasons for opening windows were related to specific times

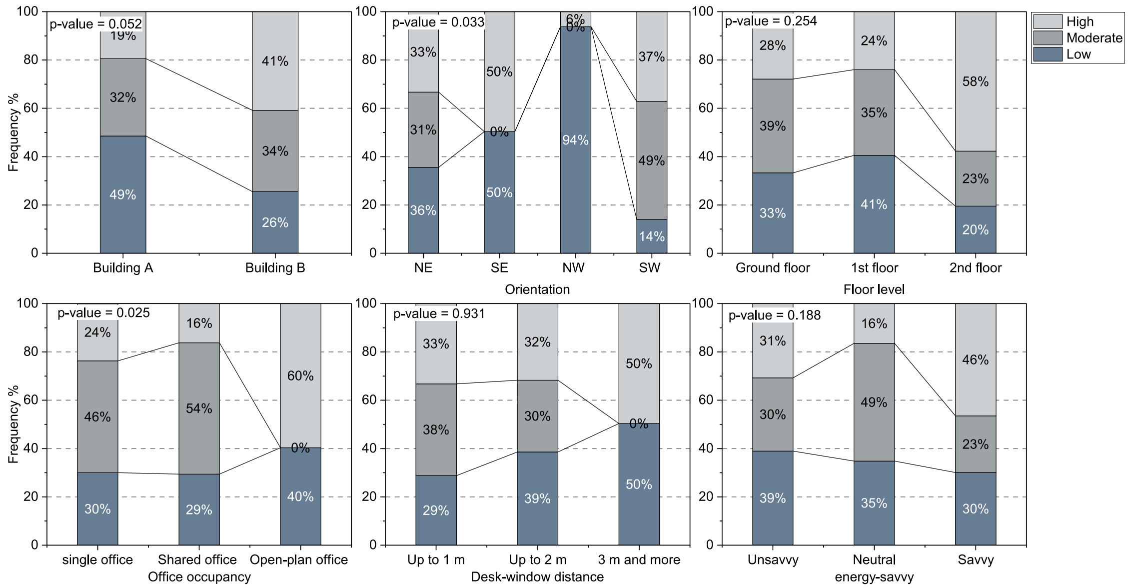


Fig. 11. Window opening patterns in terms of building, office orientation, floor level, occupancy level, desk-to-window distance, and savvy | unsavvy.

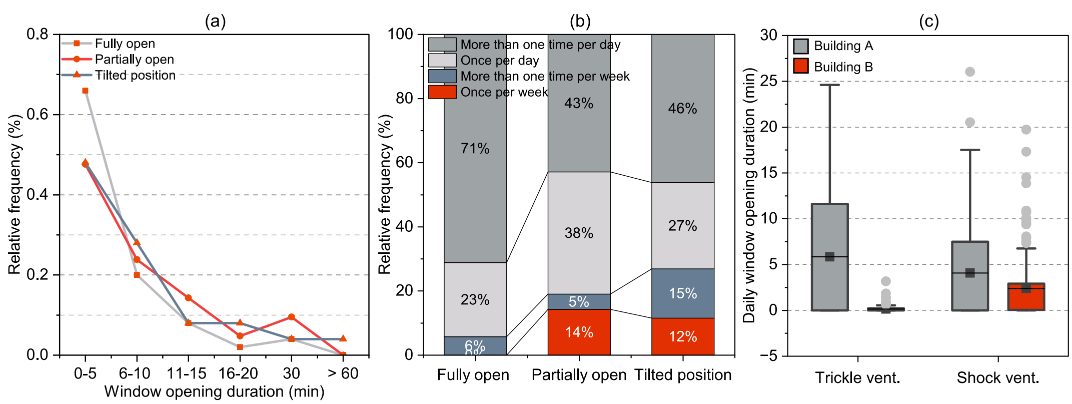


Fig. 12. Window position states (a) duration (min) and (b) relative frequency, and (c) daily window opening duration (min) in Building A and B during the study period.

of the day, particularly in the morning when they arrive (33%), or to obtain fresh air (48.3%). Fewer respondents (12%) cited thermal discomfort such as feeling too warm, as a reason for opening windows. These findings are in line with previous studies [46–49], which highlighted that factors affecting window opening can be not only thermal conditions but also other factors such as cultural factors or daily routine.

Overall, it is suggested that the availability of adaptive controls—such as JuControl and TRVs—may lead to higher satisfaction among users by reducing the need for frequent manual adjustments. This outcome may be attributed to the well-designed user-interface (i.e., JuControl), which improves the transparency of heating controller and provides users with essential information (e.g., indoor temperature) to effectively use the system. This is in line with Brackley et al. [21], by adding new interface features that help users better understand the mechanism of the system, and Liu et al. [35] by developing a novel interface to consider real-time energy use information to support setpoint decisions. Moreover, the effectiveness of the heating controller was influenced by contextual and physical factors—including building construction, office orientation, occupancy levels, and desk type (e.g., fixed or shared). It is challenging to draw concrete conclusions since the sample size was small and the data was divided into smaller comparison groups. Further research across various building types is needed to enhance generalizability.

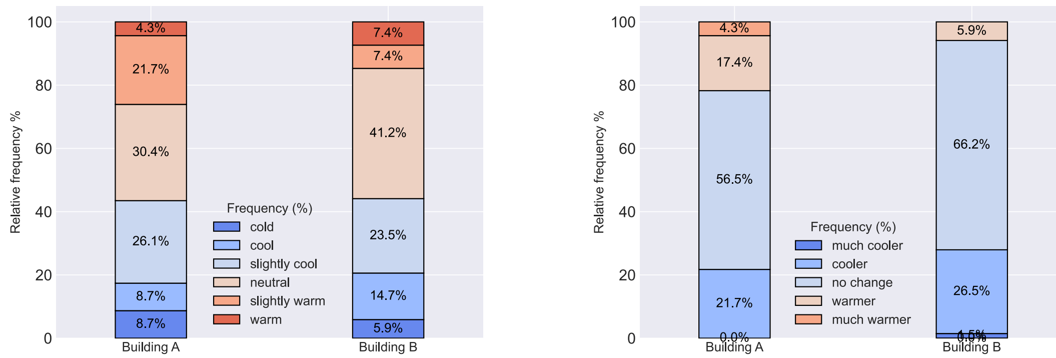
On the other hand, the study observed that occupants frequently opened windows, with higher occurrences in Building B, particularly in south-facing and open-plan offices. The primary reason for window opening was to get fresh air or a habit rather than to adjust thermal conditions. Preferences were more common for short duration of full window openings, while partially window positions were preferred for extended periods.

4.2.3. *Thermal comfort assessment*

Thermal sensation votes, thermal preferences, acceptance and satisfaction are evaluated and presented in this section as follows:

Thermal sensation and preferences

Participants were asked about their thermal sensation using ASHRAE 7-point scale (+3: hot, +2: warm, +1: slightly warm, 0: neutral, −1: slightly cool, −2: cool, −3: cold) [12]. About 78.3% of respondents felt within comfort range (−1 to +1) in Building A and 72.1% in Building B. On the contrary, few people felt cold with only 8.7% in Building A and 5.9% in Building B as shown in Fig. 13(a). Fig. 13(b) illustrates the distribution of the thermal preferences votes for each building. It shows that more than half of respondents in Building A and B (56.5% and 66.2%, respectively) preferred that the thermal environment of their workplace remain the same — with no change. In Building A, 21.7% preferred a bit warmer conditions compared to Building B (5.9%). This preference can be attributed to the lower indoor temperatures



(a) Relative frequency of thermal sensation votes (TSV)

(b) Relative Frequency of thermal preferences

Fig. 13. Relative frequency of thermal sensation and preferences.

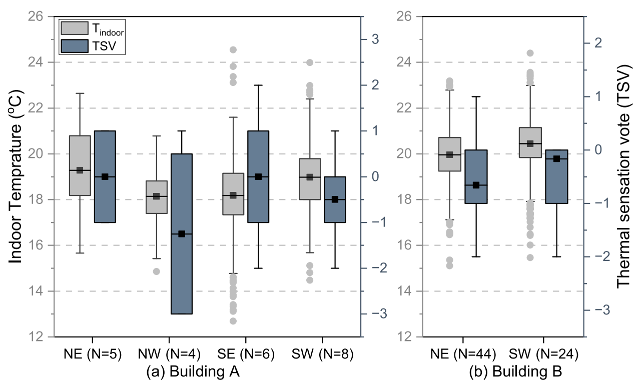


Fig. 14. Thermal sensation votes as a function of indoor temperature per office orientation in (a) Building A and (b) Building B.

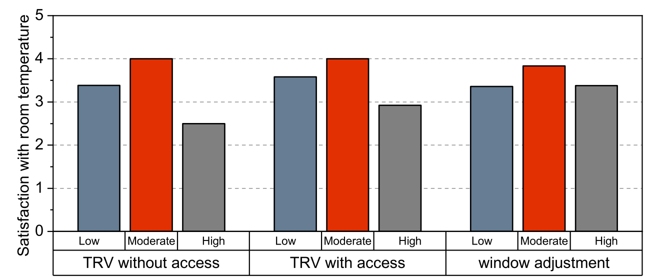


Fig. 15. Thermal satisfaction mean between the different users groups considering thermostat and window use.

measured in the offices of Building A compared to Building B during the study period, as shown in Fig. 7.

Fig. 14 illustrates the boxplot distribution of thermal sensation votes as a function of indoor temperature per office orientation in Building A and B. The results indicate that people of NE facing offices in Building B and NW facing offices in Building A reported feeling slight cooler than those in other orientations. This aligns with the measured data findings, which showed the lowest mean of daily average indoor temperatures in similar offices orientations. Despite of similar indoor temperature observed in NW& SE facing offices in Building A, the participants reported higher thermal sensation votes (neutral) in SE compared to NW facing offices (cool). This can be explained that the measured temperature is not the operative temperature, which exclude the impact of direct sunlight or nearby heat sources. Additionally, the TRVs was providing the temperature setpoint to the heating controller as a reference during the study period, which is higher than the measured indoor temperature of the office.

Thermal satisfaction and acceptance

People were asked about their thermal satisfaction with the indoor temperature based on a 5-point scale (1: very unsatisfied, 5: very satisfied). Approximately half of the respondents in Building A (47.8%) and Building B (52.9%) reported their satisfaction with the current indoor temperature in their work environment. While few people reported their dissatisfaction with 17.4% in Building A and 19.1% in Building B. Non-significant difference was found between the two buildings in terms of thermal satisfaction using Mann–Whitney U statistical test (p-value = 0.94), see Appendix A.2 for normality test. Fig. 15 shows that people who were less satisfied with the room temperature, tended to adjust the thermostat more often. Based on Independent-samples Kruskal–Wallis test, active users (high group) were significantly less satisfied with the current indoor temperature compared to low group (p-value = 0.04).

People were also asked about their thermal acceptance of the current indoor conditions, including indoor temperature, air movement, and the overall thermal conditions, on a 3-point Likert scale (1: unacceptable, 2: neutral, 3: acceptable). More than half of the respondents rated the indoor temperature in their workspaces as acceptable, with 52.2% in Building A and 52.9% in Building B. As opposed to 17.4% in Building A and 16.2% in Building B who evaluated their offices as unacceptable. The air movement was rated as neutral to acceptable by 87% of respondents in Building A and 89% in Building B. In Building A, about 17.4% rated the overall thermal conditions as unacceptable and 10.3% in Building B. The former result can be assigned to the higher indoor temperature in the offices of Building B compared to Building A during the study period.

Thermal discomfort frequencies and actions

Participants were asked about their experiences with thermal discomfort, using a scale where 0 represents *never* and 5 represents *continuously*. Fig. 16 (a, b) illustrates the frequencies of feeling uncomfortably cold for each building and office orientation. In Building A, 43.5% of respondents reported feeling uncomfortably cold rarely or once per month in their offices, compared to 48.5% in Building B. The majority of occupants in SE and NW facing offices in Building A reported feeling uncomfortably cold more often than those in other offices. This finding can be attributed that the mean of indoor temperature daily averages in those offices was below the default temperature setpoint (19 °C). Similarly, in Building B, occupants in SW facing offices reported feeling cold more often compared to those in NE facing offices. The difference is likely due to the shading from the surrounding forest on the south of Building B.

Fig. 16 (c, d) shows that the majority of respondents reported feeling uncomfortably warm once per month or less often in Building A (69.5%) and Building B and (85%). In Building A, fewer people felt

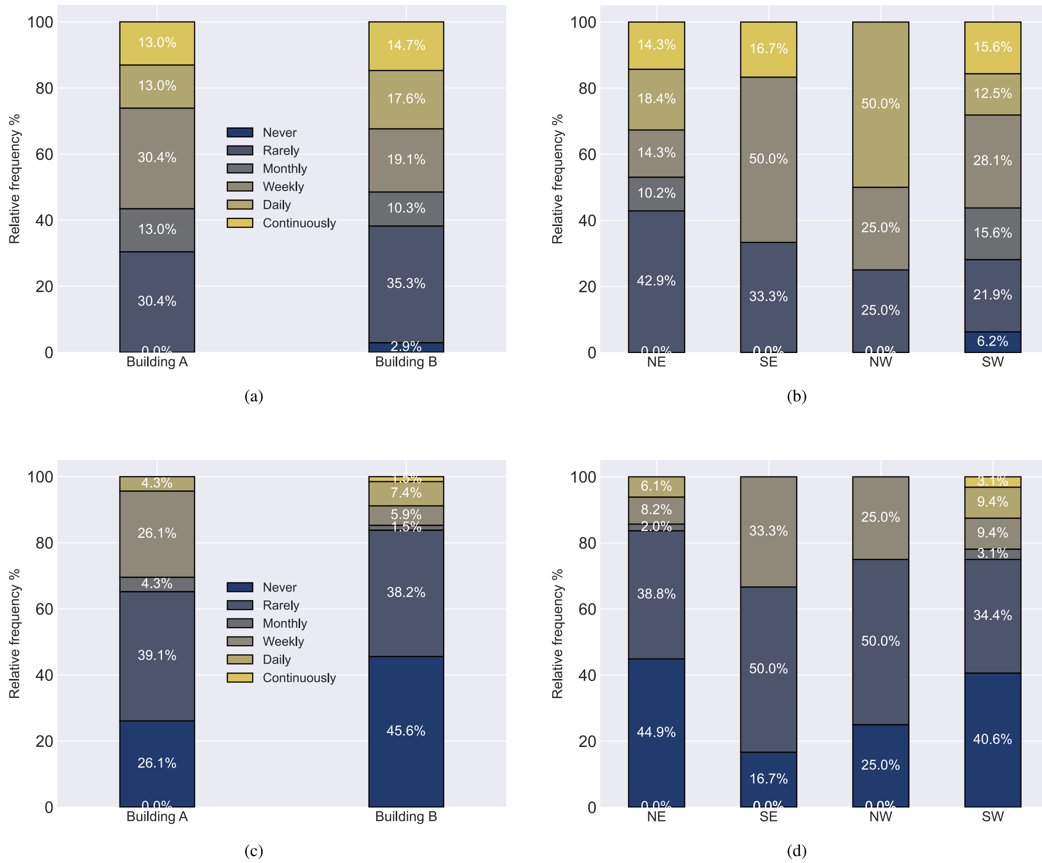


Fig. 16. Frequency of thermal discomfort: (a, b) uncomfortably cold and (c, d) uncomfortably warm, shown per building and per office orientation.

uncomfortably warm in NW and SW facing offices compared to other offices. In Building B, only 11.5% of respondents in NE facing offices and 20.8% in SW facing offices reported feeling uncomfortably warm weekly or more often. Statistical differences between building A and B were calculated in terms of cold and warm discomfort using Mann–Whitney U test, but the differences were found to be not statistically significant (p-value = 0.80, 0.06), see Appendix A.2 for normality test. Moreover, 78% of respondents in Building B reported that they never or rarely faced unpleasant thermal conditions that interfere with their ability to focus on their work more than 30 min, and 69.5% in Building A agreed on that.

Thermal discomfort usually lead to several responses rather than just one. In this study, participants were asked to identify their principal actions when feeling uncomfortably cold and hot. During winter, when indoor temperatures fall below the desired setpoints, 22.7% of respondents reported putting on more clothing as their principal action. Approximately 19% increased the thermostat setpoints or closed the windows. These results are in line with the findings of Karjalainen [16] study, that the principle action when people feel cold is to put more clothes. Other actions include closing the door (15.9%), walking around (3.1%), having a hot drink (13.1%), or using a personal heater such as a blanket (5.6%) were less common. The sequences of the above mention actions frequency is similar across both buildings. On the contrary, when temperatures exceeded the desired setpoints, occupants tended to do the opposite. For example, 29.1% of respondents reported decreasing the thermostat setpoints or opening the window (26.9%), while 21% chose to take off some clothing.

Overall, the majority of the respondents (74%) reported feeling within the thermal comfort range, and more than half preferred to maintain current thermal conditions. The analysis indicated that indoor thermal comfort was efficiently maintained by the automatic heating controller. However, thermal discomfort was still present in certain orientation and building zones in extreme cold weather, often leading to behavioural adaptations, such as clothing adjustments and TRVs interventions.

4.2.4. User satisfaction and perceived control

Given the heating controller were provided in each office of both buildings, users would expect that the heating system is always working to meet their thermostat setpoints wishes. Accordingly, participants rated their satisfaction with the thermostat's ability to control the temperature setpoint according to their comfort preferences on a 5-point Likert scale (1: very dissatisfied to 5: very satisfied). In Building B, 69% of respondents reported being neutral to satisfied with the heating controller's performance, compared to 52.2% in Building A. However, one third (35.2%) of all participants expressed their dissatisfaction with the performance. The former finding may be attributed to the slow thermal response of the heating controller. Previous studies indicated that ineffective or slow control response may affect their satisfaction even if they have personal control, or may cause low perceived control in their offices [22,50]. Therefore, occupants were asked about their satisfaction with the change speed of temperature after adjusting the thermostat settings. About 23.5% of respondents in Building B reported their dissatisfaction, while about 35% of respondents in Building A felt the same way. in [34] study, they suggested that the users should receive feedback as the rate of temperature change is slow. First, the user should receive a notification after the adjustments that the system is working to fulfil the request. Later, the user should receive a feedback when the desired temperature is achieved. Similarly, Brackley et al. [21] added time-to-temperature feature to assure for users that the system will reach their setpoint and clarify the response time. Despite the small sample size in their study, all the participants rated this feature as valuable.

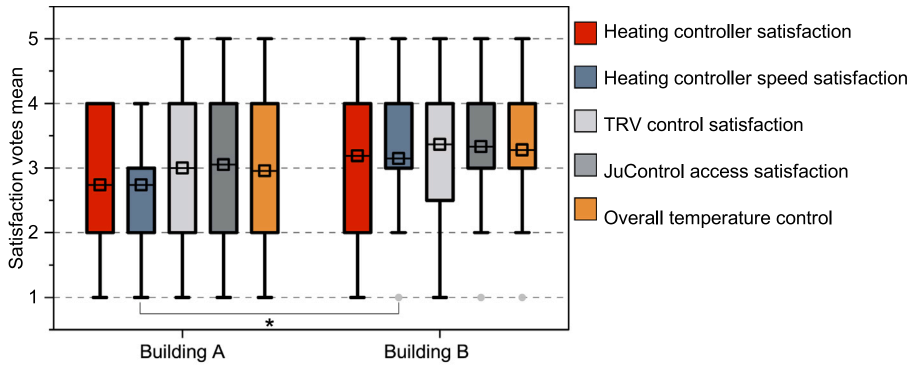


Fig. 17. Satisfaction votes of heating controller performance, controller speed, ability to control thermostat via TRVs and JuControl and overall control of room temperature.

Interestingly, this study found that 84% of the respondents located in the 2nd floor reported their satisfaction with the heating controller more than people in 1st (71.4%) and ground floor levels (26.1%). Based on authors' knowledge, occupants on the 2nd floor were informed about the heating controller's automation and familiar with its mechanism more than other offices. This finding aligns with Day and Gunderson [33] studies, they found that occupants who received training on using building controls were significantly more likely to be satisfied with their workplace environment more than others.

Participants were asked about their perceived control of having the ability to adjust the thermostat using both JuControl and TRVs. In Building A, 65% of respondents reported their satisfaction with their ability to control the thermostat using the TRVs, with a higher percentage in Building B (75%). Additionally, the results showed that 69.5% of respondents in Building A reported having clear access to the TRVs, while a higher percentage in Building B (86.8%). Majority of the respondents were satisfied with their ability to adjust the thermostat using JuControl, with 68% in Building A and 80% in Building B. This finding can be explained due to easy-to-access control compared to TRVs access, as indicated in [51,52].

Participants were also asked about the overall temperature control in their offices. People in Building B were more satisfied (76%) compared to Building A (69%). Interestingly, the mean of satisfaction votes of participants was higher in Building B compared to Building A, as shown in Fig. 17. The Mann–Whitney U test revealed non-significant differences in satisfaction levels between the buildings, except for the satisfaction with the speed of temperature adjustment, which was significantly higher in Building B compared to Building A (p-value = 0.04), see Appendix A.2 for normality test. Overall, the findings suggest that providing users information and clear feedback of the heating system's response time, along with improving ease-of-access, user training and familiarity of the controller automation, can significantly enhance occupant perceived control and satisfaction with controller performance as well as thermal environment in office buildings.

4.2.5. User engagement and energy-savvy measures

Approximately 82% of respondents in Building A and B reported that they are neutral to savvy in terms of energy awareness and they consider energy-savvy measures in their offices. Additionally, participants were asked about the specific energy-savvy measures they usually implement. The most common measures included shock ventilation (25.9%), keeping radiators uncovered (25.5%), and adjusting the thermostat when needed (25.2%). Other measures such as closing the door and dressing warmly were less common. Interestingly, the energy-savvy users in Building A were more likely to dress warmly or use cross ventilation by opening windows, as illustrated in Fig. 18. However, the majority of energy-savvy people in Building B tended to adjust the thermostat if needed or close the door. These findings highlight the importance of engaging users in energy-efficient practices and increasing their awareness of the impact of their involvement in achieving energy efficiency goals.

Table 4
Odds ratios from ordinal logistic regression for perceived control and thermal satisfaction.

Explanatory variables	Satisfaction with temperature Control (OR)	Thermal Satisfaction (OR)
Thermostat combined adjustment	0.69	0.72
Window adjustment	1.48	1.25

4.2.6. Combined impact on thermal comfort and perceived control: Regression results

To quantify the effects of thermostat controller use and window operation on key comfort-related outcomes, we conducted ordinal logistic regression analyses. The response variables included thermal satisfaction—as indicator for thermal comfort—and satisfaction with temperature control—as indicator of perceived control. Both were measured on a 5-point Likert scale (1 = very unsatisfied, 5 = very satisfied). Odds Ratios (ORs) were used to interpret effect sizes and estimate the strength of association between predictor and outcome variables. User interactions with the thermostat—via both JuControl and TRVs—were aggregated into a single predictor representing overall thermostat interventions. Window adjustment frequency was included as a second explanatory variable. Both predictors are coded as ordinal variable ranging from 1 (Never) to 5 (More than once per day).

As shown in Table 4, window adjustment frequency exhibited the strongest positive association with perceived control (OR = 1.48) and a smaller but still positive association with thermal satisfaction (OR = 1.25). These findings suggest that manual control over the indoor environment—through window operation—can improve user comfort and sense of control. In contrast, increased frequency of thermostat adjustments (via TRVs or JuControl) was associated with lower odds of reporting high satisfaction with temperature control (OR = 0.69) and lower thermal satisfaction (OR = 0.72). This suggests that frequent thermostat intervention may reflect or contribute to a sense of thermal discomfort or dissatisfaction. Overall, these insights highlight the importance of intuitive and responsive control systems in enhancing user comfort and satisfaction. Therefore, it is recommended that building system should support hybrid control—combining automation with manual control—to accommodate diverse user preferences and reduce the effort required to maintain comfort.

5. Conclusions and recommendations

This paper presents a questionnaire-based analysis evaluating the performance of a cloud-based heating controller and window operation in terms of user comfort and perceived control of the indoor environment. The questionnaire was conducted in two office buildings comprising 77 offices, located in different floors and orientations. The questionnaire was distributed at the end of the heating season in March 2024. From January to March, the indoor environmental, occupant and

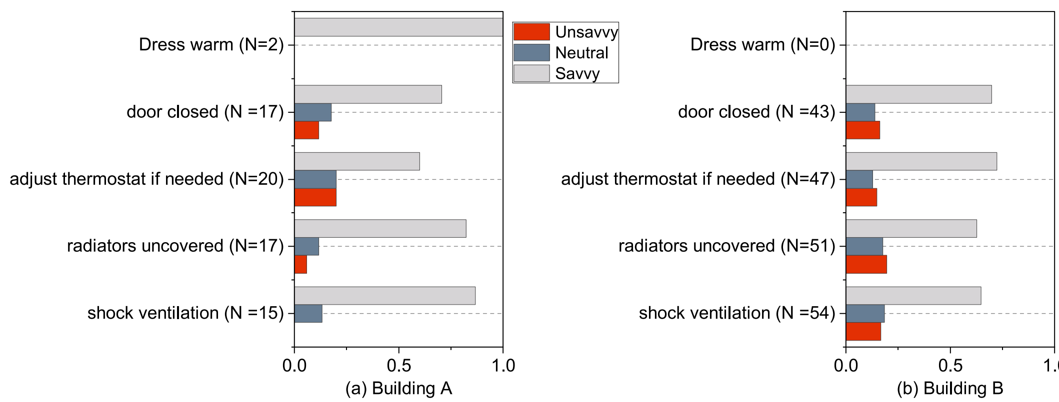


Fig. 18. Relative frequency of energy-savvy measures in (a) Building A and (b) Building B.

energy-related data were collected. A total of 91 respondents completed the questionnaire. The main conclusions are summarized as follows:

- Building A and B exhibited distinct heating consumption profiles, which can be attributed to differences in heating system supply, building construction age, occupancy levels, and user preferences. Moreover, variations in temperature setpoints and indoor climate conditions were observed across different office orientations.
- Increased adaptive opportunities, such as web-based user interface (i.e., JuControl) and TRVs, were associated with reduced thermostat interventions, particularly when users became more familiar with automation system. This finding supports the idea that providing more control options can enhance user satisfaction. Additionally, the frequency of thermostat adjustments was significantly influenced by contextual factors such as offices type and orientation. A key novel finding of this study is the influence of shared desk configurations by reducing thermostat adjustments frequency. On the other hand, occupants in south-facing offices and open-plan environments exhibited a higher tendency to open windows frequently. Preferences for fully opening windows were common for short durations, while longer openings were more likely with partially or tilted positions—primarily for fresh air rather than thermal comfort.
- The majority of respondents (74%) reported feeling within the comfort range, and 64% preferred to maintain current indoor thermal conditions, suggesting that the heating controller was generally effective to maintain the indoor thermal comfort. Variations in thermal sensation were significantly influenced by office orientation and occupancy level. Additionally, 92% of the respondents indicated that they never or rarely experienced a continuously unpleasant thermal conditions for more than 30 mins.
- About 65% of respondents reported their satisfaction with the heating controller's efficiency. However, a notable portion (26%) reported dissatisfaction, which may be attributed to the speed of temperature change, suggesting that slow thermal response may be a key factor contributing to overall dissatisfaction with the system.
- Energy-savvy measures are common practice among occupants in both buildings—with 82% of respondents consider themselves as either neutral or energy-savvy. Common behaviours included shock ventilation, keeping radiators uncovered, and adjusting thermostats, while passive measures such as dressing warmly were less common. This emphasize that user engagement and awareness are crucial for enhancing energy efficiency.
- Regression results showed positive association between frequent window operation and perceived control, while frequent thermostat interventions are associated with lower satisfaction.

The main findings of this study highlight the importance of occupant-centric room automation and user engagement in optimizing comfort and energy efficiency in office buildings. To improve the control of the heating system and window operation, the following design recommendations are suggested:

- Utilize adaptive and easy-to-use web-based interfaces (i.e., JuControl) for personal control while maintaining energy-efficient setpoints.
- Consider contextual factors in temperature control such as adjusting heating settings based on office orientation, and differentiate temperature control for fixed vs. shared desks.
- Implement zone-based heating optimization by considering contextual factors such as office orientation and desk type (fixed vs. shared), using localized sensors to enable precise, location-specific temperature adjustments in areas with higher thermal discomfort (e.g., NE facing offices).
- Encourage smart window operation for ventilation such as notifying occupant on when to open the window (i.e., CO2 threshold) or alert users if windows are left open too long.
- Increase communication and feedback: providing users with real-time feedback about the heating status and estimated time to reach the desired comfort, that could help manage user expectations and improve their satisfactions.
- Improve training and user awareness by educating occupants about the heating automation, and the best practices for optimizing their comfort (e.g., TRVs use and ventilation impact). Moreover, integrate gamifications features into web interfaces to encourage energy-efficient behaviours via feedback and rewards.
- Implement hybrid control systems—combining automation and manual control—may enhance occupant comfort and perceived control in office environments.

6. Limitations of the study

This study has two main limitations:

- **Sample size and Generalizability**: The study received 91 full responses from a total of 160 occupants in two office buildings, resulting in a relatively small sample size for broader generalization. Moreover, demographic factors such as age, gender and job position were not considered in the analysis, which may affect the results. While office orientation was accounted in this study, other building-related factors—such as building age and envelop—may differ from other workspaces. To improve generalizability, future studies should be conducted in a wider range of buildings with different characteristics and more diverse occupants.

- **Data collection and Timing:** The questionnaire data was cross-sectional, reported at once time about a continuous activity, not in parallel with the monitored data. Additionally, the questionnaire was distributed during the first week of March—a period that may be warmer than January and February. This seasonal variation could affect user interaction with windows more than thermostat adjustments, as the indoor temperature in the offices were controlled during the study period.

CRediT authorship contribution statement

Ghadeer Derbas: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **André Xhonneux:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Dirk Müller:** Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A.1. Questionnaire

The questionnaire includes six main sections summarized as follows:
Section 1: Demographic information

1. What is your Gender? (Female, male, other)
2. What is your age range? (18–29, 30–39, 40–49, 50–59, Over 60)

Section 2: Work activity and workplace context

- How long have you stayed at your current workplace? (Less than 6 months, 6 to 12 months, 1 to 2 years, More than 2 years)
- What type of work desk do you have? (Fixed desk, Desk sharing with 2–3 people, Desk sharing with more than 3 people)
- How many days per week do you work from office? (Everyday, 3–4 days a week, 2 days or less)
- During a typical workday, when are you usually at your workplace? (Multiple options)
- In which buildings are you located as illustrated in the figure below? (Building A, Building B)
- In which direction does the nearest window to your work desk face based on the above figure? (NE, SE, NW, SW)
- On which floor are you located? (Ground floor, 1st floor, 2nd floor)
- What type of office do you have? (Private single office, Shared office, Open-plan office)
- How far is your workdesk from the nearest window? (Up to 1 metre, Up to 2 m, 3 metres and more)
- How far is your workdesk from the nearest thermostat radiator valve (TRV)? same as above
- Do have a clear access (i.e., not covered with furniture) to the thermostat radiator valve (TRV)? (Yes, No)

Section 3: Thermostat and window user interaction

- Do you have access to JuControl dashboard? (Yes, No)
- If yes, how often did you adjust your thermostat setpoints using JuControl dashboard *during the last week*? (multiple options)
- How often did you adjust your thermostat radiator valve (TRV) physically *during the last week*? (multiple options) for with and without access to JuControl.
- How often did you open the window at your workplace *during the last week*? (multiple options)
- At which position do you usually open the window in wintertime? (Fully open, Partially open, tilted position)
- For how long do you usually open the window in wintertime?
- When do you usually open the window in wintertime? (Multiple options)

Section 4: Thermal comfort at the workplace

- How do you feel about the room temperature? [ASHRAE 7-point scale]
- How do you prefer the air temperature at the moment in your workspace? [1- much cooler, 5- much warmer]
- How satisfied are you with the current temperature at your workplace? (1: very unsatisfied, 5: very satisfied)
- Please select how acceptable for you the current conditions (air temperature, air movement, overall thermal conditions) at your workplace? (Unacceptable, neutral, acceptable)
- How often do you feel uncomfortably cold at your workplace during the wintertime? (multiple options)
- How often do you feel uncomfortably warm at your workplace during the wintertime? (multiple options)
- In wintertime, when you experience higher temperature than the desired temperature, what actions do you take to reduce discomfort? (multiple options)
- In wintertime, when you experience lower temperature than the desired temperature, what actions do you take to reduce discomfort?
- During your stay in the office last week, were there any occasions where the thermal conditions was continuously unpleasant and/or interfering with your ability to focus on your work for more than 30 min? (multiple options)

Section 5: Perceived control and satisfaction

- How satisfied are you with the thermostat at controlling the temperature setpoint to your comfort preferences? (1: very dissatisfied, 5: very satisfied)
- How satisfied are you with the speed that the temperature of your workplace changes after you change the thermostat settings? (1: very dissatisfied, 5: very satisfied)
- How satisfied are you with having the ability to adjust the temperature setpoint via the thermostat radiator valve (TRV)? (1: very unsatisfied, 5: very satisfied).
- How satisfied are you with having the ability to control the thermostat setpoint via JuControl dashboard? (1: very unsatisfied, 5: very satisfied).

[1] Juracle is an engine that evaluates the thermal energy-related aspects of occupant behaviour based on two criteria: window interaction (ventilation) and room heating (temperature setpoint).

Table 5
Shapiro–Wilk normality test results summary.

	W-Statistics	*P*-value
Thermal satisfaction	0.89	0.00*
Uncomfortably cold	0.87	0.00*
Uncomfortably warm	0.76	0.00*
HC satisfaction	0.89	0.00*
HC speed satisfaction	0.88	0.00*
TRV control satisfaction	0.90	0.00*
JuControl access satisfaction	0.89	0.00*
Overall temperature control	0.91	0.00*

* $p \leq 0.05$: Data is not normal.

- In general, how satisfied are you with the temperature control at your workplace? (1: very unsatisfied, 5 : very satisfied)

Section 6: Energy-savvy measures

- How energy-savvy would you consider yourself? (1: very unsavvy, 5: very savvy)
- Which of the following energy-saving measures do you usually consider in terms of correct heating and ventilation? (Multiple options)

A.2. Shapiro–Wilk normality test

Table 5 summarize Shapiro–Wilk normality test results summary of the tested variables.

Data availability

The data that has been used is confidential.

References

[1] European Commission, Towards reaching the 20% energy efficiency target for 2020, and beyond, 2017, URL: https://ec.europa.eu/commission/presscorner/detail/en/MEMO_17_162.
[2] OrbEEt, D1.2 Specs of SEOR Methodology and Enhanced Display Energy Certificates, Technical Report, 2017.
[3] IPCC, Global Warming of 1.5° C: An IPCC Special Report on the Impacts of Global Warming of 1.5° C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, Cambridge University Press, 2018, Online. URL: https://www.ipcc.ch/sr15/. (Accessed 31 May 2023).
[4] Donna Vakalis, Runa T Hellwig, Marcel Schweiker, Stephanie Gauthier, Challenges and opportunities of internet-of-things in occupant-centric building operations: towards a life cycle assessment framework, Curr. Opin. Environ. Sustain. 65 (2023) 101383.
[5] N Fernandez, S Katipamula, W Wang, Y Xie, M Zhao, CD Corbin, Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction; PNNL-25985, Pacific Northwest National Laboratory, Richland, DC, USA, 2017.
[6] Atiye Soleimanijavid, Iason Konstantzos, Xiaoqi Liu, Challenges and opportunities of occupant-centric building controls in real-world implementation: A critical review, Energy Build. (2024) 113958.
[7] Runa T. Hellwig, Marcel Schweiker, Atze Boerstra, The ambivalence of personal control over indoor climate–how much personal control is adequate? in: E3S Web of Conferences, vol. 172, EDP Sciences, 2020, p. 06010.
[8] Kathryn B. Janda, Buildings don't use energy: people do, Archit. Sci. Rev. 54 (1) (2011) 15–22.
[9] Federico Garzia, Stijn Verbeke, Cristian Pozza, Amaryllis Audenaert, Meeting user needs through building automation and control systems: A review of impacts and benefits in office environments, Buildings 13 (10) (2023) 2530.
[10] Ruth Tamas, Mohamed M. Ouf, William O'Brien, A field study on the effect of building automation on perceived comfort and control in institutional buildings, Archit. Sci. Rev. 63 (1) (2020) 74–86.
[11] Mohammed Arif, Martha Katafygiotou, Ahmed Mazroei, Amit Kaushik, Esam Elsarrag, et al., Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature, Int. J. Sustain. Built Environ. 5 (1) (2016) 1–11.
[12] A Ashrae, ASHRAE Standard 55: Thermal environmental conditions for human occupancy, American Society of Heating, Refrigerat- ing and Air-Conditioning Engineers Inc, USA, 2013.
[13] Simona D'Oca, Valentina Fabi, Stefano P. Corgnati, Rune Korsholm Andersen, Effect of thermostat and window opening occupant behavior models on energy use in homes, Build. Simul. (ISSN: 19968744) 7 (2014) 683–694, http://dx.doi.org/10.1007/s12273-014-0191-6.
[14] Walid Belazi, Salah Eddine Ouldboukhitine, Alaa Chateauneuf, Abdelhamid Bouchair, Experimental and numerical study to evaluate the effect of thermostat settings on building energetic demands during the heating and transition seasons, Appl. Therm. Eng. (ISSN: 13594311) 152 (2019) 35–51, http://dx.doi.org/10.1016/j.applthermaleng.2019.02.020.
[15] H. Burak Gunay, William O'Brien, Ian Beausoleil-Morrison, Implementation and comparison of existing occupant behaviour models in EnergyPlus, J. Build. Perform. Simul. 9 (6) (2016) 567–588.
[16] Sami Karjalainen, Thermal comfort and use of thermostats in finnish homes and offices, Build. Environ. (ISSN: 03601323) 44 (2009) 1237–1245, http://dx.doi.org/10.1016/j.buildenv.2008.09.002.
[17] Minyoung Kwon, Hilde Remøy, Andy van den Dobbelsteen, Ulrich Knaack, Personal control and environmental user satisfaction in office buildings: Results of case studies in the netherlands, Build. Environ. 149 (2019) 428–435.
[18] Chengcheng Xu, Shuhong Li, Influence of perceived control on thermal comfort in winter, a case study in hot summer and cold winter zone in China, J. Build. Eng. 40 (2021) 102389.
[19] Bernt Meerbeek, Marije te Kulve, Tommaso Gritti, Mariëlle Aarts, Evert van Loenen, Emile Aarts, Building automation and perceived control: a field study on motorized exterior blinds in dutch offices, Build. Environ. 79 (2014) 66–77.
[20] A Wagner, E Gossauer, C Moosmann, Th Gropp, R Leonhart, Thermal comfort and workplace occupant satisfaction—Results of field studies in german low energy office buildings, Energy Build. 39 (7) (2007) 758–769.
[21] Connor Brackley, William O'Brien, Chantal Trudel, Jayson Bursill, The in-situ implementation of a feature-rich thermostat: A building engineering and human factors approach to improve perceived control in offices, Build. Environ. (ISSN: 03601323) 199 (2021) http://dx.doi.org/10.1016/j.buildenv.2021.107884.
[22] Sami Karjalainen, Olavi Koistinen, User problems with individual temperature control in offices, Build. Environ. 42 (8) (2007) 2880–2887.
[23] Bill Bordass, Adrian Leaman, Roderic Bunn, Controls for end users, Build. Control. Ind. Assoc. 86022 (2007) 662,
[24] Philipp Althaus, Sascha Johnen, André Xhonneux, Dirk Müller, Cloud-based controller architecture for the testing of conventional and model predictive room heating controllers in a real-world environment, in: 2024 10th International Conference on Control, Decision and Information Technologies (CoDIT), IEEE, 2024, pp. 1792–1797, http://dx.doi.org/10.1109/CoDIT62066.2024.10708077.
[25] William O'Brien, Andreas Wagner, Marcel Schweiker, Ardeshir Mahdavi, Julia Day, Mikkel Baun Kjæ rgaard, Salvatore Carlucci, Bing Dong, Farhang Tahmasebi, Da Yan, et al., Introducing IEA ebc annex 79: Key challenges and opportunities in the field of occupant-centric building design and operation, Build. Environ. 178 (2020) 106738.
[26] Zoltan Nagy, Burak Gunay, Clayton Miller, Jakob Hahn, Mohamed M Ouf, Seungjae Lee, Brodie W Hobson, Tareq Abuimara, Karol Bandurski, Maíra André, et al., Ten questions concerning occupant-centric control and operations, Build. Environ. 242 (2023) 110518.
[27] June Young Park, Mohamed M Ouf, Burak Gunay, Yuzhen Peng, William O'Brien, Mikkel Baun Kjæ rgaard, Zoltan Nagy, A critical review of field implementations of occupant-centric building controls, Build. Environ. 165 (2019) 106351.
[28] Jakob Hahn, Sarah Heiler, Michael B Kane, Sumee Park, Werner Jensch, The information gap in occupant-centric building operations: lessons learned from interviews with building operators in Germany, Front. Built Environ. 8 (2022) 838859.
[29] Poul O. Fanger, Thermal comfort. Analysis and applications in environmental engineering., 1970.
[30] Ioannis Sakellaris, Dikaia Saraga, Corinne Mandin, Yvonne de Kluizenaar, Serena Fossati, Andrea Spinazzè, Andrea Cattaneo, Tamas Szigeti, Victor Mihucz, Eduardo de Oliveira Fernandes, et al., Personal control of the indoor environment in offices: Relations with building characteristics, influence on occupant perception and reported symptoms related to the building—The officair project, Appl. Sci. 9 (16) (2019) 3227.
[31] Sanaz Ahmadpoor Samani, The impact of personal control over office workspace on environmental satisfaction and performance, J. Soc. Sci. Humanit. 1 (3) (2015) 163–175.
[32] H.B. Rijal, M.A. Humphreys, J.F. Nicol, Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings, Energy Build. 202 (2019) 109371.
[33] Julia K. Day, David E. Gunderson, Understanding high performance buildings: The link between occupant knowledge of passive design systems, corresponding behaviors, occupant comfort and environmental satisfaction, Build. Environ. 84 (2015) 114–124.
[34] Sami Karjalainen, Usability guidelines for room temperature controls, Intell. Build. Int. 2 (2) (2010) 85–97.

[35] Xiaoqi Liu, Seungjae Lee, Ilias Bilionis, Panagiota Karava, Jaewan Joe, Seyed Amir Sadeghi, A user-interactive system for smart thermal environment control in office buildings, Appl. Energy (ISSN: 03062619) 298 (2021) http://dx.doi.org/10.1016/j.apenergy.2021.117005.

[36] Helen Stopps, Marianne F. Touchie, Managing thermal comfort in contemporary high-rise residential buildings: Using smart thermostats and surveys to identify energy efficiency and comfort opportunities, Build. Environ. (ISSN: 03601323) 173 (2020) http://dx.doi.org/10.1016/j.buildenv.2020.106748.

[37] Mostafa Meimand, Farrokh Jazizadeh, A personal touch to demand response: An occupant-centric control strategy for HVAC systems using personalized comfort models, Energy Build. 303 (2024) 113769.

[38] Philipp Althaus, Florian Redder, Eziama Ubachukwu, Maximilian Mork, André Xhonneux, Dirk Müller, Enhancing building monitoring and control for district energy systems: Technology selection and installation within the living lab energy campus, Appl. Sci. 12 (7) (2022) 3305.

[39] Florian Redder, Philipp Althaus, Eziama Ubachukwu, Maximilian Mork, Sascha Johnen, Christian Küpper, Paul Lieberenz, Marieluise Oden, Lidia Westphal, Thomas Storek, André Xhonneux, Dirk Müller, Information and communication technologies (ICT) for holistic building energy system operation in living labs: Conceptualization, implementation, evaluation: preprint, 2024.

[40] Eziama Ubachukwu, Philipp Althaus, André Xhonneux, Lea Riebesel, Jana Pick, Paul Lieberenz, Dirk Müller, LLEC energy dashboard suite: User engagement for energy-efficient behavior using dashboards and gamification, in: ECOS 36TH, Modellierung von Energiesystemen, 2023.

[41] Eziama Ubachukwu, Jana Pick, Lea Riebesel, Paul Lieberenz, Philipp Althaus, André Xhonneux, Dirk Müller, User engagement for thermal energy-efficient behavior in office buildings using dashboards and gamification, Appl. Therm. Eng. (2025) 125598.

[42] Ghadeer A Derbas, Eziama Ubachukwu, Philipp Althaus, Andre Xhonneux, Dirk Müller, Thermostat control and window opening: Impact on indoor environmental conditions and building performance, in: BauSim Conference 2024, 10, IBPSA-Germany and Austria, 2024, pp. 463–470.

[43] Renata De Vecchi, Christhina Candido, Richard de Dear, R Lamberts, Thermal comfort in office buildings: Findings from a field study in mixed-mode and fully-air conditioning environments under humid subtropical conditions, Build. Environ. 123 (2017) 672–683.

[44] P. Althaus, C. Küpper, A. Xhonneux, D. Müller, Analysis of monitoring data for improved operation of building heating systems: IN preparation, 2024, In preparation.

[45] Marcel Schweiker, Sabine Brasche, Wolfgang Bischof, Andreas Wagner, Is there a method for understanding human reactions to climatic changes?–developing experimental designs for climate chambers and field measurements to reveal further insights to adaptive processes, in: Proceedings of 7th Windsor Conference: The Changing Context of Comfort in an Unpredictable World Cumberland Lodge, Windsor, UK, 2012.

[46] M Schweiker, S Carlucci, RK Andersen, B Dong, W O'Brien, Occupancy and Occupants' Actions. Exploring Occupant Behavior in Buildings, Springer, Cham, Switzerland, 2018.

[47] Sam Borgeson, Gail Brager, Occupant control of windows: accounting for human behavior in building simulation, 2008.

[48] Marcel Schweiker, Eleni Ampatzi, Maedot S Andargie, Rune Korsholm Andersen, Elie Azar, Verena M Barthelmes, Christiane Berger, Leonidas Bourikas, Salvatore Carlucci, Giorgia Chinazzo, et al., Review of multi-domain approaches to indoor environmental perception and behaviour, Build. Environ. 176 (2020) 106804.

[49] Hiroshi Mori, Tetsu Kubota, I Gusti Ngurah Antaryama, Sri Nastiti N Ekasiwi, Analysis of window-opening patterns and air conditioning usage of urban residences in tropical southeast Asia, Sustainability 12 (24) (2020) 10650.

[50] Atze C. Boerstra, Tim C. Beuker, Impact of perceived personal control over indoor climate on health and comfort in dutch offices, in: 12th International Conference on Indoor Air Quality and Climate 2011, 2011, pp. 2402–2407.

[51] Julia K Day, Claire McIlvennie, Connor Brackley, Mariantonietta Tarantini, Cristina Piselli, Jakob Hahn, William O'Brien, Vinu Subashini Rajus, Marilena De Simone, Mikkel Baun Kjæ rgaard, et al., A review of select human-building interfaces and their relationship to human behavior, energy use and occupant comfort, Build. Environ. 178 (2020) 106920.

[52] William O'Brien, H. Burak Gunay, The contextual factors contributing to occupants' adaptive comfort behaviors in offices–a review and proposed modeling framework, Build. Environ. 77 (2014) 77–87.