



The potential of gamification in IEQ monitoring: Open-source hardware development and field studies

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HIGHLIGHTS

- Open-source gamified system developed for Indoor Environmental Quality monitoring.
- System usability rated highly across field studies with diverse participant groups.
- Gamification potentially encourages intentional ventilation and sustained engagement.

ARTICLE INFO

Keywords:

Indoor environmental quality
Gamification
Monitoring
User behavior
Hardware

ABSTRACT

Building operation accounts for nearly one-third of global final energy consumption, and occupant behavior remains a critical factor influencing both energy demand and Indoor Environmental Quality (IEQ). Gamification has emerged as a promising approach to encourage energy-efficient behaviors. However, there is a lack of open, deployable systems that enable researchers to study behavioral responses in real-world settings. This work introduces an open-source, modular IEQ monitoring system with a gamified graphical user interface designed to raise awareness and promote energy-efficient indoor practices. The system was deployed in three small-scale field studies to evaluate its usability and potential to prompt behavioral changes. Overall, the 16 participants rated the system as highly usable. Although no changes in self-reported heating or cooling behaviors were observed, participants reported more frequent and longer ventilation periods during the study. However, the differences between the intervention and control conditions were small and not statistically significant, likely due to the limited sample size and short study duration. Sensor data also implied the potential for more energy-efficient ventilation strategies. These findings highlight the potential and limitations of using gamified feedback mechanisms to influence IEQ-related behavior.

1. Introduction

Although the International Energy Agency observes a change in the increase of CO₂ emissions by buildings since 2015, building operation is still consuming 30% of the global final energy [1]. In order to achieve international climate goals, building operations need to further reduce consumption, especially when considering that the demand for constructed floor space is ever increasing [2]. Lastly, when keeping in mind the majority of our daily time spent indoors, indoor environmental conditions not only affect health and well-being but are also a major

lever to influence energy consumption associated with establishing and maintaining suitable indoor conditions.

Besides technological and construction-based approaches to more efficient energy use, new systems, as well as thermal insulation and retrofitting of buildings, need to be accompanied by behavioral changes of occupants. Depending on the intensity of behavioral intervention, between 10 and 20% of savings can be achieved by altering occupants' actions [3,4]. If occupants and their behaviors are ignored, rebound effects might offset or at least reduce the anticipated effects of any measure intended to conserve energy or reduce emissions [5,6].

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<https://doi.org/10.1016/j.buildenv.2026.114657>

Received 9 January 2026; Received in revised form 17 February 2026; Accepted 21 April 2026

Available online 22 April 2026

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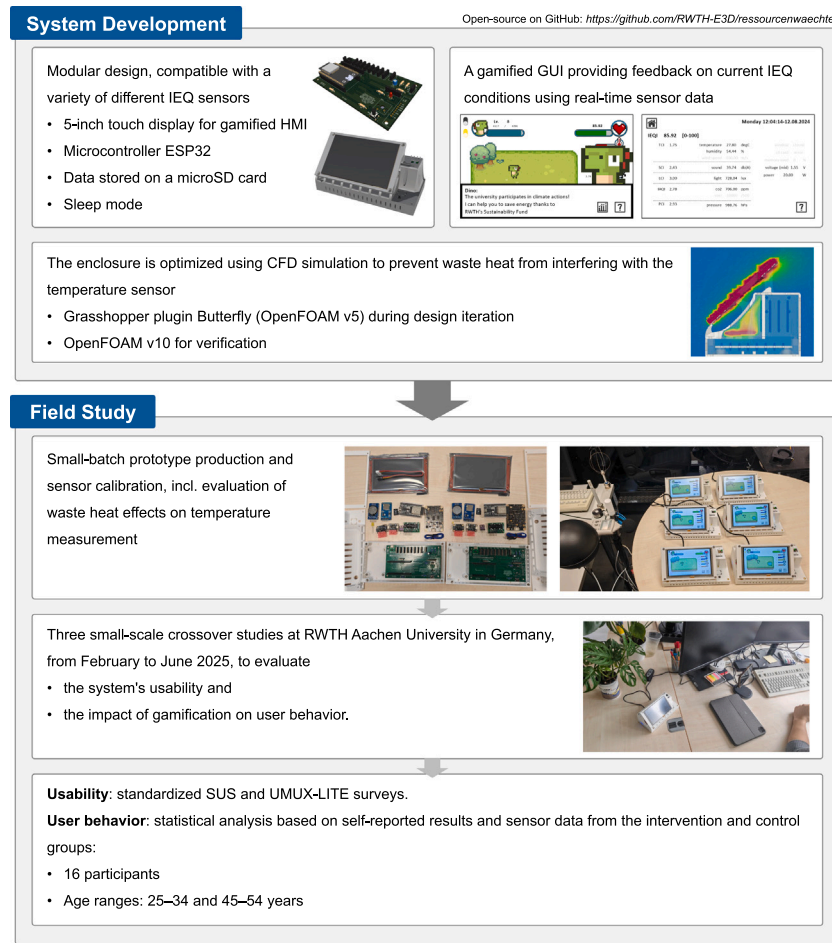


Fig. 1. Methodological framework summarizing the overall workflow of the study.

The increasing deployment of building automation and smart home technologies further facilitates behavioral and gamified interventions in building operations [7]. Gamification [8] can contribute to energy-saving efforts by providing energy use-related feedback, social comparisons, and competition with potential rewards. Several studies have explored game-based or training-oriented approaches to improve users' awareness of energy-related behavior, including serious games [9–11] and gamified immersive virtual environments [12,13]. While these approaches primarily aim to increase users' awareness and engagement with energy-related behavior, their ultimate motivation is often to induce behavioral changes that may translate into measurable energy savings. Accordingly, several reviews have sought to summarize the reported effects of gamification interventions on energy consumption. The range of reported energy savings achievable with gamification is quite large. A recent review by Abdurahmanovic and Cadenbach [14] reported savings ranging from 4% to over 40%, while other reviews indicated more moderate but still substantial effects, with reported ranges of 8–40% [15] and 5–15% [16]. However, the reported energy-saving ranges in the literature are derived from studies conducted across different types of buildings, including residential buildings, offices, and educational facilities, and under varying climatic and operational conditions. Moreover, the applied gamification approaches differ substantially in terms of interaction modality, system complexity, and intervention design. As such, these values are not directly comparable nor necessarily transferable to other contexts.

In this context, Indoor Environmental Quality (IEQ) represents a particularly relevant intervention domain, as it directly links occupants' comfort, health, and everyday interactions with building systems to

energy-related decision-making and behavior. IEQ monitoring aims not only to display sensor readings, but also to support improved indoor conditions and informed energy-related decisions. Since raw sensor values alone provide limited actionable meaning for occupants, gamification offers a way to contextualize IEQ data and promote engagement with comfort- and energy-related behaviors.

This paper presents a monitoring system with a gamification interface to inform and engage users about IEQ parameters and opportunities to conserve energy. To frame the objectives and scope of this work, the study is guided by the following research questions:

- What design considerations and technical challenges arise during the development of a compact, gamified IEQ monitoring system?
- In terms of usability, how is the system perceived and experienced by users?

2. Methods

This section covers the approach for developing the *Resource Guardian* (German: *Ressourcenwächter*), an IEQ monitoring system, and the methodology for evaluating the usability and the impact of gamification on user behavior. Fig. 1 provides an overview of the methodological workflow adopted in this study.

The hardware design and assembly guides are available at <https://rw.e3d.rwth-aachen.de/> under a Creative Commons BY-NC-SA license. The developed software and firmware are open source and published on <https://github.com/RWTH-E3D/ressourcenwaechter> under a GNU GPL-3.0 license. The hardware models and 3D printing files are also available on our GitHub repository.

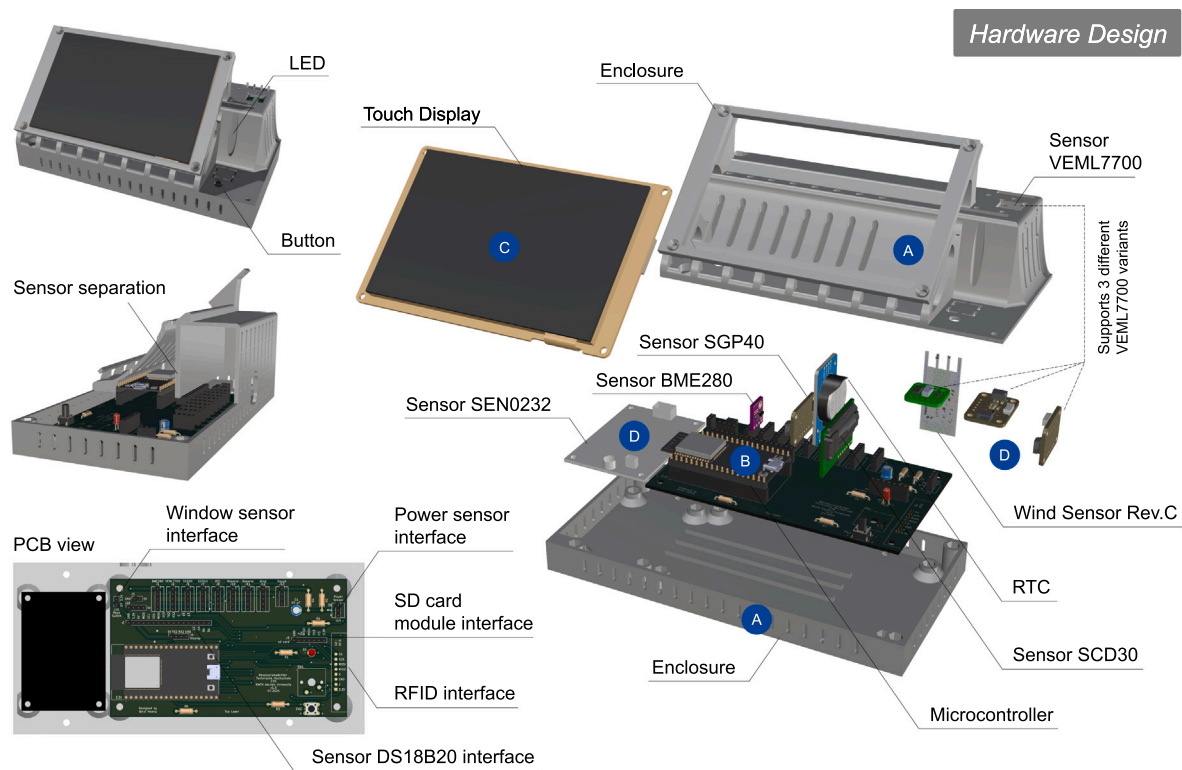


Fig. 2. The hardware design of the IEQ monitoring system, *Resource Guardian*, and its main components: A) Enclosure, B) Microcontroller, C) Touch display, D) Sensors. The device dimensions (LxBxH) are 17.8 cm x 8.9 cm x 11.3 cm.

2.1. System design

As shown in Fig. 2, the IEQ monitoring system developed in this work consists of four main components: A) a 3D-printed custom enclosure; B) a microcontroller and its firmware, responsible for the underlying logic and communication with the touch display; C) a 5-inch touch display and its Graphical User Interface (GUI), providing the Human-Machine Interaction (HMI); D) IEQ sensors, used to measure IEQ-related parameters.

2.1.1. Enclosure

Integrating Computational Fluid Dynamics (CFD) simulation allowed for a better evaluation of the impact of waste heat generated by components such as the touch display on temperature sensor measurements. Through design optimization, this interference was aimed to be minimized to ensure accurate measurements.

The enclosure was optimized through an iterative process of CFD-coupled parametric design using Rhino 7 and its parametric modeling environment, Grasshopper [17,18]. Steady-state CFD simulations were conducted during each design iteration with the Grasshopper plugin Butterfly v0.0.05 [19], which utilizes OpenFOAM v5 [20] through blueCFD-Core 2017-2 [21] under the Windows environment. The buoyantBoussinesqSimpleFoam solver was employed, and residuals were maintained below $1e^{-4}$. This convergence criterion was selected to balance numerical stability and computational efficiency during the rapid exploration of the design, where relative performance trends between design variants were of primary interest, following practices reported in previous CFD-based studies [22,23]. After completing the iterations, more refined simulations were conducted using OpenFOAM v10 [24] to verify the simulation results. The buoyantFoam solver was used with residuals controlled below $1e^{-5}$, ensuring higher numerical accuracy and robustness of the final reported results.

Fig. 3 shows results captured at various time points with an infrared camera while all components were operational. As can be seen, the touch display and microcontroller generate significant waste heat. The temperature of the touch display gradually increases over time, reaching its peak (37.8 °C) after about 20 minutes.

The design objective was to limit the local temperature rise near the temperature sensor caused by waste heat to below 0.5 K, thereby minimizing its impact on temperature measurements. Fig. 4 shows the OpenFOAM v10 simulation results for the finalized enclosure design under the worst-case wind conditions. In this context, worst-case conditions do not correspond to a zero-wind scenario. Under quiescent air, waste heat is mainly buoyancy-driven and rises away from the rear-mounted temperature sensor, whereas low-speed frontal airflow can advect heat toward the sensor, representing the most unfavorable condition.

To evaluate the system's thermal performance under more extreme conditions, the surface temperatures of the touch display and microcontroller were conservatively set to 50 °C, exceeding those measured by infrared thermography, while the ambient air temperature was set to 20 °C. Apart from the touch display surface and the microcontroller, the highest temperatures (between 35 °C and 45 °C) in the CFD results occurred within the ventilation channel between the touch display and the microcontroller, as shown in the slice view in Fig. 4.

After the system assembly was completed, measurements were conducted to validate whether the enclosure's thermal performance actually met this requirement. Although the CFD simulations were conducted at a fixed ambient temperature of 20 °C, the experimental validation was performed in parallel with sensor calibration under laboratory conditions spanning indoor air temperatures from 18.8 to 27.4 °C, mean radiant temperatures from 17.4 to 25.93 °C, and relative humidity levels between 31.9% and 59.5%.

Based on the simulation results, the position of the wind speed sensor was also optimized. This ensured that convection caused by the display

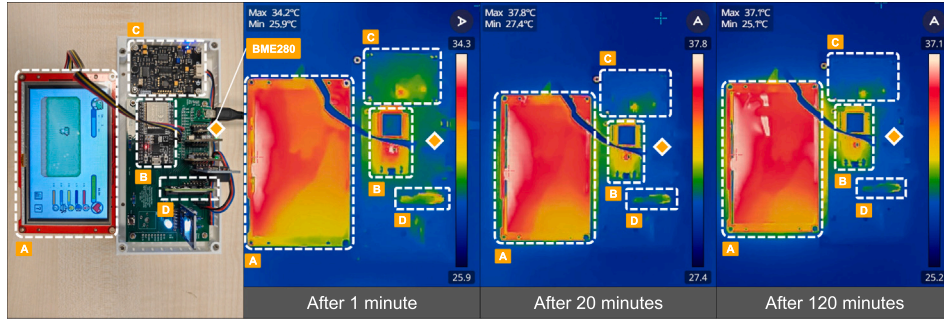


Fig. 3. Infrared thermal images showing surface temperatures of the system's main components over time. The components emitting the most waste heat are, in descending order: A) Touch display, B) Microcontroller, C) Sensor SEN0232, D) Sensor SCD30. (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article.).

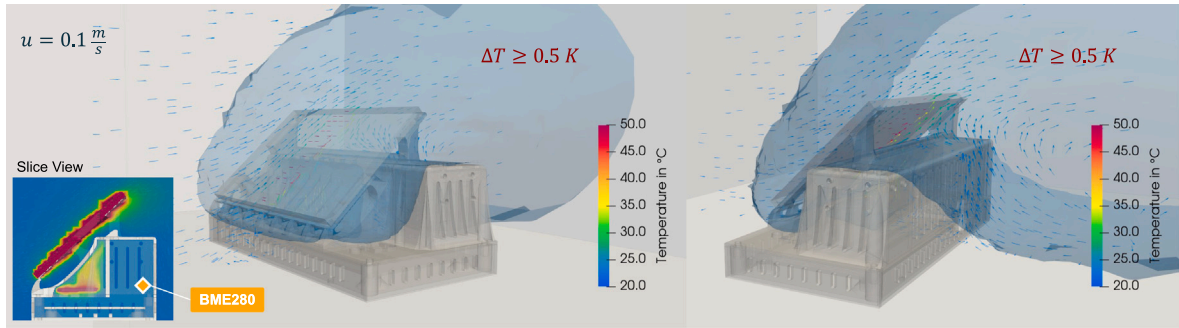


Fig. 4. Local temperature increases (ΔT) caused by waste heat under worst-case wind conditions, with regions showing a temperature rise of 0.5 K or more ($\Delta T \geq 0.5$ K) highlighted in blue. (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article.).

would have minimal influence on the measurements. The enclosure was then printed using 3D printers to produce small-batch prototypes for use in field studies.

2.1.2. Microcontroller and firmware

The microcontroller used in the system is the ESP32-DevKitC by Espressif®, supporting both WROOM-32D and WROOM-32E modules. The firmware was developed using the Arduino® framework.

In normal operating mode, the system reads sensor data every 15 s and stores all relevant measurements on a microSD card. A single physical button allows users to toggle between normal and sleep mode. In sleep mode, all components switch to a low-power state, and the sampling interval increases to 60 s. An LED indicator provides corresponding visual feedback during data writing or mode transitions.

Based on our previous work [25], raw sensor data are processed into comfort indices corresponding to different IEQ domains. A summary of the implemented indices is given below:

- **Indoor Environmental Quality Index (IEQI):** An overall IEQ index combining multiple domains through a simplified weighted linear model. Scores range from 0 to 100, where 0 indicates the poorest comfort and 100 the highest comfort, as in Eq. (1). k_i indicates the personalized weighting constant for each domain (i), ranging from 0 to 3. If certain domains are unavailable due to missing or unconfigured sensors, they are excluded from the IEQI calculation. This approach does not account for interactions (cross-modal effects), such as the hue-heat effect between light color and thermal perception (cf. [26]). The veto powers of the thermal and acoustic domains (cf. [27]) are also not fully incorporated. They are represented only through a higher weighting constant. This aims to minimize the impact of transient fluctuations in the environment and outliers in the measurement data. The default values for k_i are:

$$k_{TCI, default} = 2.0; k_{SCI, default} = 1.5; k_{LCI, default} = 1.0; k_{PCI, default} = 0.5; k_{IAQI, default} = 1.0.$$

- **Thermal Comfort Index (TCI):** Derived from Fanger's Predicted Mean Vote (PMV) model [28] and rescaled from its bipolar range to a 0–3 interval, where 0 represents the least comfortable and 3 the most comfortable state, as in Eq. (8) in the Appendix.
- **Sound/Acoustic Comfort Index (SCI):** Based on DIN EN 16798–1 [29] and WHO-ITU guidelines [30], with values ranging from 0 to 3, as in Eq. (9) in the Appendix.
- **Lighting Comfort Index (LCI):** Defined according to DIN EN 16798–1 [29], assessing visual comfort based on illuminance, with values ranging from 0 to 3, as in Eq. (10) in the Appendix.
- **Barometric Pressure Comfort Index (PCI):** A comfort index derived from barometric pressure, ranging from 0 to 3, as in Eq. (11) in the Appendix. It should be noted that the causal relationship between barometric pressure and perceived comfort remains controversial (cf. [31–34]). In contrast to the direct effects, variations in barometric pressure are more likely to influence thermal comfort indirectly, for example by altering physiological responses such as metabolic rate or heart rate [35–39].
- **Indoor Air Quality Index (IAQI):** Developed based on EPA-454/B-06-001 [40] and DIN EN 16798–1 [29], with values from 0 to 3, as in Eq. (12) in the Appendix. When multiple gas sensors (e.g., CO₂ and Volatile Organic Compound (VOC)) are available, IAQI is calculated as their arithmetic mean.

$$IEQI = \frac{100 \cdot (k_{TCI} \cdot TCI + k_{SCI} \cdot SCI + k_{LCI} \cdot LCI + k_{PCI} \cdot PCI + k_{IAQI} \cdot IAQI)}{3 \cdot \sum k_i} \quad (1)$$

The default weighting constants k_i for IEQI were defined based on qualitative considerations regarding the relative relevance of different



Fig. 5. Overview of the GUI. Top left: main screen with gamification elements; Top right: example of the feedback system; Bottom left: sensor data page (unconfigured sensors are displayed in gray); Bottom right: help page with a brief description and a QR code linking to the wiki page. Area A displays all comfort indices, and area B shows the current level and XP. In addition to automatic feedback provided every 30 minutes, users may tap area B to request feedback manually. (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article.)

IEQ domains for perceived comfort. In particular, thermal comfort and acoustic comfort were assigned higher weights to reflect their commonly reported veto-like effects on overall comfort perception, whereby dissatisfaction in these domains can dominate occupants' overall evaluation of the indoor environment. Visual comfort and indoor air quality were assigned baseline weights, as their effects are typically more gradual and context-dependent. Barometric pressure was assigned a lower weight due to the ongoing debate regarding its direct influence on perceived comfort and its predominantly indirect physiological effects. The selected values are intended to represent approximate relative importance rather than precise quantitative ratios.

The system was designed to be highly modular. Aside from the microcontroller, which is responsible for logic control, and the Real-Time Clock (RTC) used for timekeeping, all other components, including the sensors and the microSD card module, can be configured or replaced as needed. The Printed Circuit Board (PCB) also includes an interface for a Radio Frequency Identification (RFID) module, which is intended for the future implementation of personalized comfort models. Such models could be enabled by assigning each user an individual RFID card, allowing personalized comfort settings to be activated automatically when the user scans their card.

Another key design objective was to create a self-sufficient system that does not rely on network or Bluetooth connectivity, allowing it to be deployed in a wider range of environments. Nevertheless, since the ESP32 microcontroller supports both Wi-Fi and Bluetooth, these connectivity features can be added to the open-source firmware with minimal effort if necessary.

2.1.3. GUI

The system uses a 5-inch touch display NX8048P050-011 from Nextion® to provide a GUI for gamified HMI. It is also possible to operate the system without the touch display and use the device as a non-interactive measurement instrument. In contrast to traditional

IEQ monitoring systems [41–49], the interface not only presents real-time sensor data but also includes an interactive gamification layer that evaluates IEQ against comfort indices and provides an integrated feedback system, see Fig. 5.

As shown in Figs. 5 and 6, a virtual dinosaur accumulates Experience Points (XP) based on the current IEQ, and its environment gradually becomes more detailed as the user progresses. New visual elements such as trees, water bodies, and other features appear on the dinosaur's island when higher levels are reached. This is intended to reinforce long-term engagement. Given that each study in this work lasted less than 1 month and users would need at least 29 days of optimal IEQ conditions to reach level 25, the prototype's GUI only implements background elements for levels 0 through 25. Beyond level 25, the background remains unchanged. However, these background elements can be extended or modified in the open-source GUI firmware to suit the desired usage time of the system. Detailed development guides are provided. The virtual dinosaur was selected as a neutral and non-competitive representation. The gradual enrichment of the environment was chosen to provide continuous visual feedback rather than abrupt or disruptive notifications. The green color scheme of the character was chosen due to its common association with sustainability and environmental awareness, reinforcing the conceptual link between the gamification elements and the system's energy- and IEQ-related goals.

The leveling mechanism is designed to support both initial motivation and sustained use, as defined by Eqs. (2) and (3), where ΔXP represents the XP (rounded to the nearest integer) awarded to the user per sensor reading based on the current IEQI, and XP (L) denotes the total XP required to reach the next level (L). Users progress more quickly during the early stages, which facilitates familiarization with the interface and offers immediate positive reinforcement. As the level increases, the XP required for further advancement grows gradually. This prevents excessively rapid progression that might cause users to miss intermediate levels when they are not interacting with the system and helps maintain interest over extended periods.

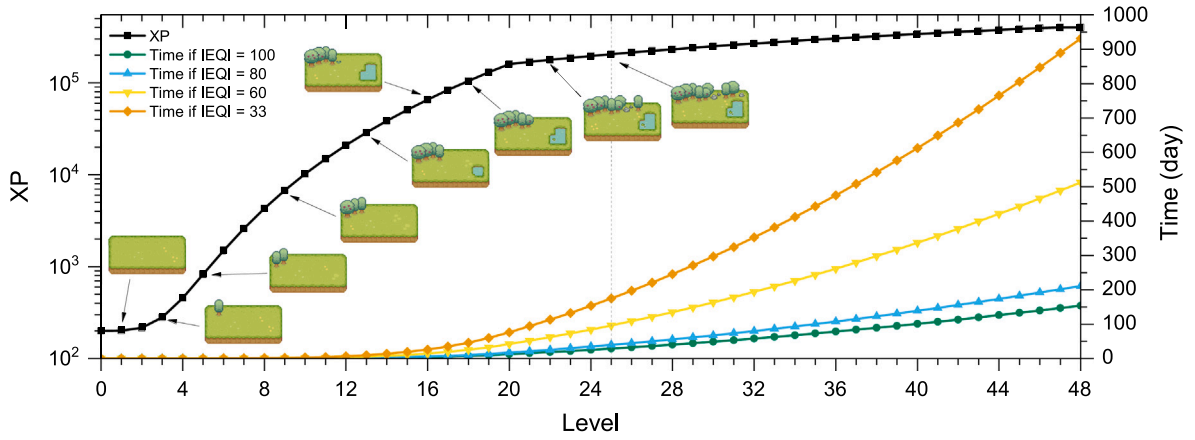


Fig. 6. XP required for each level and the time needed to reach that level under different IEQI conditions. Note: In this prototype, dynamic GUI backgrounds are only implemented up to level 25. For visual clarity, not all level-specific background elements are displayed in this Figure.

Users can receive textual feedback automatically every 30 minutes or on-demand by interacting with the touch display (see Fig. 5). The feedback is provided in three categories: 1) basic system information, 2) IEQ-based recommendations, action-oriented advice, and energy-saving tips, and 3) interesting facts and scientific background information related to IEQ, sustainability, and energy-saving. Automatic feedback is enabled by default and issued every 30 minutes. This feature ensures that users receive feedback even when they are not actively interacting with the system, allowing the feedback mechanism to consistently influence user behavior. Additionally, automatic feedback can serve as a regular reminder to take ventilation or rest breaks.

All feedback messages are generated using a predefined, rule-based mechanism. When automatic feedback is triggered every 30 minutes, or when users manually request feedback, the system first selects a feedback category probabilistically according to predefined weights (see Fig. 13 in the Appendix). If the selected category is basic system information or interesting facts and scientific background information related to IEQ, a message is randomly drawn from the corresponding pool. If the selected category is IEQ-based recommendations and energy-saving advice, the system evaluates the current IEQ state based on the most recent valid sensor readings and determines the corresponding IEQI range. A message is then randomly selected from the predefined subset associated with the identified IEQ state.

$$\Delta XP = \begin{cases} \left\lfloor \frac{IEQI}{10} \right\rfloor, & \text{if } IEQI \geq 90 \\ \left\lfloor \frac{IEQI}{11} \right\rfloor, & \text{if } 67 \leq IEQI < 90 \\ \left\lfloor \frac{IEQI}{20} \right\rfloor, & \text{if } 33 \leq IEQI < 67 \\ 0, & \text{if } IEQI < 33 \end{cases} \quad (2)$$

$$XP(L) = \begin{cases} 200 + L^4, & \text{if } L \leq 20 \\ 160200 + 9000(L - 20), & \text{if } 20 < L \leq 46 \\ 400000, & \text{if } L > 46 \end{cases} \quad (3)$$

2.1.4. Sensors

Besides the touch display, which serves as the main interaction component, the 3D-printed enclosure contains a PCB, which can be modularly equipped with up to four sensors connected via the Inter-Integrated Circuit (I²C) bus and up to five analog sensors, including a

coil-based power measurement module. The PCB provides interfaces for various commercially available sensor breakout boards, including power supply connections offering both 3.3 V and 5 V to ensure compatibility with a wide range of modules.

All I²C sensors are automatically detected by the system, while the analog sensors can be configured manually within the firmware. Table 1 lists all sensors currently supported, along with their accuracy specifications as provided in the manufacturers' data sheets.

After producing and assembling a small batch of systems for field studies, all sensors used were calibrated using reference sensors from the Ahlborn ALMEMO[®] system. The models and performance of the reference sensors are detailed in Table 7 in the Appendix. Sensors that were not used in the field study (wind speed, wet-bulb temperature, electrical power, and window-status sensors) were not part of the calibration procedure.

The temperature and humidity sensor BME280 was calibrated using a mean offset adjustment. Specifically, the average deviation between the low-cost and reference sensors was calculated and applied as a constant offset correction. This choice reflects the observation that the raw temperature readings showed strong linear alignment with the reference device and differed primarily by a small additive bias. In contrast, the illuminance sensor VEML7700 exhibited both offset and gain drift, requiring calibration by linear regression.

Given that the intended application of the system is long-term monitoring, the SCD30 CO₂ sensor was operated with Automatic Self-Calibration (ASC) enabled. In this configuration, the sensor updates its internal 400 ppm reference every seven days by assigning the lowest measured concentration within that period as the new baseline. This mechanism compensates for potential long-term drift. The ASC used in this study differs conceptually from the Forced Re-Calibration (FRC) method used in our previous short-term CO₂ measurement device [50], as the two methods serve different calibration purposes.

The SGP40 sensor used for VOC measurements was not calibrated, as it outputs a VOC index rather than an absolute concentration. The index ranges from 0 to 500. A value of 100 represents the Indoor Air Quality (IAQ) unchanged over the past 24 hours. Values between 100 and 500 indicate deteriorating IAQ, while values between 1 and 100 indicate improving conditions [51,52].

The performance of the low-cost sensors was evaluated using the Mean Absolute Error (MAE) between their measurements and the reference values, as defined in Eq. (4).

$$MAE(y, \hat{y}) = \frac{1}{n_{\text{samples}}} \sum_{i=1}^{n_{\text{samples}}} |y_i^{\text{measurement}} - \hat{y}_i^{\text{reference}}| \quad (4)$$

Table 1
Overview of sensors and precision according to manufacturers' data sheets.

Sensor	Parameter	Precision	Range
Bosch® BME280	Air temperature	± 1.0 K	0...65 °C
	Rel. humidity	± 3%	20...80 %
	Air pressure	± 1.0 hPa	300...1100 hPa & 0...65 °C
Vishay® VEML7700	Illuminance	± 10%	0...140k lx
Sensirion® SGP40	VOC	± 5%	0...1000 ppm ¹
Sensirion® SCD30	CO ₂ concentration	± 30 ppm + 3%	400...10000 ppm
DFRobot® SEN0232	Sound level	± 1.5 dB	30...130 dB(A) & 31.5...8.5k Hz
Modern Device® Wind Sensor Rev.C	Wind speed	n.a.	0...26.8 m/s
Dallas® DS18B20 ²	Wet-bulb globe temperature	± 0.5 K	− 10...85 °C
YHDC® SCT-013	Electricity power	± 3%	0...100 A
Reed switch	Binary status of the window	n.a.	n.a.

¹ Ethanol in pure air.

² In a black globe thermometer.

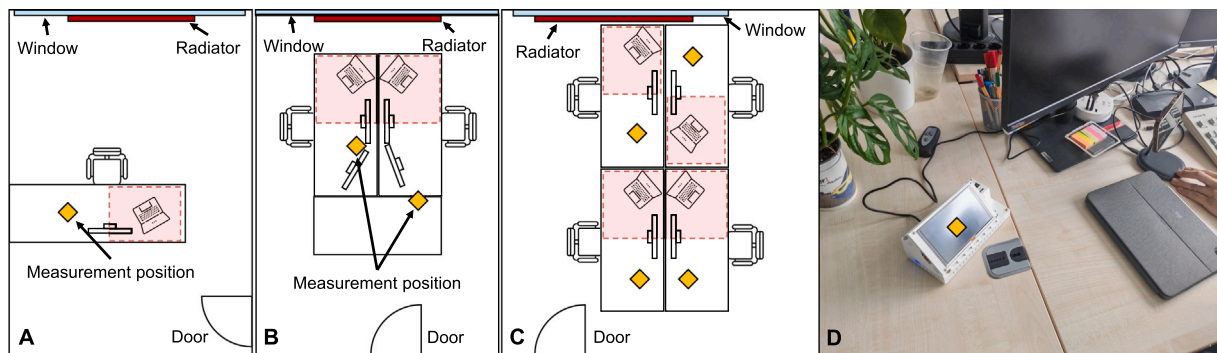


Fig. 7. Examples of monitoring device placement in the field study: A) single-person office, B) two-person office, C) four-person office, D) actual photograph of one placement location in a two-person office. Locations are selected based on user preference while avoiding placement near laptops in red zones. The dimensions of all rooms are detailed in Table 8 of the appendix. (For interpretation of the references to colour in this Figure legend, the reader is referred to the web version of this article.).

2.2. Field study

The field study was approved by RWTH Aachen University's Interfaculty Ethics Committee (FÜEK; Ref. 18/2025). Three different departments of RWTH Aachen University were contacted to evaluate the prototypes. This section presents the studies conducted at each of these departments. The first sub-study has been published in the *Bauphysik-Kalender* [53]. The present paper incorporates the analyses from all three sub-studies.

Participants in the field study were divided into an intervention group (Group A) and a control group (Group B). During the study, the intervention group could use the touch display to access the gamified HMI features, whereas the control group did not have access to the touch display and therefore could not view the GUI. All three sub-studies employed a two-period crossover design. Within each study, participants were randomly allocated to one of two sequences: intervention group followed by control group (AB), or control group followed by intervention group (BA). In the second study, this two-period cycle was repeated once, providing two independent exposure episodes to each condition. This additional repetition was conducted only when participants were willing and available to continue after the first round, allowing additional data to be collected. Since each participant was exposed to both conditions, the intervention effect could be estimated within subjects.

In all three studies, monitoring devices were randomly assigned to participants and placed on the desk's side opposite the computer to minimize potential interference from the electronic equipment's heat dissipation and noise. The top of the device was also kept clear to ensure accurate illuminance measurements. Fig. 7 shows the typical placement of the monitoring device.

The GUI used in the field study included 60 feedback messages integrated into the feedback system. These messages included 11 general system messages, 35 IEQ-related evaluations and recommendations, including energy-saving advice, and 14 informational messages providing scientific facts related to IEQ, sustainability, and energy-saving. The architecture of the feedback system is shown in Fig. 13 in the Appendix, and all feedback messages are provided in Tables 9–11 in the Appendix. The GUI and feedback messages were available in English and German, but all participants used the German version.

Data were collected through a structured online questionnaire that was administered in multiple phases. At the beginning of the study, participants completed a general questionnaire (SQ1) about workplace characteristics and their overall perception of environmental factors, including noise and lighting. During the study, a short questionnaire (SQ2) was sent via email every two hours during working hours to record participants' current comfort perceptions. Thermal comfort was assessed using a seven-point scale ranging from −3 (cold) to +3 (warm). Other domains were evaluated using a seven-point satisfaction scale ranging from 1 (unsatisfied) to 7 (satisfied). At the end of each workday, the intervention group completed a system usability questionnaire (SQ3) based on the Usability Metric for User Experience Lite (UMUX-LITE) [54]. After the study concluded, participants completed a final questionnaire (SQ4) that assessed system usability using the System Usability Scale (SUS) [55] and collected demographic information. In addition, SQ4 included self-reported questions on changes in heating, cooling, and ventilation behavior. The exact wording of these items is provided in Table 12.

The system's usability is evaluated according to Eqs. (5) and (6), where Q denotes the item numbers of the questionnaire, scored on a 0–10 scale for the SUS and a 1–2 scale for the UMUX-LITE [56,57].

Then, these scores are converted to the intuitive A+ to F grading scale using the Sauro-Lewis Curved Grading Scale (CGS) [58], which assigns discrete letter grades ranging from A+, A, and A- through B+, B, and lower grades down to F. In this scale, A+ represents the highest level of system usability, whereas F indicates poor usability.

$$SUS = 2.5 \cdot \left(20 + \sum (Q01, Q03, Q05, Q07, Q09) - \sum (Q02, Q04, Q06, Q08, Q10) \right) \quad (5)$$

$$UMUX-LITE = 0.65 \cdot ((Q1 + Q2 - 2) \cdot \frac{100}{12}) + 22.9 \quad (6)$$

To account for differences in sensitivity to various aspects of IEQ among individuals, the questionnaire SQ1 included several established instruments. Noise sensitivity was assessed using Weinstein's Noise Sensitivity Scale (WNSS-21) [59] and its German translation by Zimmer and Ellermeier [60]. Visual sensitivity related to light and brightness was assessed using the Visual Light Sensitivity Questionnaire – 8 (VLSQ-8) from Verriotto et al. [61] and translated into German for this study. No standardized questionnaire specifically suited to assess sensitivity to IAQ was found for this context, so smoking status and respiratory conditions were collected as coarse proxy indicators of whether individuals might be more or less susceptible (cf. [62,63]). Thermal sensitivity was not assessed using a standardized instrument. However, demographic information, such as age and gender, was collected in SQ4 to support the interpretation of thermal comfort responses. Barometric pressure sensitivity was not assessed because the relationship between barometric pressure and perceived comfort remains inconclusive (cf. [31–34]). Given the longer completion time of SQ1 and SQ4, a brief arithmetic item was included as an attention check to maintain the overall quality of the questionnaire data.

To evaluate the effects of gamification on user behavior, sensor data collected during work hours (9:00 a.m.–5:00 p.m.) and self-reported behavioral changes collected via questionnaire SQ4 were analyzed using within-participant difference scores. For each participant and metric, all available measurements within a condition were aggregated to obtain a condition-specific mean or median. For continuous sensor metrics, the mean was used. For categorical and ordinal self-report items, the median was used. Then, an individual difference score was computed using Eq. (7), where a positive D_i indicates higher values of i during the intervention condition.

$$D_i = \text{Agg}_i(\text{Intervention}) - \text{Agg}_i(\text{Control}) \quad (7)$$

For continuous sensor data, a two-sided, one-sample t -test was performed to determine if the mean difference score was significantly different from zero. Cohen's d was computed as an effect size to quantify the magnitude of the intervention effect. The normality of the difference-score distribution was assessed using the Shapiro-Wilk test prior to applying one-sample t -tests. For categorical and ordinal self-report items, a two-sided Wilcoxon signed-rank test was used, and the effect size was reported as rank-biserial correlation (RBC). The statistical analyses were performed in Python using the pandas [64] and pingouin [65] libraries.

The field study took place in Aachen, Germany, classified as Cfb in the Köppen-Geiger climate classification (cf. [66]). The evaluation consisted of three separate field studies (hereafter referred to as Study 1, Study 2, and Study 3), conducted sequentially between February and June 2025 in office environments at RWTH Aachen University. Each study represents an independent deployment of the same monitoring system and experimental protocol, differing primarily in the dates, building context, office configuration, and participant composition. All studies took place in academic or administrative buildings and were designed as two-period crossover experiments. Participants were randomly assigned to groups A and B, and across the three studies, a total of 16

Table 2

Overview of field study settings, office characteristics, and participant information.

Nr.	Study period	Office type(s)	Age range & Gender
1	10–21 Feb	Six two-person offices	25–34 & 4 female, 2 male (one not reported)
2	10 Apr–9 May	One single-person office; two four-person offices	25–34 & 2 female, 2 male (two not reported)
3	2–17 Jun	Two single-person offices; one two-person office	45–54 (one not reported) & 3 female

participants worked in single-, two-, or four-person offices. Office allocation was either random or constrained by availability. Group assignment was balanced wherever possible to minimize systematic bias.

All study buildings were oriented with their longitudinal axes rotated approximately 46–52 ° toward the northwest. This resulted in offices facing either northwest or southeast, depending on the site. In Study 1, offices with different orientations were evenly distributed across groups to minimize the effects of solar exposure. In Study 2 and Study 3, all participating offices within each building shared the same orientation. None of the buildings had mechanical ventilation systems, so ventilation relied exclusively on natural ventilation. In some offices, the windows could only be opened in tilt positions or could not be freely controlled by the participants.

Heating in all offices was provided by radiators located beneath the windows. In most offices, occupants could manually adjust the heating, although this was not possible in some shared offices. Cooling options varied by building and included electric fans and, in one building, a ceiling-mounted cooling system (no mechanical ventilation). Lighting was manually operated in all offices and typically offered only discrete on/off or partial-on settings, without continuous dimming.

The participants' demographics varied across the three studies. The majority of participants were between 25 and 34 years old, while a smaller number were between 45 and 54 years old. Several participants did not report their age. Gender was self-reported, with both female and male participants represented. Some participants chose not to disclose their gender. A small number of participants reported individual adaptations to thermal comfort, such as the occasional use of heated cushions or access to heated furniture.

In Study 1, an additional participant was included as a reference individual to verify the technical functionality of the online questionnaire system. This participant used the same touchscreen interface as the intervention group, but was excluded from the main statistical analysis. All other participants followed the same study protocol. The environmental conditions, office characteristics, and participant information across the three studies are summarized in Table 2.

3. Results

3.1. Technical part

A total of 19 IEQ monitoring systems were produced in this work, numbered RW001 to RW019. Table 3 summarizes the hardware cost of the developed system and available alternative components. The 3D-printed enclosure is manufactured in white to prevent excessive impairment from radiant heat. The system is designed with a Do It Yourself (DIY) philosophy, enabling users to assemble the device themselves using commercially available parts and the included assembly guide. Fig. 8 shows all the components required for system assembly.

As listed in Table 3, all sensors supported (cf. Table 1) were used during the field study except for the wind speed, wet-bulb temperature, electricity power, and window-status sensors. Power and window sensors were not deployed due to installation constraints at the study sites. The wet-bulb temperature sensor was not deployed due to budget constraints and practical installation considerations, as it requires an external black globe that could interfere with normal office workflows.

Table 3

Hardware cost of the monitoring system. All prices reflect the market prices in 2024 and are listed in Euro (€). *Required* indicates components that are essential to the baseline system configuration. Optional components may be added depending on specific use cases. *Used* indicates whether it was used in the field study.

Category	Model	Unit Price (€)	Required	Used
Microcontroller	Espressif® ESP32-DevKitC V4 development board	10.80	Yes	Yes
Sensor	Bosch® BME280 sensor breakout board (5V & 4-pin version)	4.00	No	Yes
	Adafruit® 5378 (Vishay® VEML7700) sensor breakout board	5.47	No	Yes
	YHDC® SCT-013-010 (10 A) AC current sensor for electricity power	6.00	No	No
	Adafruit® 4829 (Sensirion® SGP40) sensor breakout board	16.54	No	Yes
	Modern Device® Wind Sensor Rev.C ¹	19.95	No	No
	DFRobot® Gravity Analog Sound Level Meter SEN0232 sensor breakout board	36.83	No	Yes
	Sensirion® (Sensirion® SCD30) sensor breakout board	63.50	No	Yes
Touch display	Nextion® Intelligent HMI Display 5" NX8048P050-011R (Resistive) ²	78.00	No	Yes
Storage	Harztec® CP09004 TF microSD card memory module	0.99	No	Yes
	Intenso® 3411460 MicroSDHC memory card 8GB	3.50	No	Yes
Accessories	Screws, hex nuts, etc., for the enclosure	2.80	Yes	Yes
	Polylactic Acid (PLA) 3D printing filament for the enclosure	2.98	Yes	Yes
	PCB	5.00	Yes	Yes
	DS3231 RTC module with battery	6.49	Yes	Yes
	Pushbutton, resistor, and socket header, etc.	24.42	Yes	Yes
		$\Sigma(\text{Required}) =$	52.49	
		$\Sigma(\text{All}) =$	287.27	

¹ Alternative: Modern Device® Wind Sensor Rev.P 35.95 € with its required DC-DC step-up voltage boost converter (3.3 V/5 V to 12 V) 4.75 €.

² Alternative: Nextion® Intelligent HMI Display 5" NX8048P050-011C (Capacitive) 83.00 €

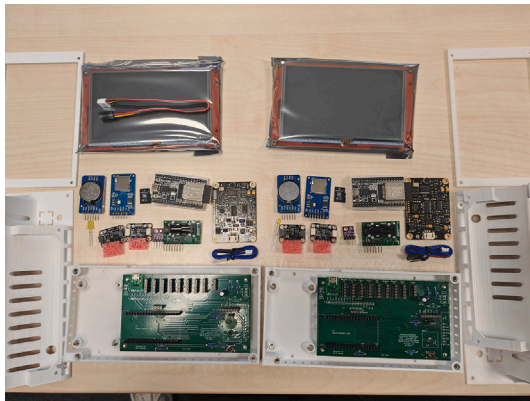


Fig. 8. All necessary components for system assembly. DIY guides are available on our wiki or GitHub pages.

The wind speed sensor was excluded due to budget constraints and insufficient accuracy observed during preliminary evaluations. The Rev.C model exhibited large deviations regardless of which calibration method from the literature [44,49,67] was applied, as shown in Fig. 9. Consistent with the findings reported by Geck et al. [49], the measurement inaccuracy of low-cost wind speed sensors increases with air velocity and is also influenced by indoor temperature. In addition, the consistency between sensors from different production batches is limited. To avoid introducing additional uncertainty, it was not included in the final system. Although another model from the same manufacturer (Rev.P) demonstrated higher accuracy using the manufacturer-provided calibration method [68], its cost was nearly double that of Rev.C and was therefore not adopted.

Before deployment, all sensors were calibrated in batches, as shown in Fig. 10. Sensor accuracy after calibration was quantified using the MAE between measured and reference values, and the aggregated results are presented in Table 4.

During calibration, an additional validation of the device enclosure's thermal behavior was performed. The temperature offset caused by the waste heat of the touch display was assessed by comparing measurements obtained with the screen turned on and disconnected. For the devices used in the field study (RW001–RW009), the average

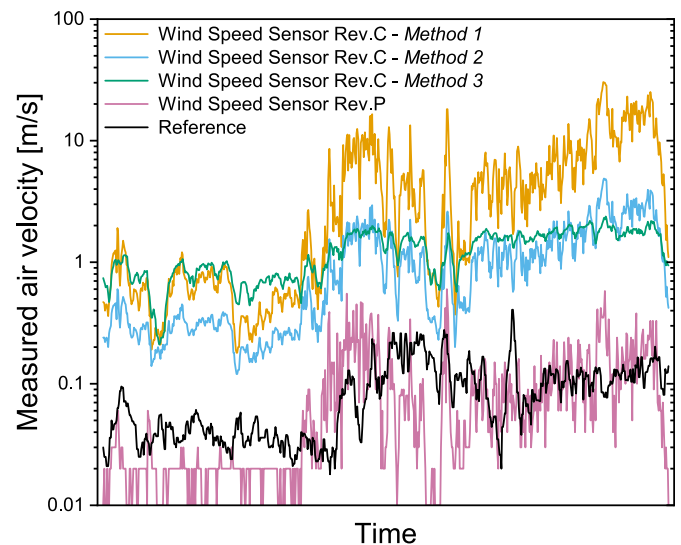


Fig. 9. Comparison of wind speed sensors Rev.C and Rev.P with the reference sensor (Ahlborn ALMEMO® system). Both Rev.C and Rev.P sensors were calibrated under no-wind conditions in accordance with the manufacturer's guidelines. For Rev.C, three calibration approaches were compared: Method 1 (manufacturer-provided) [67], Method 2 (Salamone et al.) [44], and Method 3 (Geck et al.) [49].

temperature offset with the touch display activated was 0.47 K (SD = 0.17 K). This result is consistent with the expectations derived from our CFD simulations (0.5 K).

The system's power consumption was also measured under several operating conditions: normal mode, dimmed-screen mode, sleep mode, normal mode without the touch display, and sleep mode without the touch display. The average power consumption in these conditions was 2.05 W, 1.61 W, 1.25 W, 0.49 W, and 0.48 W, respectively.

3.2. Field study

Across Study 1, Study 2, and Study 3, the numbers of collected responses were as follows:

- SQ1: 8, 6, and 3 responses, respectively;

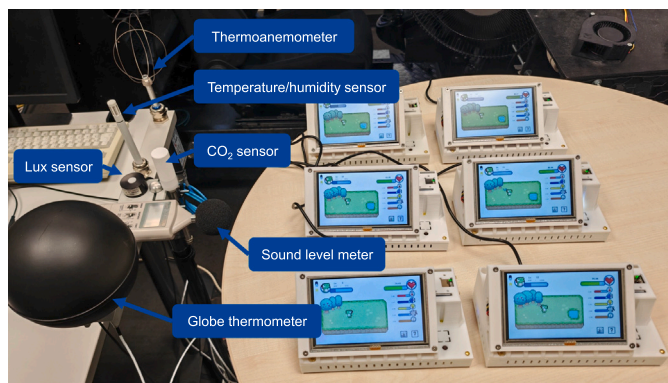


Fig. 10. Photograph of one batch of sensor calibration. The Ahlborn ALMEMO® system was used as the reference device, and its performance specifications are listed in Table 7.

Table 4

Summary of sensor precision based on calibration results, expressed as MAE. Values in parentheses denote Standard Deviation (SD). Rounded to two decimal places.

Sensor	Parameter	MAE (SD)
Bosch® BME280	Air temperature	0.25 (0.03) K
	Rel. humidity	0.70 (0.19) %
	Air pressure	n.a.
Vishay® VEML7700	Illuminance	28.05 (26.61) lx
Sensirion® SGP40	VOC index	n.a.
Sensirion® SCD30	CO ₂ concentration	97.64 (93.89) ppm
DFRobot® SEN0232	Sound level	4.27 (0.34) dB(A)

Note: The results represent the average of all systems used, specifically RW001 to RW009.

- SQ2: 230, 212, and 47 responses, respectively;
- SQ3: 30, 20, and 1 response, respectively;
- SQ4: 9, 10, and 4 responses, respectively.

After excluding blank submissions, duplicates, failed attention checks, and responses indicating that the system was not in use at the time of completion, the valid datasets consisted of 7, 6, and 3 responses for SQ1 (16 in total); 168, 121, and 44 for SQ2 (333 in total); 30, 15, and 1 for SQ3 (46 in total); and 9, 10, and 1 for SQ4 (20 in total).

Participant sensitivities across different IEQ domains are summarized in Fig. 11. Variation in noise sensitivity (WNSS-21) was observed, with scores ranging from 0.44 (less sensitive) to 0.73 (more sensitive) and an average value of 0.58. Visual light sensitivity (VLSQ-8) was low on average. The normalized mean was 0.37, reflecting limited sensitivity to glare and brightness among most participants. Furthermore, one participant in Study 3 met the criteria for classification as IAQ sensitive.

3.2.1. System usability

In Study 1, the SUS score was 80.5, corresponding to a CGS grade of A-. The CGS is a curved grading scale that maps SUS scores onto percentile-like performance intervals. The associated CGS band for an A- is 85–89%. Excluding the reference participant's rating decreased the score to 77.5, corresponding to a B+ (80–84%). Study 2 resulted in a SUS score of 83.1, corresponding to an A (90–95%). Study 3 yielded a SUS score of 62.5, corresponding to a grade D.

Combining all SUS responses from the three sub-studies produced an overall system usability score of 75.4, corresponding to a grade B. The UMUX-LITE results were comparable to the SUS findings. The mean UMUX-LITE score was 79.05, which corresponds to an A-.

The system's wiki page (<https://rw.e3d.rwth-aachen.de/>) usage was minimal. It provided background information on the system's hardware design, GUI, and IEQ fundamentals underlying the comfort models used

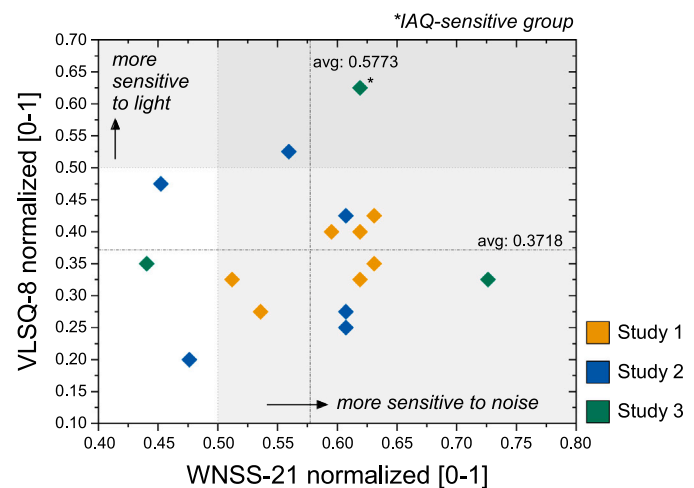


Fig. 11. Participants' noise sensitivity (WNSS-21) and visual light sensitivity (VLSQ-8), with average values indicated. All scores are normalized to the range 0 to 1, where 0 represents the lowest sensitivity and 1 represents the highest. An asterisk indicates a participant who was classified as IAQ-sensitive.

in the system. Participants rated their level of wiki usage on a five-point ordinal scale ranging from no awareness of the wiki (1) to having read all of its content (5). The mean response was 2.1 (SD = 0.32), indicating that almost all participants were aware of the wiki but did not open it. Only one participant reported reading part of its content.

The distribution of responses to the feedback-related questions is summarized in Fig. 12. Participants generally viewed the feedback content positively. All respondents either agreed or strongly agreed that the feedback content was useful, and many expressed interest in receiving more detailed feedback (Q1 in Fig. 12). There were a few negative reactions to the automatic feedback. A minority found the automatic messages annoying or distracting, while most responses were neutral (Q2 and Q3).

Opinions regarding the gamified GUI were more diverse. Several participants indicated that the gamification elements increased their interest in using the system (Q8), whereas others found the GUI distracting or childish (Q6 and Q9). Preferences for a simple sensor-data display instead of the gamified GUI were also observed. It revealed a polarized pattern in which some participants strongly favored the gamified presentation, and others clearly preferred a non-gamified interface that focused on sensor readings (Q7). No participants expressed a global dislike of the feedback system as a whole (Q5), and only one person reported that the system interfered with their ability to concentrate on work or studying (Q10). Overall, the pattern of responses suggests broad acceptance of the feedback content itself, accompanied by more heterogeneous preferences regarding the style of interface presentation.

Viewing frequencies were assessed using a seven-point ordinal scale ranging from 1 (very frequently, several times an hour) to 7 (never), with intermediate values representing decreasing interaction frequencies. Across the studies, touch display interactions occurred most frequently, on average several times a day (mean = 2.4), followed by feedback messages at a comparable frequency (mean = 3.0). In contrast, detailed sensor readings were consulted less frequently overall (mean = 3.5).

The questionnaire SQ3 also asked how closely the system's comfort indices matched the respondents' own sensations. This item used a five-point scale ranging from 1 (completely different), through intermediate categories such as 3 (sometimes different, sometimes the same), to 5 (completely the same). The mean rating was 3.6 (SD = 0.79) in Study 1 and 3.5 (SD = 0.62) in Study 2, indicating a moderate level of alignment between the system-provided indices and subjective sensations. No valid responses were available for Study 3. Respondents were additionally asked which index or indices differed most from their own

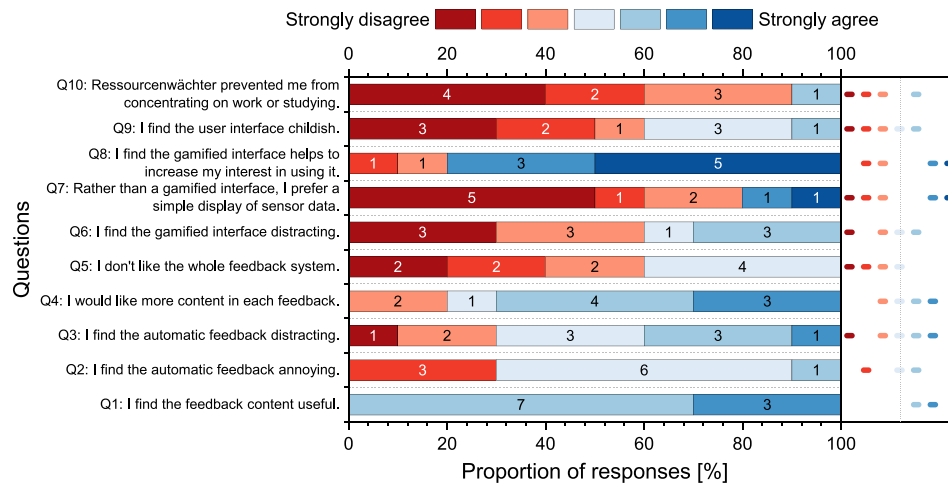


Fig. 12. Responses to the feedback system-related questionnaire items. The numbers in the chart indicate the specific number of respondents who selected each answer. A rug plot on the right shows the distribution of responses.

Table 5

Summary of descriptive statistics and Wilcoxon signed-rank test results for difference scores (D_i , see Eq. (7)) for self-reported behavioral changes.

Metric	Mean(D_i)	Median(D_i)	SD(D_i)	W-value	p-value	RBC	CLES
Self-reported ventilation frequency	-0.1	0.0	0.74	2.5	1.0	-0.17	0.4
Self-reported ventilation duration	0.1	0.0	1.14	3.0	1.0	0.0	0.4

Note: The self-reported behavioral changes were measured using the questionnaire SQ4 on a 5-point Likert scale (1 = significantly decreased, 3 = no significant change, 5 = significantly increased). Mean and SD are reported for completeness, while median-based statistics were used for hypothesis testing. The W-value denotes the Wilcoxon test statistic. RBC denotes the rank-biserial correlation as a standardized effect size; absolute values of approximately 0.1, 0.3, and 0.5 are commonly interpreted as small, medium, and large effects, respectively. CLES (Common Language Effect Size) represents the probability that a randomly selected participant shows a higher score in the intervention condition than in the control condition.

perception. In Study 1, the 21 selections were distributed across thermal comfort (1), acoustic (2), lighting (6), and IAQ (12), with IAQ and lighting most frequently identified as divergent. In Study 2, the 14 selections focused primarily on thermal comfort (7), followed by lighting (5) and acoustic (2). The single valid respondent in Study 3 selected thermal comfort, acoustic, and barometric pressure. Overall, the results show that the indices were generally considered reasonably aligned with subjective sensations ranging from “3: sometimes different, sometimes the same” to “4: mostly the same.” However, discrepancies were noted more frequently in IAQ and lighting in Study 1, and in thermal comfort in Study 2.

3.2.2. User behavior

Table 5 summarizes the descriptive statistics and Wilcoxon signed-rank test results for the difference scores obtained from self-reported behavioral changes. Self-reported changes in heating and cooling behavior showed no intervention effect. For the heating power level, heating duration, cooling power level, and cooling duration, the difference scores were all zero. Therefore, these variables had identical responses under the intervention and control conditions, and no statistical tests were applicable. On average, participants rated their ventilation frequency (mean = 3.63, median = 4) and ventilation duration (mean = 3.50, median = 3) slightly higher for self-reported ventilation behavior. However, the difference scores between the intervention and control groups did not differ significantly from zero. These results show that although participants reported more frequent or longer ventilation behavior during the field study, there were no statistically significant

differences between conditions. The associated effect sizes were negligible to small ($|RBC| \leq 0.17$), indicating minimal within-participant change attributable to the intervention.

The sensor data further revealed differences between the intervention and control conditions. For continuous sensor data, Table 6 summarizes the descriptive statistics and *t*-test results for the difference scores. Air temperature in the intervention group (mean = 24.25 °C) was significantly higher than in the control group (mean = 23.26 °C) with a mean difference of 1.02 K and a large effect size ($d = 1.0374$). Relative humidity showed the opposite pattern, with significantly lower values during the intervention phase (mean = 33.06% and 34.69%) and an effect size of $d = 0.8129$. Both metrics met the normality assumption, and their 95% confidence intervals did not include zero.

For all remaining environmental variables, the difference scores were not statistically significant (all $p > 0.30$). Effect sizes were generally small ($d < 0.15$) for air pressure, VOC index, sound level, and CO₂ concentration, indicating minimal differences between the two groups. Illuminance was the only metric with a small-to-medium effect size ($d = 0.28$), though the difference remained nonsignificant ($p = 0.30$). Mean illuminance values differed only slightly between the intervention and control conditions (intervention: 168 lx, control: 154 lx). Similarly, VOC index values were close (intervention: 168, control: 154), sound levels were nearly identical (37.2 dB(A) for both groups), and CO₂ concentrations differed only slightly (intervention: 775 ppm, control: 768 ppm). Normality assumptions were met for most metrics, and all 95% confidence intervals for the non-significant effects crossed zero.

Table 6

Summary of descriptive statistics and *t*-test results for difference scores (D_i , see Eq. (7)) for sensor data during work hours. Normality was assessed using the Shapiro-Wilk test.

Metric	Mean(D_i)	SD(D_i)	Normal	<i>t</i>	df	<i>p</i> -value	95%-CI	Cohen's <i>d</i>
Air temperature** [°C]	1.02	0.98	True	4.02	14	0.001	[0.47, 1.56]	1.04
Relative humidity** [%]	−1.75	2.15	True	−3.15	14	0.007	[−2.94, −0.56]	0.81
Air pressure [hPa]	−0.31	3.27	False	−0.36	14	0.721	[−2.12, 1.5]	0.09
VOC index [0-500]	7.08	59.64	True	0.46	14	0.653	[−25.95, 40.1]	0.12
Illuminance [lx]	715.66	2580.65	False	1.07	14	0.301	[−713.46, 2144.78]	0.28
Sound level [dB(A)]	0.17	2.96	True	0.22	14	0.827	[−1.47, 1.81]	0.06
CO ₂ concentration [ppm]	12.21	91.93	True	0.51	14	0.615	[−38.69, 63.12]	0.13

Note: The asterisk denotes statistical significance (*p*-value), *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. The *Normal* column reports whether the Shapiro-Wilk test indicated no significant deviation from normality ($p \geq .05$). *t* and *df* denote the one-sample *t*-statistic and its degrees of freedom. The 95%-CI represents the confidence interval for the mean difference score between the intervention and control conditions; negative values indicate lower ratings under the intervention condition relative to the control condition. Cohen's *d* indicates the standardized effect size; values around 0.2, 0.5, and 0.8 are commonly interpreted as small, medium, and large effects, respectively.

4. Discussion

4.1. Measurement accuracy and calibration

The thermal behavior of the device enclosure was an important design consideration. Validation results showed an average temperature offset of approximately 0.47 K when the touch display was active. This offset closely matched the 0.5 K CFD prediction, indicating that the current enclosure design provides a reasonably stable thermal environment for the embedded sensors. Although the offset is small and can be corrected during calibration, it underscores the need to account for self-heating effects when integrating displays or other active components into compact IEQ monitoring devices, particularly for applications requiring high-precision temperature measurements. The CFD configuration was deliberately conservative, with waste-heat temperatures of the touch display and microcontroller exceeding the measured offsets (see Figs. 3 and 4), to assess extreme-case scenarios. The influence of enclosure material and color on temperature measurements was not quantified in this study and warrants further investigation.

The results also highlight several limitations of low-cost sensors and their implications for calibration and long-term consistency. The temperature and humidity sensor BME280 showed good batch consistency, with an SD of 0.88 K for temperature offsets and 3.77% for humidity, indicating that inexpensive sensors can achieve acceptable agreement when deployed at scale. In contrast, greater variability was observed for the sound level and illuminance sensors. The SEN0232 exhibited moderate variability (SD = 5.81 dB(A)), making it suitable for identifying indoor noise patterns but less appropriate for applications requiring high measurement precision. The VEML7700 showed comparatively poor consistency, suggesting that low-cost illuminance sensors may require per-unit calibration or more robust factory binning to achieve higher accuracy.

The CO₂ sensor SCD30 showed acceptable consistency across devices, with an SD of 94 ppm for the MAE. However, reliance on ASC introduces a limitation: sensors in environments with limited access to fresh air may diverge over time, increasing inter-device variability. CO₂ sensors' sensitivity to installation location and airflow conditions further constrains their use in tightly controlled comparative studies. For short-term measurements, as in our previous work [50], it is recommended to calibrate the CO₂ sensor using FRC. The system is also compatible with a lower-cost sensor from the same manufacturer (Sensirion® SCD40). However, its single-channel architecture results in larger signal fluctuations and reduced measurement stability. The dual-channel SCD30 provides smoother and more stable readings and was therefore selected for this study. For VOC measurements, the employed sensor SGP40 provides only a relative index derived from recent exposure history. This precludes meaningful calibration and currently prevents conclusions about batch consistency from being drawn.

Overall, these findings reveal that, while low-cost sensors can suffice for multi-modal IEQ monitoring, their accuracy and long-term stability vary considerably across sensing modalities. Applications requiring high absolute accuracy, strict comparability between devices, or robust long-term stability may require more frequent recalibration, sensor-specific correction models, or replacement with higher-grade components. Nevertheless, the performance observed here demonstrates that with appropriate calibration procedures and awareness of sensor-specific limitations, low-cost systems can offer a viable, scalable alternative for many IEQ research and deployment scenarios.

Furthermore, the choice of sensors restricts which comfort models can be implemented, as each model has specific input requirements. The computational demands of these models must also be feasible for embedded systems. These considerations highlight the need to evaluate sensor selection and model implementation jointly.

Beyond the sensors included in the present study, each IEQ domain could be expanded to include additional modalities, such as frequency measurements for acoustics or correlated color temperature in the lighting domain. However, these enhancements must be balanced against budget constraints and the intended measurement accuracy for specific applications.

4.2. Field study insights

The three sub-studies showed notable differences in perceived usability. Studies 1 and 2 yielded high SUS scores (80.5 A- and 83.1 A, respectively), consistent with the positive qualitative feedback. These scores indicate that the system was intuitive and responsive during everyday use. In contrast, Study 3 obtained a much lower score (62.5, D), suggesting a divergent interaction experience. This difference may be attributed to the smaller, less diverse participant group in Study 3, as well as its higher average age compared to the previous sub-studies. Given the fixed touch display size and font layout, age-related visual or interaction preferences may have affected the usability ratings. These findings underscore the importance of adjustable interface modes, such as simplified views, larger touch targets, and reduced information density, to accommodate a broader spectrum of user needs. Overall, while the system demonstrated robust usability among younger, digitally experienced users, usability may vary across different user groups.

A comparison of the three studies indicates that the comfort indices most frequently perceived as inconsistent with subjective sensations did not consistently correspond to participants' sensitivity profiles regarding lighting, acoustics, and IAQ. Rather, these mismatches appear to be primarily driven by local environmental conditions and the general assumptions embedded in the underlying comfort models.

Perceived inconsistencies in IAQ were often linked to external boundary conditions that were not directly observable to participants. For instance, when outdoor air quality deteriorates (e.g., during an air

quality alert, as observed during the first study), occupants may still open windows to ventilate based on habit or thermal needs. Under such conditions, ventilation may introduce outdoor pollutants and temporarily increase indoor VOC concentrations, causing the model-based IAQI to worsen, contrary to occupants' expectations. This can create a mismatch between the index and subjective impressions, especially when changes in IAQ are not visually apparent. Thermal comfort mismatches were more likely to occur in shared office environments. Variations in metabolic rate, clothing insulation, seating position, and local airflow can lead to divergent thermal sensations among occupants. However, commonly used population-based models assuming whole-body near-thermal neutrality, such as Fanger's PMV model, rely on averaged assumptions that cannot fully capture this intra-room heterogeneity. Finally, mismatches involving air pressure indices appeared to be dominated by individual perception rather than by systematic measurement discrepancies. Due to the subjective nature of pressure-related comfort and the limited empirical evidence linking moderate indoor pressure variations to consistent subjective effects, these reports are likely based on personal experience rather than objectively measurable environmental differences.

In summary, these findings highlight that discrepancies between model-based indices and perceived comfort primarily stem from environmental variability and the limitations of non-personalized comfort models when applied to individuals with diverse perceptual responses. These limitations are further shaped by the computational and sensing constraints of embedded systems. Such systems cannot support computationally intensive or data-driven comfort models. Additionally, the available sensors are limited, so only simplified, population-based thermal comfort models can be implemented. While cloud-based approaches could theoretically enable more complex modeling by offloading computation to external servers, they require stable, low-latency connectivity and depend on network availability and data transmission reliability.

The questionnaire results indicate that, although the content of the feedback was generally accepted, participants had different preferences regarding the presentation style. In particular, the gamified GUI appeared motivating to some users but distracting or inappropriate to others. This suggests that interface design plays a critical role in user acceptance beyond informational content alone.

Although the difference-score analysis did not yield statistically significant intervention effects, possibly due to the limited sample size, the descriptive self-report results offer useful insights. On average, participants reported ventilating slightly more frequently and for longer periods during the study. This increase was observed across both conditions and was not attributable to the intervention. This pattern indicates that merely introducing an IEQ monitoring device may have increased occupants' awareness of indoor conditions, prompting more active ventilation. These short-term behavioral adjustments align with the Hawthorne effect [69], whereby behavior temporarily changes in response to being monitored. Whether this increased awareness will persist and lead to lasting behavioral change remains an open question.

Beyond the observed behavioral responses, qualitative feedback highlights the potential of the gamified interface. Several participants described the gamification elements as engaging and motivating. This implies that these elements could sustain user interest beyond the initial novelty phase, a common challenge in behavioral interventions. Therefore, gamification could support long-term user adherence and reinforce positive behaviors.

Interestingly, air temperature was significantly higher in the intervention group, accompanied by a corresponding decrease in relative humidity. However, the self-reported heating and cooling behavior remained unchanged. This pattern may partly reflect natural fluctuations in outdoor weather conditions during the field study period. It is notable that CO₂ concentrations were highly similar between the intervention and control groups, indicating that the overall amount of air exchange during working hours was comparable. Given these findings,

it is possible that the intervention group retained more indoor heat while achieving the same level of CO₂ removal.

One plausible explanation is a change in ventilation strategy. Participants in the intervention group may have followed the system's recommendation to perform short, intensive ventilation (see Table 11 in Appendix, Item 3.7: "It's better to fully open a window briefly than to tilt it long! It is more energy efficient!"). This strategy would provide adequate air exchange while minimizing heat loss, consistent with the observed pattern of similar CO₂ concentrations and higher indoor temperatures. However, since the window position (tilted or fully opened) was not directly measured, this interpretation remains hypothetical. Future studies that incorporate window-state sensors are needed to determine whether the feedback interface encouraged more energy-efficient ventilation behavior.

The remaining sensor variables did not exhibit statistically significant intervention effects. Nevertheless, illuminance showed a notably larger effect size than the other non-significant metrics. This pattern likely reflects substantial differences in individual lighting preferences. Some participants preferred brightly illuminated workspaces, while others preferred dimmer environments.

4.3. Limitations

The field study was conducted with a limited number of participants and is therefore intended as a pilot study aimed at a preliminary validation of the proposed monitoring and gamification approach. Accordingly, the findings should be interpreted as exploratory rather than confirmatory, and no strong causal conclusions regarding behavioral change can be drawn. Larger-scale, longer-term studies are required to robustly assess intervention effects and improve the generalizability of the results.

In addition, the thermal comfort assessment relied on a fixed clothing insulation value of 0.7 clo, corresponding to a typical office outfit (underwear, shirt, pants, socks, shoes). This simplification was adopted to establish a consistent baseline for field deployment in naturally ventilated educational and office environments, where occupants often adapt their clothing and wear relatively light outfits even during colder seasons in heated indoor spaces. Using higher default clothing insulation values was therefore avoided to reduce systematic bias toward warmer thermal sensation estimates and frequent overheating indications during warmer periods.

Seasonal and individual variations in clothing insulation were not modeled explicitly, as clothing levels were neither monitored nor surveyed during the field study. User-adjustable clothing inputs were also intentionally omitted to keep the prototype interface simple and to avoid increasing cognitive load. Supporting adaptive or user-defined clothing insulation settings while maintaining usability represents an important direction for future system development.

Furthermore, the default weighting factors k_i used to combine individual IEQ domains into the overall IEQI were defined based on qualitative design considerations and prior literature. A systematic sensitivity analysis or optimization of these weights, potentially accounting for individual preferences or contextual factors, was beyond the scope of this study and may constitute a relevant topic for future research.

The short questionnaire SQ2, administered every two hours during the field study, captured participants' momentary subjective perceptions of IEQ. While these data were originally intended to explore potential discrepancies between model-based comfort indices (e.g., PMV) and reported sensations, a detailed quantitative analysis was not included due to the limited sample size and the primary focus on system development, usability, and behavioral responses.

Finally, because the intervention varied only in whether participants could view the GUI, the field study could not identify the most influential gamification elements. Future studies should disentangle components such as feedback content and reward mechanics to determine which

features most effectively sustain engagement and promote behavioral change.

5. Conclusion

In this study, we developed the *Resource Guardian*, an open-source, modular IEQ monitoring system featuring a gamified GUI. Combining low-cost, microcontroller-based hardware with a configurable feedback mechanism, the system was deployed in three small-scale field studies using prototype devices to assess usability and in-situ behavioral responses.

Overall, participants rated the system as highly usable, especially in the two sub-studies involving younger and more digitally experienced users. The field studies also revealed nuanced relationships between model-based comfort indices, subjective evaluations, and measured environmental conditions. Although the difference-score analyses did not show statistically significant intervention effects on self-reported user behaviors, the descriptive findings indicate that the presence of the IEQ monitoring device increased participants' awareness of their IEQ and may have encouraged more deliberate ventilation practices. Sensor data further implied the possibility of adopting more energy-efficient ventilation strategies. Taken together, these observations highlight both the potential and the limitations of gamified feedback mechanisms for influencing IEQ-related user behavior.

Future research can advance in two directions. First, larger samples and richer sensing modalities, such as monitoring window state and electricity device usage, are needed to examine the long-term effects of gamified IEQ feedback on user behavior and energy use. While large-scale field deployments are time- and resource-intensive, this challenge could be mitigated by leveraging the system's low-cost, modular hardware design, which enables scalable replication, as well as by integrating additional low-cost sensors (e.g., window-state sensors or smart plugs) to capture behavior-related events with minimal installation effort. Beyond increasing sample sizes within a single deployment, the scalability challenge can also be addressed at the community level. By open-sourcing the complete hardware design, firmware, and software stack, and by providing detailed DIY guidelines, the proposed system enables reproduction of identical or functionally comparable setups. This facilitates coordinated or independent field studies across sites and institutions, thereby supporting the accumulation of larger and more diverse datasets without requiring centralized large-scale deployments.

Second, personalized comfort modeling is another promising research direction. While the current system relies on population-based models such as Fanger's PMV model, future iterations could use the reserved RFID interface for user identification and individualized comfort assessment. This could also help design more personalized recommendations and feedback. Realizing such comfort models will require additional sensing inputs and careful consideration of computational feasibility on resource-constrained microcontroller platforms. To address computational and hardware constraints on resource-limited platforms, personalized comfort models should be designed with deployability and offline operation in mind. Rather than relying on continuous server-side computation, personalization could be achieved through lightweight or hybrid approaches, such as rule-based adaptations or simple data-driven models that operate directly on the device. For more demanding modeling tasks, the modular system architecture also allows migration to more capable embedded platforms (e.g., single-board computers) without altering the sensing or interaction logic. Such strategies enable individualized comfort modeling while preserving the system's low-cost, scalable, and site-independent deployment characteristics.

This work aims to facilitate further experimentation and extension of the gamified IEQ monitoring system in research and practice by open-sourcing the hardware design, as well as the software and firmware code.

CCRediT authorship contribution statement

Qirui Huang: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Marc Syndicus:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Funding acquisition. **Dono Jamoliddinova:** Investigation. **Jérôme Frisch:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Christoph van Treeck:** Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interests

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.

Acknowledgements

The project *Resource Guardian* (“Ressourcenwächter”) was funded by RWTH Aachen University's Sustainability Fund (Ref. 02-2023-004). We are grateful for the support.

We also thank the creators of their open-source and freely available graphical assets used in the GUI:

- ArksDigital for the Dino Characters Sprites (Version 1.1), available at <https://arks.itch.io/dino-characters>.
- DemChing for the Dino Family asset pack (Version 1.5.0, CC BY 4.0), available at <https://demching.itch.io/dino-family>.
- fliflily for the Hearts asset (CCO), available at <https://fliflily.itch.io/hearts-and-health-bar>.
- Cup Nooble for the Sprout Lands - Basic Sprite Pack, available at <https://cupnooble.itch.io/sprout-lands-asset-pack>.

These third-party graphical assets were used to support the graphic design of our system.

Appendix A

The equations for TCI, SCI, LCI, PCI, and IAQI are shown in Eqs. (8)–(13). The technical specifications of the reference sensors are listed in Table 7. The metadata, including room orientation, dimensions, etc., for all rooms in the field study are detailed in Table 8. The structure of the feedback system is shown in Fig. 13, with all feedback content (English version) listed in Tables 9–11. The self-reported behavior questionnaire items in SQ4 are listed in Table 12.

$$TCI = 3 - |PMV| \quad (8)$$

The default parameters used in calculating the PMV index are as follows:

- Air temperature: Measured by sensor BME280, if available, or TCI is equal to 0.
- Mean radiant temperature: Measured by sensor DS18B20, if available, or equal to air temperature.
- Relative air humidity: Measured by sensor BME280, if available, or TCI is equal to 0.
- Air speed: Measured by Wind Sensor Rev. C, if available, or equal to 0 m/s.
- Clothing insulation: 0.7 clo for “underwear, shirt, pants, socks, shoes”.
- Metabolic rate: 1.2 met for “sitting activity (office, apartment, school, laboratory)”.

Table 7
Technical specifications of the reference sensors (Ahlborn ALMEMO® system).

Sensor	Parameter	Precision
Digital sensor FHAD46C41A	Air temperature [°C] Relative humidity [%] Air pressure [hPa]	typ. ± 0.2 K & max. ± 0.4 K ± 3.0% RH ± 2.5 mbar at 23 °C ± 5 K
Globe thermometer FPA805GTS	Wet-bulb globe temperature [°C]	± (0.3 + 0.005 · t) K
Lux sensor FLA613-VL	Illuminance [lx]	± 5%
CO ₂ sensor FYAD00CO2M3B05	CO ₂ concentration [ppm]	± (50 ppm + 3%)
Sound level meter MA86193	Sound level [dB(A)]	± 2.0 dB at 1000 Hz 94 dB
Thermoanemometer (omnidirectional) FVAD05TOK300	Wind speed [m/s]	± (3% of measured value + 1% of final value + 2 digits)

Table 8
The metadata about all the rooms in the field study.

Study	Room	Room Type	Floor ¹	Room Orientation	Dimensions			Number of Participants
					Length	Width	Height	
Study 1	Room 1	Two-person office	2 of 3	Northwest	4.72 m	3.86 m	2.72 m	1 ²
	Room 2	Two-person office	2 of 3	Northwest	4.72 m	3.86 m	2.73 m	1
	Room 3	Two-person office	2 of 3	Northwest	4.71 m	3.90 m	2.72 m	1
	Room 4	Two-person office	2 of 3	Southeast	4.71 m	3.86 m	2.73 m	2
	Room 5	Two-person office	2 of 3	Southeast	4.72 m	4.02 m	2.73 m	2
Study 2	Room 1	Single-person office	2 of 4	Southeast	5.47 m	2.97 m	2.27 m	1
	Room 2	Four-person office	2 of 4	Southeast	4.38 m	4.47 m	2.33 m	4
	Room 3	Four-person office	3 of 4	Southeast	4.60 m	4.47 m	2.32 m	1
Study 3	Room 1	Two-person office	6 of 7	Northwest	6.46 m	3.05 m	2.82 m	1
	Room 2	Single-person office	6 of 7	Northwest	6.43 m	3.05 m	2.83 m	1
	Room 3	Two-person office	6 of 7	Northwest	6.46 m	3.05 m	2.86 m	1

¹ The ground floor is labeled as Floor 1.

² Reference participant.

Table 9
English version of the feedback system messages used in the field study for category 1: general information. The ID corresponds to the ID in the system architecture shown in Fig. 13. Each feedback message consists of three lines of text, with no more than 50 characters per line.

ID	Text
Category 1: General information	
1.1	I saw so many sensors. Also a lot of letters like BME, SCD. Have you heard these before?
1.2	The energy around me is gathering towards me. I feel stronger, and the island also different. ROAARRRR!!!!!!!
1.3	I've heard that everything happens is recorded. Can you delete all the pictures of me? I don't like paparazzi!!!
1.4	I found a button somewhere on the island. After pressing it, I fell asleep. It's amazing, isn't it? Can you find it?
1.5	Did you know? I only need 1.2-2 Watts of power to help you save energy! What a good invest...
1.6	The university participates in climate actions! I can help you to save energy thanks to RWTH's Sustainability Fund
1.7	How realistic are the saving tips I give? A detailed description can be found at https://rw.e3d.rwth-aachen.de/
1.8	What can I do to improve my work? Please take part in our survey, so that I can improve for the future. Thanks!
1.9	Should I cause any problems or malfunction, please contact my creator at ressourcenwaechter@e3d.rwth-aachen.de
1.10	Should you feel annoyed by me, activate the sleep mode. But do not forget to reactivate me again.
1.11	Before I go to sleep, please don't forget to check the standby devices and windows and turn down the thermostat.

$$SCI = \begin{cases} 3.0 - |x| \cdot \frac{3.0-2.8}{x_{1,max}} & \text{when } x < x_{1,max} \\ 2.8 - |x - x_{1,max}| \cdot \frac{2.8-2.3}{x_{2,max}-x_{1,max}} & \text{when } x_{1,max} \leq x < x_{2,max} \\ 2.3 - |x - x_{2,max}| \cdot \frac{2.3-1.0}{x_{3,max}-x_{2,max}} & \text{when } x_{2,max} \leq x < x_{3,max} \\ 0 & \text{when } x \geq x_{3,max} \end{cases} \quad (9)$$

Where:

- x : Measurement value in A-weighted decibels (dB(A)).
- $x_{1,max}$: Maximum threshold of the zone “very good/very comfortable”. Default: 30 dB(A).
- $x_{2,max}$: Maximum threshold of the zone “good/comfortable”. Default: 55 dB(A).

- $x_{3,max}$: Maximum threshold of the zone “bad/uncomfortable”. Default: 80 dB(A).

$$LCI = \begin{cases} 0 & \text{when } x < x_{3,min} \\ 2.3 - |x - x_{2,min}| \cdot \frac{2.3-1.0}{x_{2,min}-x_{3,min}} & \text{when } x_{3,min} \leq x < x_{2,min} \\ 2.8 - |x - x_{1,min}| \cdot \frac{2.8-2.3}{x_{1,min}-x_{2,min}} & \text{when } x_{2,min} \leq x < x_{1,min} \\ 3 & \text{when } x \geq x_{1,min} \end{cases} \quad (10)$$

Where:

- x : Measurement value in lux (lx).
- $x_{1,min}$: Minimum threshold of the zone “very good/very comfortable”. Default: 750 lx.
- $x_{2,min}$: Minimum threshold of the zone “good/comfortable”. Default: 300 lx.

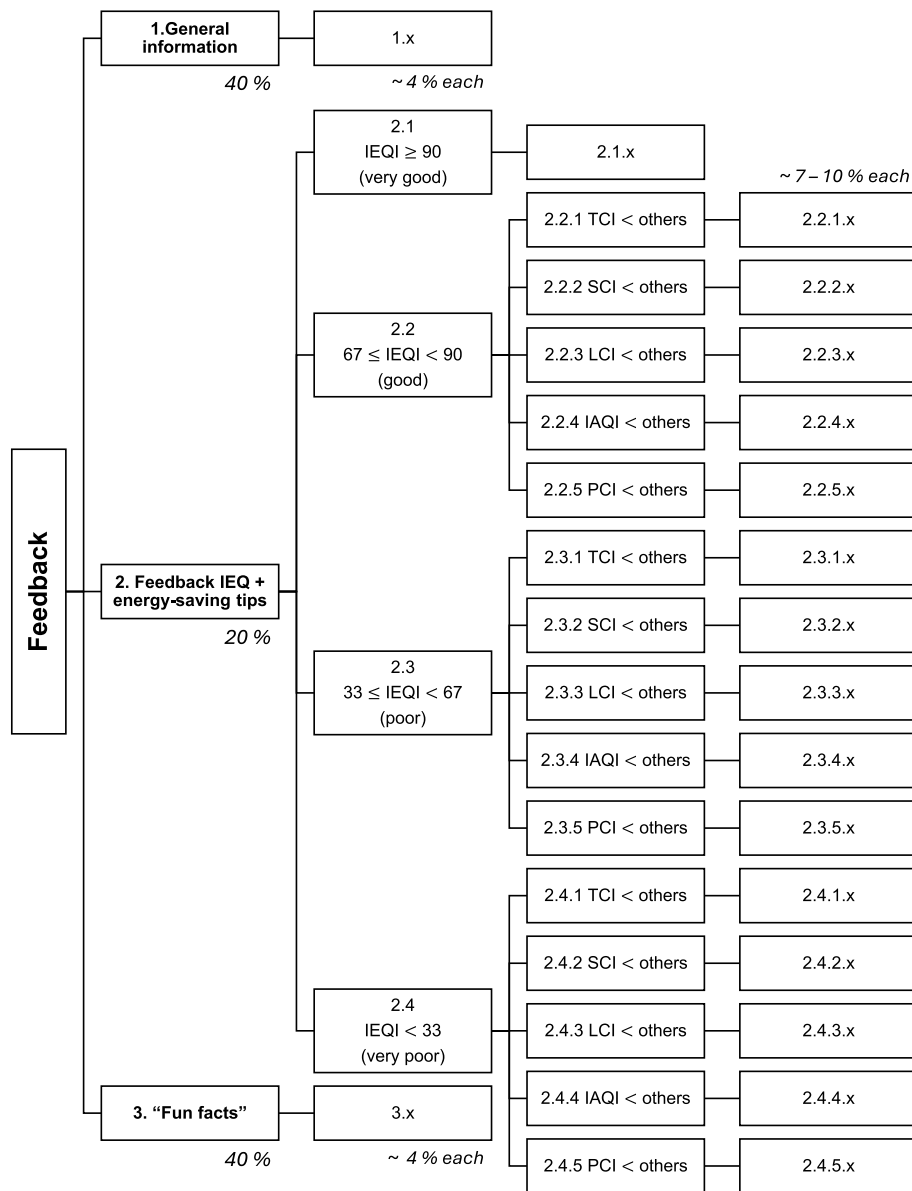


Fig. 13. Event-based feedback system with probability-based random message selection, where the selection probabilities are indicated by the percentage values shown in the diagram.

Table 10

English version of the feedback system messages used in the field study for category 2: feedback based on IEQ and energy-saving tips. The ID corresponds to the ID in the system architecture shown in Fig. 13. Each feedback message consists of three lines of text, with no more than 50 characters per line.

ID	Text
Category 2: Feedback based on IEQ and energy-saving tips	
2.1.1	The indoor environment here is fantastic! Remember to unplug any devices not in use. It saves a lot of energy!
2.1.2	How are you? The environmental conditions are great, I hope that facilitates your work!
2.2.1.1	Feeling a little cool? Fun fact: Your perception can also be influenced by the weather outside.
2.2.1.2	If you feel slightly cold, get up and move around a bit. This also helps against tiredness!
2.2.1.3	You should have heard this before: A breeze cools you down. Open the window and take a deep breath!
2.2.1.4	Do you feel a little warm? Electrical devices can produce a lot of heat. Remember to unplug all unused devices.
2.2.2.1	Is someone on the phone? Would you like to go for a coffee with me and also for some fresh air?
2.2.2.2	Is there some device that's buzzing? Remember to turn off the equipment you don't use. Let's save our earth, starting with energy saving!
2.2.3.1	If you want to read, don't forget to turn the light on brighter. It's good for your eyes.
2.2.3.2	I love bright, sunny places. Good light also allows the plants on the island to thrive magnificently!
2.2.4.1	Is someone smoking? Did you know smoking is a major source of VOCs? Such as formaldehyde, naphthalene, PAHs, etc.
2.2.4.2	May you open the window for me? I'd love a breeze! It should be fresh outside.
2.2.5	The air pressure is fluctuating a little. Will that bring a change in the weather? I'm curious!
2.3.1.1	It's chilly here. My hands are cold. Wait, where are my hands?
2.3.1.2	It's chilly here. My feet are already cold. Eh?! Why have my hands disappeared?
2.3.1.3	It's warm here. I feel a bit sweaty. Have you seen my fan?
2.3.1.4	I'm overdressed today. My back's a little sweaty. Can you let in some fresh, cold air?
2.3.2.1	It's a bit noisy right now. Take a little break, or move to a quieter room!
2.3.2.2	It's a bit noisy here at the moment. That can disrupt your focus. Take a short break!
2.3.3.1	The lighting is poor. This can strain your eyes. Get more light for better vision!
2.3.3.2	The lighting is a bit poor. I look like a shadow! Get more light, otherwise I won't find anything!
2.3.4.1	The air is stuffy. This can make you tired. Open the window for fresh air!
2.3.4.2	The air is a little stale. This can be unpleasant. Ventilate the room for fresh air!
2.3.5	The air pressure is fluctuating. Is it about to rain? I'm curious!
2.4.1.1	It's too cold, you might get a cold. Please adjust the thermostat immediately, and if possible, put warm clothes on.
2.4.1.2	Brrr, it's really cold here! It can be very unpleasant. Dress warmly and turn on the heating!
2.4.1.3	Attention: The temperature is too high. Please open the windows immediately to cool down the air.
2.4.1.4	Uff, it's pretty warm in here! Drink some water and ventilate the room. This will refresh the air and you too!
2.4.2.1	Aww! It is too noisy. If possible, close the window or try to locate the source of the noise and to reduce it.
2.4.2.2	Aww! It's too noisy. If possible, switch off the noise source or change the room. Noise-canceling headphones can also help.
2.4.3.1	Aww! It's too dark here. I can't read the words well. My eyes are tired...
2.4.3.2	Aww! The lighting is really poor. That makes it difficult to see. Get more light for better visibility!
2.4.4.1	Cough! Could you please open the window? Apparently, it hasn't been aired for a long time. That's good for the health!
2.4.4.2	Cough! The air is not good. It feels unpleasant. Ventilate quickly for fresh air!
2.4.5	The air pressure is very high/low. In case you perceive dizziness/nausea, take a break and consult a doctor in case the feeling lasts.

Table 11

English version of the feedback system messages used in the field study for category 3: "fun facts" related to IEQ, sustainability, and energy-saving. The ID corresponds to the ID in the system architecture shown in Fig. 13. Each feedback message consists of three lines of text, with no more than 50 characters per line.

ID	Text
Category 3: "Fun facts" related to IEQ, sustainability, and energy-saving	
3.1	You can save Energy elsewhere as well: Dishwashers often run longer in ECO mode, but use less energy.
3.2	Every little bit helps: Mobile phones, laptops and many other consumer devices have an ECO mode – check it out!
3.3	Should you need a new office device, please also check the EU energy label. If possible, choose category A+ ;)
3.4	To make sure you are well during the day, remember to stay hydrated Glouglou...Glouglou...Glouglou...
3.5	Guess what? New buildings could use 5 times less energy than old buildings. (Source: BMWK)
3.6	If you're using mechanical ventilation: Remember to change filters regularly to keep them working efficiently.
3.7	It's better to fully open a window briefly than to tilt it long! It is more energy efficient!
3.8	Guess what? The use of local air-conditioning systems could save up to 4 million tCO ₂ eq/a.
3.9	Don't forget to clean regularly! This will help you avoid dust and allergens. Look at my clean island!
3.10	Have you heard of local air-conditioning systems? They let you control the climate individually, which makes it more comfortable and efficient.
3.11	I found some interesting statistics within Germany. 28% of German citizens feel annoyed by noise (destatis.de). 20% of dwellings have moisture issues (verbraucherzentrale.nrw).
3.12	Home office share increased from 10% (2019) to 24%. Large companies: 32% home office, small only 21%. IT industry: front runner with approx. 75%, Wow!
3.13	If 1/4 of the employees in Germany work 1 day a week from home, it could save as much CO ₂ as 17k + flights FFM–NYC!
3.14	It is important, even when working from home, that you get enough physical activity. Why not get up and move around a little?

Table 12
Self-reported behavior questionnaire items in SQ4.

Question	Response options
Please select the option that best describes how often you use the following wiki pages of Ressourcenwächter	I didn't know there was a wiki I knew there was a wiki but I didn't open it I've read some of the content I've read most of the content I've read all of the content Other: ...
Please rate the truthfulness of each statement below: I find the feedback content useful I find the automatic feedback annoying I find the automatic feedback distracting I would like more content in each feedback I don't like the whole feedback system I find the gamified interface distracting Rather than a gamified interface, I prefer a simple display of sensor data I find the gamified interface helps to increase my interest in using it I find the user interface childish Ressourcenwächter prevented me from concentrating on work or studying	1: Strongly Disagree ... 7: Strongly Agree
On average, since using Ressourcenwächter... ¹ How has the power level of your heating system changed? How has your heating duration changed? How has the power level of your cooling system changed? How has your cooling duration changed? How has your ventilation frequency changed? How has the duration of each of your ventilations changed?	1: Significantly decreased ... 5: Significantly increased

¹ Participants could additionally select “I don't know/I can't remember”.

- $x_{3,\min}$: Minimum threshold of the zone “bad/uncomfortable”. Default: 100 lx.

$$PCI = \begin{cases} 3.0 - \frac{|x - \frac{x_{1,\max} + x_{1,\min}}{2}| \cdot 2}{x_{1,\max} - x_{1,\min}} & \text{when } x_{1,\min} \leq x < x_{1,\max} \\ 2.8 - |x - x_{1,\min}| \cdot \frac{2.8 - 2.3}{x_{1,\min} - x_{2,\min}} & \text{when } x_{2,\min} \leq x < x_{1,\min} \\ 2.8 - |x - x_{1,\max}| \cdot \frac{2.8 - 2.3}{x_{2,\max} - x_{1,\max}} & \text{when } x_{1,\max} \leq x < x_{2,\max} \\ 2.3 - |x - x_{2,\min}| \cdot \frac{2.3 - 1.0}{x_{2,\min} - x_{3,\min}} & \text{when } x_{3,\min} \leq x < x_{2,\min} \\ 2.3 - |x - x_{2,\max}| \cdot \frac{2.3 - 1.0}{x_{3,\max} - x_{2,\max}} & \text{when } x_{2,\max} \leq x < x_{3,\max} \\ 0 & \text{when } x < x_{3,\min} \\ & \text{or } x \geq x_{3,\max} \end{cases} \quad (11)$$

Where:

- x : Measurement value in hectopascal (hPa).
- $x_{1,\min}$: Minimum threshold of the zone “very good/very comfortable”. Default: 950 hPa (ca. 500 meters above sea level).
- $x_{2,\min}$: Minimum threshold of the zone “good/comfortable”. Default: 900 hPa (ca. 900 meters above sea level).
- $x_{3,\min}$: Minimum threshold of the zone “bad/uncomfortable”. Default: 800 hPa (ca. 1700 meters above sea level).
- $x_{1,\max}$: Maximum threshold of the zone “very good/very comfortable”. Default: 1050 hPa.
- $x_{2,\max}$: Maximum threshold of the zone “good/comfortable”. Default: 1100 hPa¹.
- $x_{3,\max}$: Maximum threshold of the zone “bad/uncomfortable”. Default: 1200 hPa¹.

¹Note: The highest air pressure ever recorded on Earth is approximately 1090 hPa [70]. Pressures above this level have not been observed in natural atmospheric conditions and would require artificially pressurized

environments such as climate chambers.

$$IAQI = \frac{1}{n} \sum_{i=1}^n IAQI_i \quad (12)$$

$$IAQI_i = \begin{cases} 3.0 - |x| \cdot \frac{3.0 - 2.8}{x_{1,\max}} & \text{when } x < x_{1,\max} \\ 2.8 - |x - x_{1,\max}| \cdot \frac{2.8 - 2.3}{x_{2,\max} - x_{1,\max}} & \text{when } x_{1,\max} \leq x < x_{2,\max} \\ 2.3 - |x - x_{2,\max}| \cdot \frac{2.3 - 1.0}{x_{3,\max} - x_{2,\max}} & \text{when } x_{2,\max} \leq x < x_{3,\max} \\ 0 & \text{when } x \geq x_{3,\max} \end{cases} \quad (13)$$

Where:

- x : Measurement value in ppm for CO₂ and between 0 and 500 for the VOC index.
- $x_{1,\max}$: Maximum threshold of the zone “very good/very comfortable”. Default: 950 ppm for CO₂ and 80 for the VOC index.
- $x_{2,\max}$: Maximum threshold of the zone “good/comfortable”. Default: 1200 ppm for CO₂ and 120 for the VOC index.
- $x_{3,\max}$: Maximum threshold of the zone “bad/uncomfortable”. Default: 1750 ppm for CO₂ and 200 for the VOC index.

Data availability

Data will be made available on request.

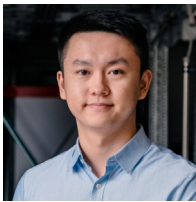
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