Building and Environment 189 (2021) 107535

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Design and in-field testing of a multi-level system for continuous subjective occupant feedback on indoor climate

Niels Lassen [a,b,*], Terje Josefsen [b], Francesco Goia [a]

[a] Department of Architecture and Technology, Norwegian University of Science and Technology, Trondheim, Norway
[b] Skanska Norge AS, Oslo, Norway

ARTICLE INFO

Keywords:
Occupant satisfaction voting systems
Polling station
Subjective feedback
Thermal comfort
Field tests

ABSTRACT

Information gaps between the building and the occupant often lead to sub-optimal building performance, impairing the efforts towards more sustainable buildings. New information and communication technology creates new possibilities to reduce this gap, enhancing the interaction between occupants and their environments while providing operational usage data. Continuous subjective feedback from occupants can be used directly to improve building operation and tuning, but may also inform building design and research applications. In this study, we perform a literature study of existing systems for continuous subjective occupant feedback (CSOF) regarding indoor climate. Based on our findings we design a multi-level CSOF system which gathers occupant feedback regarding complaints, control actions and satisfaction evaluations. We qualitatively evaluate the systems in field tests in three buildings with a total of 63 un-informed occupants for a total of 167 days, and identify a series of "practical" lessons learned. Occupant opinions were collected through regular surveys and a final focus group interview. Deliberate temperature interventions were performed in two of the buildings. The experiments collected a total of 56 complaints, 133 control actions via smartphone, 1344 control actions via manual control and 311 satisfaction evaluations. The occupants provided useful data to the system through their daily interaction with it. They expressed satisfaction with the increased level of interaction and control they were offered through the system and showed a preference for solutions that give an immediate feedback to their actions and have a simple and intuitive interface.

1. Introduction

An information gap exists between buildings and occupants, often leading to sub-optimal design and performance [1]. Designer's perspectives on subjects like indoor climate and architecture often diverge from the occupants' expectations. This is reflected in a large performance gap between design (simulated) and actual (measured) performance [2–5]. Occupant interactions with building systems are often discouraged, as the building operators seek to avoid disturbance of the settings in the finely tuned systems [6]. However, a growing body of literature shows that this strategy often leads to the opposite effect: occupant tolerance for discomfort is significantly reduced as occupant control possibilities are removed [7–9] and occupants' interaction with the building operation positively affects their satisfaction [6,10–14]. It is suggested that people are not passive receivers of sensations and perceptions, but active and dynamic participants in a system for maintaining equilibrium of the environment [15]. Comfort expectations and the availability and constraints of effective control measures are clearly important in this context [16], although they are normally under estimated in building design. Modern information and communication technology (ICT) solutions now make it possible to directly ask the occupants about their preferences and satisfaction with the indoor environment, hence bringing the occupant into the loop and closing the gap between building and occupant. They separate from traditional Post Occupancy Evaluations (POE), who are point-in-time measurements, in that they are continuous in time and can capture occupant opinions or reactions at any given time, at a low cost. Continuous subjective feedback from occupants can be used directly to improve building operation and tuning, but may also inform building design and research applications. Knowing better how the user perceives the indoor environment can impact how we design and how we operate our buildings.

In this paper, we present the outcomes of a study aimed at designing and testing in the field a cheap, simple, and non-intrusive system for subjective feedback and occupant control of the indoor climate.

While a complete research project should involve both the

* Corresponding author. Norwegian University of Science and Technology, Trondheim, Norway.
E-mail address: niels.lassen@skanska.no (N. Lassen).

https://doi.org/10.1016/j.buildenv.2020.107535
Received 30 August 2020; Received in revised form 27 October 2020; Accepted 15 December 2020
Available online 17 December 2020

List of acronyms

API	Application Programming Interface
BAS	Building Automation System
BREEAM	Building Research Establishment Environmental Assessment Method
CSOF	Continuous Subjective Occupant Feedback
FM	Facility Management
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communications Technology
IEQ	Indoor Environmental Quality
IoT	Internet of Things
OCC	Occupant Centric Control
OVS	Occupant Voting Systems
QR	Quick Response (code)
SPS	Satisfaction Polling Station
SQL	|Structured Query Language

qualitative and quantitative assessment of the system, the focus of this paper is placed on the qualitative analysis, its usability and occupant acceptance, due to the relevance of these aspects and the limits set for a single research paper. Quantitative analysis will be presented in a separate article combining data from tests in a larger number of buildings. The research questions addressed in this article are:

1) What limitations exist in the current research panorama for continuous subjective data collection from occupants regarding indoor climate?
2) What are the key features for a low-cost, non-intrusive system?
3) What is the response of occupants to a system when tested in real buildings, in terms of interest, usage, and feedback?

2. Overview of research methodology

The methodological approach to the research has been broken down in a series of steps that are described by the following objectives: i) to gather the current know-how from previous research on subjective feedback systems regarding indoor climate; ii) to develop a possible design for a low cost and non-intrusive system for multi-level occupant feedback; iii) to test the performance of the feedback system and the interaction with the occupants, and iv) to derive "practical" lessons learned about the use and development of simple systems for occupant-building communication. Methods used are closer described in each section. Answers to objective i) are found in Section 3 where a brief literature study of existing systems for CSOF is presented and discussed. Objective ii) is presented in Section 4 where we describe the design af a low-cost multi-level CSOF system. Objective iii) is in Section 5 where we present methodology and results from testing the system in field., Objective iii) is presented in Section 6 where we sum up the lessons learned from the research.

3. Research panorama

New technologies such as cloud computing, pervasive Internet of Things (IoT), and sensor technology have brought the possibility of better recording occupant's satisfaction and interaction with the built environment. Several approaches already exist to exploit these new possibilities, and several reviews cover concepts that overlap what we in this study have chosen to call Continuous Subjective Occupant Feedback (CSOF). The emerging field of Occupant Centric Control (OCC), recently reviewed by Park et al. [17] refers to controlling building systems based on presence/absence data, data from the environment (e.g., illuminance, temperature, humidity, CO_2) in conjunction with human-building interactions (e.g., use of light switch, window, blind, or thermostat, etc.). Jung and Jazizadeh [18] reviewed Human-in-the-loop HVAC operations, referring to human interactions related to the dynamics of occupants in indoor environments (e.g., occupancy and thermal comfort). Most recently Khan et al. [19] presented a thorough review of Occupant Voting Systems (OVS) including a framework for characterization. OVS is in that case defined as 'a system using information and communication technology that occupants can use at any given time to provide "continuous" and real-time feedback on their perception of IEQ', and does not include information gathered from occupant control actions (behaviour-based occupant-centric control systems).

For the sake of the development of a continuous subjective occupant feedback system, we therefore performed a dedicated survey of the literature to identify current trends, experiences, and outcomes only focused on research activities where subjective feedback systems were used. The systems studied should collect continuous information from subjective actions from the occupants. They should be non-intrusive, meaning that occupants could choose when (or if at all) to submit information. Examples included in this literature study must also demonstrate original research performed with human subjects in the field or in laboratory experiments. Via searches in online scientific publication databases, using the so-called snowball sampling method, we selected and analysed studies which fell within the definition. Studies that we have developed ourselves in the last two years which therefore were affected by the current research panorama, were not included.

3.1. General characterization

The literature panorama shows twenty-three scientific articles covering the field, and a couple of commercial products are already available in this category [20]. A brief list of the studies covered is given in Table 1. The topic and nature of the articles is varied, and the relatively low number of studies, together with the recent publishing dates, shows that this field still is un-explored (first article is dated 2012) and there is still much to be discovered. The articles are evenly distributed between journal articles and conference articles, with most conference articles for the older studies. The articles are published within the fields of building science, mechanical engineering and computing, thus showing how the field is mostly covered by technical domains (both computing and building science), rather than the domains of environmental psychology or social sciences. A variety of approaches is also seen from a methodology point of view: in most of the studies the subjects are fully informed of the study objective, while 3 of the studies use uninformed subjects. Study group sizes vary significantly, from 1 to 4300.

3.2. Research focus and data collection strategies

Different research goals are seen in the reviewed studies. Some studies focus on the data collection method itself, others have a control-oriented approach focusing on the further use of occupant feedback. In general, the aims of the studies can be categorized as follows;

- "Study" - Test data collection method for control, learning or benchmarking
- "Model" - Test personal preference models utilizing subjective feedback
- "Direct control" - Test direct control algorithms utilizing subjective feedback

A few of the studies, such as [21,31,37,39] propose a system design and perform field tests, focusing on qualitative tests. In many studies, hypotheses are tested by comparing quantitative results of energy use, occupant satisfaction, or model predicting accuracy before and after the

Table 1
List and key information on selected studies investigating systems collections of for continuous subjective data.

Ref. No.	Interface type	Participants	Research focus
[21]	Common Polling station, Smiley face buttons [Polling station]	Uninformed visitors, Unknown number	Presents a method to conduct continuous longitudinal studies of IEQ and occupant comfort
[22]	Common LCD screen thermostat showing current room temperature. [Intelligent thermostat]	Informed, 7	Explores the means of making HVAC systems respond automatically to local occupant temperature preferences
[23]	Personal manual thermostat control [Personal Comfort System w/IOT]	Informed, 38	Explores use of feedback with a personal comfort system (PCS) to learn occupants' heating and cooling behaviour for the development of personal comfort models
[24]	Personal digital interface, widget and WebApp [Personal App/Feedback]	Uninformed, Approx. 4300	Tests a software tool that solicits thermal feedback from students, and analyses its impact on energy use and energy management procedures
[25]	Personal Smartphone App [Personal App/ Feedback]	Informed, 1 + 1 occupants	Tests a mobile application for thermal preference feedback for training personal models
[26]	Personal tablet with 3 different levels of automation [Intelligent thermostat]	Informed, 30 households	Occupant perspectives from testing smart thermostats that automate heating based on occupants' heating preferences and real-time price variations.
[27]	Personal Smartphone App [Participatory sensing]	Informed, 61	Proposes 5 application feedback types that use various methods of data presentation and environmental stimuli to promote specific behaviour. Occupant perspective.
[28]	Smartphone App [Participatory sensing]	Informed, 49	Energy savings potential is examined in context with occupant subjective feedback.
[29]	Website or personal smartphone app [Participatory sensing]	Informed, 60	Satisfaction and energy saving by implementation of a system that integrates building occupants' personalized thermal profiles into the HVAC control logic.
[30]	Touch screen, personal single office [Personal App/Feedback]	Informed, 6	Test a data-driven learning method to implement personal models with thermal complaint behaviour in a control system.
[31]	Mini interaction device registering preferences, mobile application for alternative interface [Personal App/ Feedback]	Informed, 12	Occupant responses from testing a system that allow occupants to report subjectively perceived comfort levels.
[32]	Smartphone App [Participatory sensing]	Informed, 4	Tests framework to integrate building occupants in the HVAC control loop and control the HVAC system based on personal comfort profiles
[33]	Personal Smartphone App/web interface [Participatory sensing]	Partially uninformed, 12	Tests satisfaction and energy use with system that captures occupant's favourite temperature non-intrusively and optimizes the set-point temperature with a model
[34]	Personal Smartphone App [Participatory sensing]	Informed, 20	Tests satisfaction and energy use framework to integrate building occupants in the HVAC control loop and controls the system directly
[35]	Personal Smartphone App [Participatory sensing]	Informed, 4	Tests satisfaction and energy use with framework to integrate building occupants in the HVAC control loop and controls the system based on personal comfort profiles
[36]	Personal WebApp [Participatory sensing]	Informed 65	Tests energy use with an embedded sensing and information management architecture that provides for effective participation by the building occupants.
[37]	Personal Polling station at desk [Polling station]	Informed, 44	Tests occupant usage of a personal polling station with embedded sensors
[38]	Personal Smartphone App [Participatory sensing]	Informed, 39	Tests satisfaction and energy use with system for participatory voting. Demonstrate a learned and real-time method of utilizing occupant data.
[39]	Personal Smartphone App [Participatory sensing]	Informed, 60	Tests communication platform, which enables occupants to communicate preferences to building control system.
[40]	Personal Smartphone App [Personal App/ Feedback]	Informed, 616	Demonstrates how occupants can be clustered into comfort personality types for prediction and recommendation systems
[41]	Personal Smartwatch App [Personal App/ Feedback]	Informed, 15	Demonstrates how large data sets of human feedback can be analysed to reveal building anomalies, occupant behaviour, occupant personality clustering, and general feedback related to the building
[42]	Personal Smartphone App [Personal App/ Feedback]	Informed, 25	Case study implementation of app for Activity Based Working (ABW) allocation platform demonstrating how occupants can be classified into specific types who can be matched.
[43]	Personal Smartphone App [Personal App/ Feedback]	Informed, 41	Discusses methodological aspects of the photograph-based smartphone post-occupancy evaluation for collecting qualitative results

feedback system is used. The systems have been categorized by the type of system, according to system types defined in Table 2.

Most of the studies involve smartphones as interfaces for collecting occupant feedback. By registering information through personal smartphones, the information may be linked to a personal ID tag, and in some cases additional questions regarding personal information, such as age and gender, may be asked of the user. Many of the studies [27–29,32,33,35,36,38,39,44] use the concept of "participatory sensing" for collection of preference votes. In some of the studies [24,25,30,31], this

Table 2
System types.

System types	Description
Participatory sensing	A Smartphone app or Web widget collects occupants' preferences by location. Occupants "vote" when they wish a change.
Personal App/Feedback	Occupants vote or specify their preferences, as on a virtual thermostat. Also used for a wider range of feedback, such as maintenance etc.
Intelligent thermostat	Analog or digital touch screen thermostats log and learn from occupant interactions to improve the control of the room temperature.
Polling station	Personal or communal device with quick questions/ surveys where occupants leave their answers when they wish.
Personal Comfort System w/IoT	Personal heating or cooling system that is controlled by the occupant. Usage data can be logged and transmitted in real-time.

feature is extended with a more general feedback-oriented approach, where users can use the smartphone to communicate with the building regarding other issues, such as reporting technical problems etc.

The use of personal devices is not the only way to collect occupant's feedback, and several of the studies make use of different solutions. Some use intelligent thermostats [22,26] that learn from occupants' interactions or, on a personal level, intelligent Personal Comfort Systems (PCS) [23] that register occupant interactions. Another approach is instead seen with the adoption of a polling station [21,37], i.e. a geographically stationary device where occupants can enter information freely or "vote". The polling stations are either centrally located and shared by occupants [21] as they pass by, or personal polling stations located at the work desk [37]. In more recent years the research on Participatory Sensing type interfaces appears to have decreased, and other methods such as polling stations and personal comfort systems with IoT have been studied more intensively. Only three of the studies provide the occupants with an immediate physical reaction after the feedback, as most of the systems either offer no direct control over the environment, or only control the ambient room temperature, which has a long response time.

3.3. Knowledge gap

The literature review shows that there exist some knowledge gaps for the field of continuous subjective occupant feedback that have not been fully addressed. Relatively few of the discovered studies focus on the data collection methods themselves, or on how the occupants receive them. On the contrary, many focus on how occupant feedback can perform for the benefit of building professionals and researchers. Further, few of the studies compare or question how one should best collect data. Nor do they tend to study the effect the feedback method has on the occupants. As far as we know, no studies have questioned the validity and nature of the collected data if compared to traditional survey methods, or to other feedback. It is clear the different types of continuous subjective occupant feedback (CSOF) methods will collect different types of data as there are variations in theme, sensitivity or threshold for responding, and differences in the psychological origin of different types of subjective feedback. Hence, CSOF systems will by their design target different data types, and it may be desirable to combine several designs to get a comprehensive set of occupant data. There is no established framework for differentiating or classifying the different types of subjective data on the occupant-side. Work should be done to clarify the links between human psychology and data collection methods (or system types) such as control actions and satisfaction evaluations.

4. Continuous subjective occupant feedback (CSOF) system design

4.1. Background

The knowledge available in the literature has been used to drive the design of a system targeting the collection of 3 types of subjective information regarding indoor climate from the occupants: *occupant complaints, occupant control actions*, and *occupant satisfaction evaluations*. We see the establishment of such a distinction and organization of subjective occupant feedback as a theoretical contribution to the research field, since current types of subjective data described did not allow a clear schematization of the differing nature of the collected information.

The system we designed coupled the acquisition of subjective information with physical measurements of the indoor climate (temperature, CO_2 concentration) to allow further analyses of the feedback system performance, although a quantitative assessment of such a performance is not presented in this paper.

The overarching goal of the system was to reduce the barrier between building and occupant, providing occupants with control and feedback possibilities while collecting valuable information about occupant preferences, perceptions, and satisfaction evaluations that can be correlated in time to other measured data. During the design phase, the system requirements were set to be non-intrusive, capable of collecting continuous "real-time" data, and to give a best possible representation of the subjective preferences and satisfaction levels of the occupants. It should also be possible to install the chosen solutions in existing buildings, only using low cost and commercially available technology.

Non-intrusive collection of occupant *control actions* and *complaints* proved to be possible, as these actions are driven by occupant needs or wishes (e.g. need for change or wish to inform about a problem).

Occupant *satisfaction evaluations* are however different in this sense, as occupants are not necessarily driven to perform or express them (e.g. if occupants are satisfied or oblivious to the question, they may not prioritize to submit feedback). For this type of subjective feedback, the concept of smiley-face polling stations was chosen. In recent years they have had a large success for satisfaction measurement in retail, hospitals and airports due to low cost, low customer intrusion and sufficient accuracy [21,45]. Because of their user-friendliness and ability to engage the occupants to provide feedback on their experience, these satisfaction polling stations (SPS) could also be considered as a tool for gathering votes about the indoor environmental quality of buildings. The main drawback of this method is the limited accuracy and transparency, as one has no control over who is voting and there is a risk of non- or multiple response biases. The cost estimate of Version 2 of the system is 140€ per workplace, or 12€/m^2 of office area. For comparison, modern high performance climatization systems for office buildings in Norway cost approximately 450–900€/m^2.

4.2. System characteristics

4.2.1. System overview and design

Two versions of the systems were developed during the research activity. Version 1 was designed in Mar–Nov 2018 and tested in Nov 2018 to Feb 2019, while Version 2 was created in Sep–Dec 2019 and tested in Jan–Mar 2020. The series of improvements made to Version 2 of the system were based on user comments, as well as results from surveys and focus interview and own experiences with Version 1 during the first tests. During the time between Version 1 and Version 2, system development and more focused tests on some levels of the system had taken place in four other buildings, as described in Ref. [46–48]. A graphical presentation of the two systems is shown in Fig. 1. The explicit reasons and design decisions for developing a Version 2 of the system are described in the following sections. Broadly speaking, the changes were made in an attempt to improve the usability and subsequently the

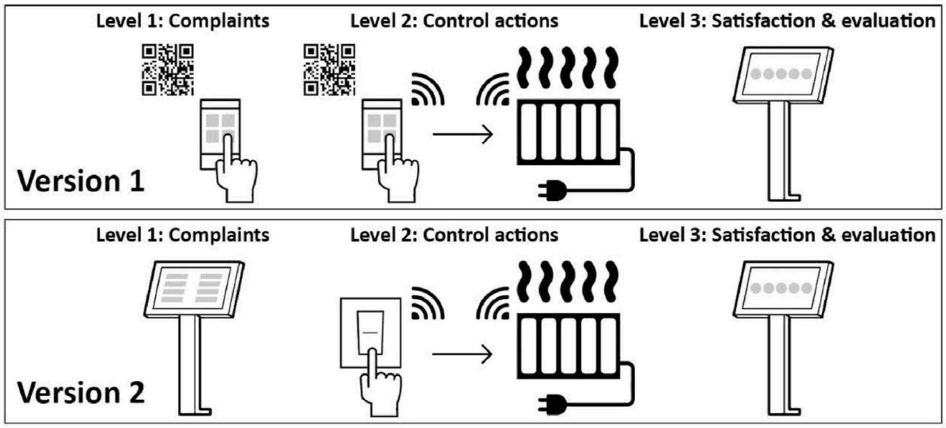

Fig. 1. General overview and illustration of multi-level feedback system in Version 1 and 2.

quantity of data collected by the system. It was clear that the changes also would reduce the detail level of some of the collected data. This was a conscious decision in line with the aim of the research.

4.2.2. System architecture

The entire feedback system was created with off-the-shelf products and simple programming techniques. All data from sensors and interfaces was transferred via internet protocol and designated Application Programming Interfaces (API) and stored in databases. Finally, data was collected in a freeware IoT platform where simple automation and visualization tasks could be performed. Data was also extracted from this database for further post-processing and study. The overall system architecture of the multi-level system is shown in Fig. 2. Levels are numbered (1) *Occupant complaints,* (2) *Control actions,* (3) *Satisfaction evaluations* and described in detail in the following sections. In Version 1, *control actions* and *complaints* were done through a smartphone complaint interface that was a mobile webpage, unique to each workplace, which occupants reached by scanning a QR code attached to the work desk. In Version 2, a simpler system was chosen where the QR-code and smartphone option were removed. Personal control of heaters was then done via a simple switch located on each office desk. SPS was made up of a simple interactive webpage that was displayed on a centrally placed tablet in kiosk mode. The occupant complaints could then be made on a second page on the SPS. The heater control in Version 2 was not registered directly in the database, but heater use was detected through mounting a temperature sensor on each heater as this solution was found to be a better trade-off in terms of accuracy vs. costs.

4.2.3. Level 1: Occupant complaints

4.2.3.1. Version 1: QR codes and smartphone interface. A solution based on a web page tailored for smartphones was used in combination with

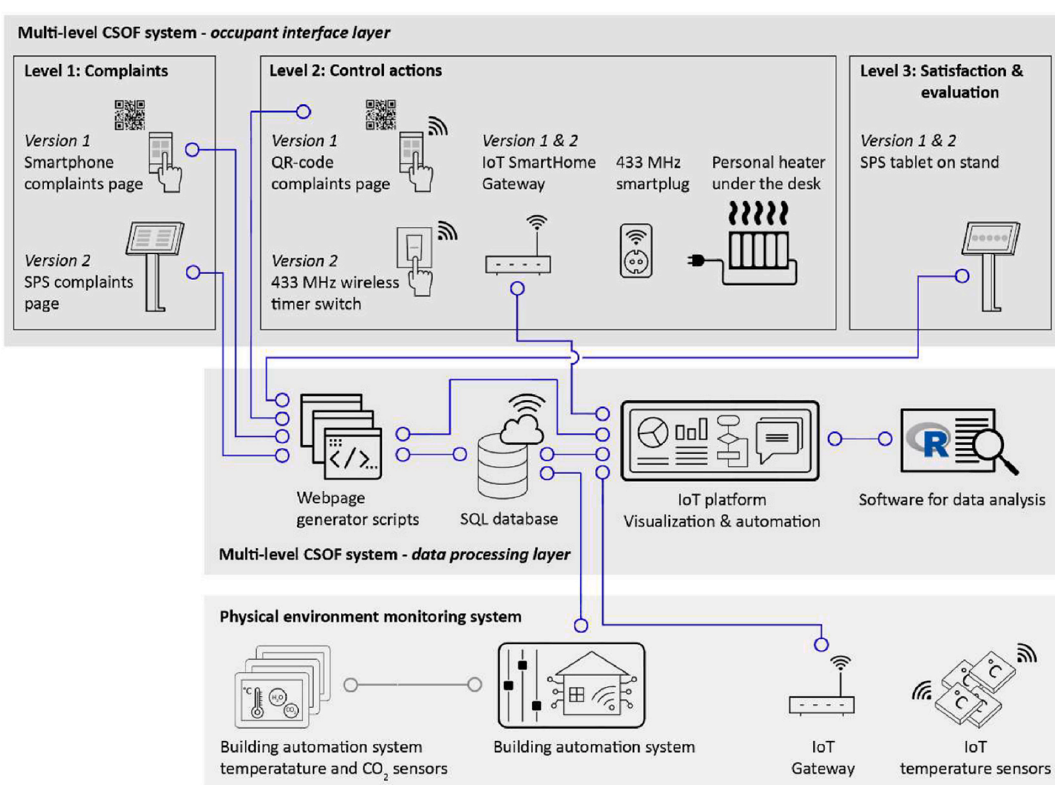

Fig. 2. System architecture, illustrated for both versions 1 and 2.

unique QR codes printed and attached to each work desk. This design was chosen by considering the goals of the system, i.e. to be non-intrusive, digital, and affordable, and providing continuous data. The feedback solution also needs to have a low threshold for user interaction, require no prior knowledge for use, and be able to provide location specific information, also in areas with free seating. In this configuration, the occupants did not need to download anything but could scan the QR code on the closest work desk with their smartphone, and thus reach a unique webpage for that work desk with buttons to complain about "Too cold"," Too hot", "Bad air" or "Draft". They could also leave a text message. The four complaint options were chosen as they are seen to cover the most common complaints regarding the indoor climate [49], that also could be related to the measured variables (temperature and CO_2). On the first visit the user was asked to enter age and gender, and a unique user number was stored using cookies. Future feedback from the same smartphone would then be linked to the user ID. No other personal information was collected. See Fig. 3. When occupants entered information, this was stored in a database. Only one complaint could be logged at a time.

4.2.3.2. Version 2: SPS complaint function. The QR-code interface was discontinued in Version 2 as the system collected low volumes of data and several occupants in focus interviews commented that the solution was cumbersome to use, or that they were not familiar with QR codes. Instead, the complaint feature was moved to the SPS feature as a second page shown to those who voted "dissatisfied" or "very dissatisfied" on the first page. If an occupant reports being dissatisfied, it seemed reasonable to give them the opportunity to report why, or which IEQ feature they were dissatisfied with. Users could then select one or more features amongst the following: "Too hot", "Too cold", "Draft", "Poor air quality", "Noise", "Poor lighting" or "Other". The feature was made with Windows PowerApps, which generated an interactive website. Data was stored and communicated to the IoT platform via an API. More than one complaint could be logged at a time. When moving the complaint function the publicly located SPS caused a crucial loss of information about who had made the complaint and where the person was located. There was no control of who used the SPS, making the information less reliable and making it impossible to connect the feedback to the user. This would make the data unfit for characterizing comfort on a personal level, but could increase the response rate. The trade-off was still considered acceptable and was found interesting for further investigation.

4.2.4. Level 2: occupant control actions

4.2.4.1. Version 1: QR/Smartphone control. Database entries for "Too cold" made with the digital complaint/QR feature would in this version activate personal heaters under each work desk. This was done by plugging each heater to a standard "smart plug" communicating over 433 MHz band to an internet enabled gateway. When occupants scanned the QR code at their desk and complained "Too cold", the smart plug under the desk would turn on and start the heater. The plugs were programmed to switch off after 30 min, and users would then have to repeat the procedure to continue receiving heat. This was both a security measure to avoid heaters being left on and a way of increasing the number of responses. The heaters are 30 × 60 cm large, attach to the underside of the desk and provide infrared heating with a power range of 40–150W (see Fig. 4 A and B), but were pre-set to approximately 50W power, producing surface temperatures of 40–50 °C. The cost of the heaters was less than 80€ per piece. All products were commercially available at low cost. The functionality of connecting the feedback for "Too cold" to the activation of the personal heater was enabled in the last phase of the field tests.

The under-desk heater was also tested with a manual ON/OFF feature in Building 1 instead of using the QR code feedback at the end of the experiment. Users then turned a plastic knob at their desk to switch the heater on and choose the power. Use was tracked by mounting a temperature sensor to the surface of each heater. In this case the heaters could be left on for longer periods of time without control actions from the occupant every 30 min.

4.2.4.2. Version 2: heater button on desk. The QR heater control function was replaced with a wireless switch located on each office desk. The buttons had a built-in timer set to 30 min and were paired via the 433 MHz radio band with the Smart Plug at the same desk. This system was more intuitive and easier to use for the occupants, as well as being more robust since the ON/OFF signal and timer function were handled locally and did not go via a cloud service.

4.2.5. Level 3: satisfaction

Overall user satisfaction was collected though a tablet solution, where a tablet mounted on a floor-stand displayed a full screen webpage with the question "How satisfied are you with the indoor climate today?" and five smiley icons. As occupants pressed buttons on the touchscreen, the response was saved in a database as integers between −2 and 2 where −2 is "Angry", 0 is "Neutral" and 2 is "Happy". Once pressed, the screen showed the message "Thank you!". See Fig. 5.

In Version 2 a dissatisfaction page was linked to the SPS, as previously described in Section 3.3, to provide a more detailed complaint pinpointing the sources of dissatisfaction. More than one complaint could be logged at the same time as a way to overcome some limitations experienced in another set of field tests on the SPS [48]. The question wording was also changed slightly between the two versions (see figure text) to make it more explicit to the user that the feedback was

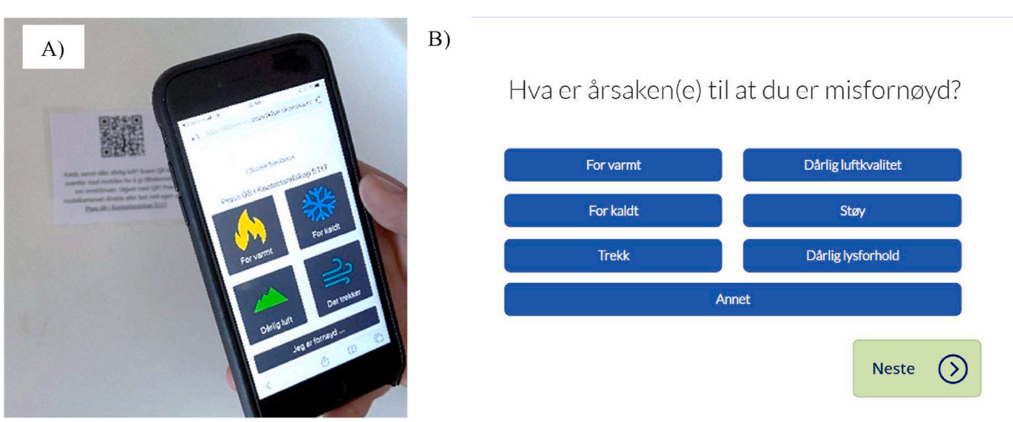

Fig. 3. Complaint system A) QR code and webpage from Version 1. B) SPS complaint page from Version 2 (in Norwegian native language, translated: "What are the reasons for your dissatisfaction?" with possible answers "Too warm; Too cold; Draft; Poor air quality; Noise; Poor lighting; Other").

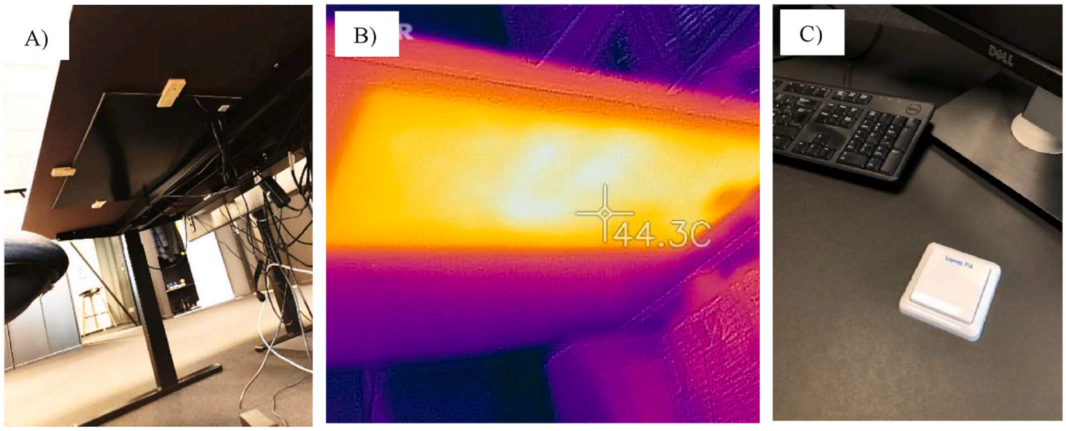

Fig. 4. Control action system A) Under desk heater mounted in case building. B) Infrared image of under desk heater in use. C) Version 2 wireless "ON" button with 30-min timer on desk.

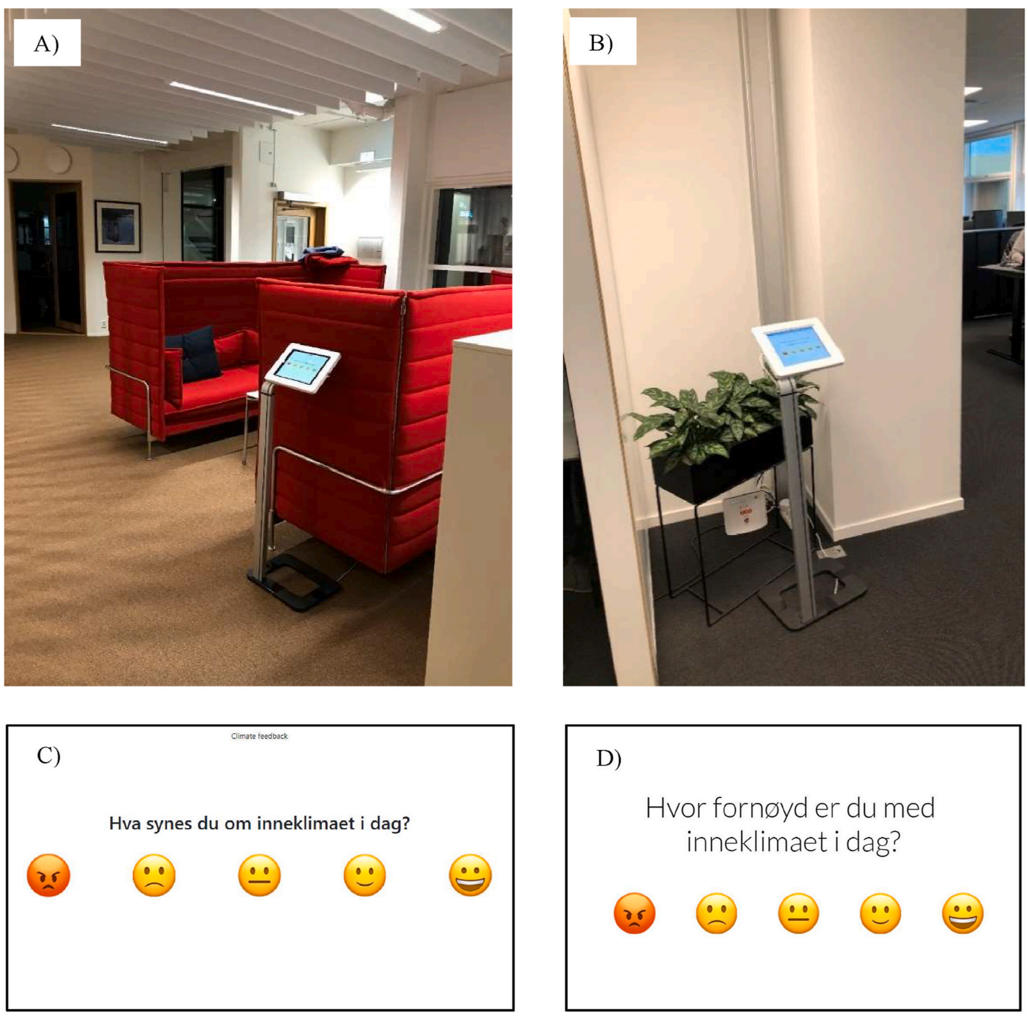

Fig. 5. Satisfaction evaluation system A-B) Two examples of SPS positioned in case buildings. Bottom row from left: Version 1 SPS screen, Version 2 SPS screen. In Version 1, the questions on the SPS screen was "What is your opinion on the indoor climate today" in Version 2 the question was "How satisfied are you with the indoor climate today".

specifically pointing at the user's level of satisfaction rather than a generic opinion.

4.3. *Measurements of physical indoor climate*

The physical indoor climate conditions were logged in two separate ways: by extracting information from the building BAS system, and by use of external sensors. The measurements of the physical indoor climate are conceptually, per se, not part of the CSOF system, but were developed as an integrated platform to visualize the connections between the data.

Where data was extracted from the BAS system, the built-in analog temperature and CO_2 sensors were checked prior to the experiments and found to have an accuracy of ± 1 °C. Data was extracted by setting up an API connection between the building automation top system and an external database. Temperature measurements with external sensors were done with wireless button sensors. The sensors have an absolute accuracy of 0.4 °C and were distributed throughout the spaces. The sensors have an integrated battery and wireless radio communication module. They communicate through an internet connected gateway to a cloud service. An API connection was established transferring data to an IoT platform where all data was finally collected and visualized.

5. Field tests

5.1. Background

A series of different field tests was designed and executed to investigate how the chosen system(s) would perform when made available to regular occupants of modern office buildings. Three field tests were conducted where the three components of the previously described system were introduced gradually, one by one, and occupant surveys were performed at certain points in time. We qualitatively evaluated the systems in field tests in different buildings with a total of 63 un-informed occupants for a total of 167 days. So-called temperature interventions were also part of the experimental design and carried out at certain points in time. The inclusion of the surveys was a strategy to establish a "ground truth" to compare with the feedback data (we thus consider the outcome of a survey the "real" occupant feedback), and a means to ask the occupants questions about how they perceived and used the CSOF system.

The temperature interventions, i.e. deliberate stepwise changes in the ambient room temperature, were performed in two of the buildings with the intention of provoking feedback and control actions from the occupants to see whether they would use the system. This type of temperature interventions in field tests with live occupants can only rarely be found in the research literature and is thus a valuable contribution.

The occupants were informed that the study was investigating the indoor climate in their space, but it was not specified that the focus of the tests was about the interactions they made with the feedback system. It was also communicated that no data linked to personal information or identities would be gathered during the experiments, and hence, it was unnecessary to apply for permissions from the Norwegian Centre For Research Data according to the current guidelines. Focus interviews, together with surveys, were also performed at the end of the field tests to let the occupants explain their experiences with the system, at the time when more information on the full design and scope of the field tests was also communicated to the occupants.

5.2. Experiment design

5.2.1. Case buildings

The system(s) were tested in three different office spaces around Oslo, Norway. All three offices were of a modern and energy efficient standard with open layout, either as part of the original design of the building (Building 2) or as a result of retrofit projects that substantially upgraded the quality of the indoor environment (Building 1 and Building 3). All buildings had a mix of designated and free seating in the space where workers perform desk jobs continuously from 9 a.m. to 5 p.m. with intermittent gaps in occupancy during lunch breaks and meetings. The description, floorplans, and interior photos from the case buildings are shown in Fig. 6.

5.2.2. Overview, sequence, and procedures

The tests were conducted as longitudinal blind tests in three real office environments described above, as further detailed in section 4.2.1. Two of the field experiments were conducted in the fall 2018 and winter 2019, and the last study was conducted during late winter 2020, until it was prematurely stopped due to the Covid-19 pandemic in March 2020. Each experiment was performed in phases (Phase 1 to Phase 3 or 4), where each phase identifies the introduction of new equipment. Not all phases were performed in all buildings, and the study sequences can be seen in Fig. 7. Details can be found in Appendix D. In Phase 1, only Level 3 *satisfaction evaluation* of the CSOF system was enabled. This means that

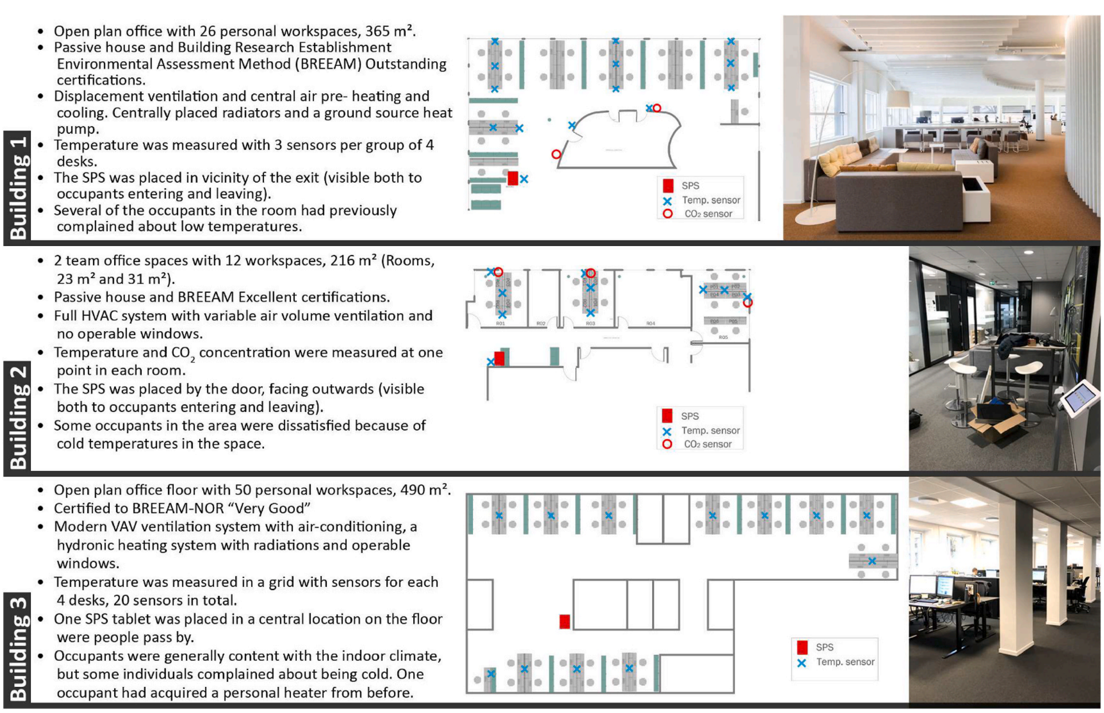

Fig. 6. Case building description with floorplans and photos.

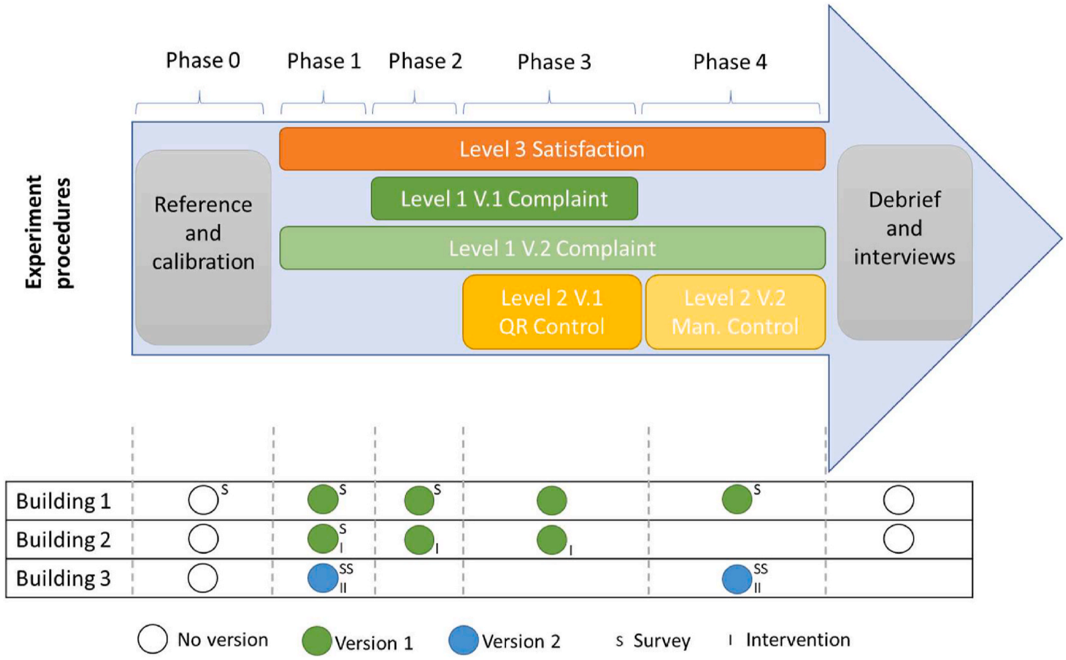

Fig. 7. Experiment procedures for all three buildings.

only the SPS was installed. However, it is important to remember that in Version 2 the SPS included also the possibility to provide feedback on complaint. In Phase 2, QR codes were installed as a Level 1 *occupant complaint* system for Version 1, for Version 2 this function was embedded in the SPS. In Phase 3 under-desk-heaters were connected to enable Level 2 *personal control* using the QR code. In Phase 3 the occupants were given manual control over the heater. The QR codes were removed where present. Phases 2 and 3 were not performed in Version 2. Phase 4 was not performed in Building 2.

Before the experiment started, occupants received an email informing them of an “IEQ measurement and occupant satisfaction project” that would start in their office space due to previous complaints about the indoor climate. They were made aware of the measurements that would take place and explained that several systems for occupant feedback and personal control would be installed. They were asked to use the systems as felt natural to them. All new equipment that was installed was made as self-explanatory as possible so that occupants would understand how to use it. A contact person in the administration was given an introduction in how the system worked in order to answer questions from occupants.

On a practical note, the temperature interventions were performed by the facility manager in the building, who adjusted the room temperature set-point at the request of the researchers. This was done as it was the easiest way to see how occupant feedback changed in response to a deliberate and clear change in the environment.

5.2.3. *Occupant survey*

Occupant surveys in Building 1 and 2 were performed differently from in Building 3.

In Buildings 1 and 2, an electronic survey was distributed to the test subjects via an email link. The survey included multiple questions, as shown in Appendix A. The respondents were asked to take the last week into consideration when answering all the questions. The survey focused on how occupants perceived the IEQ, what level of personal control they felt they had, and how they used the equipment.

The surveys in Building 3 were performed differently in order to increase the response rate of the surveys and to make survey answers representative of current day perceptions so they would be comparable to the SPS feedback. This change was based on positive experiences with this survey method in another study by the authors [48]. In Building 3 each occupant present at the time of survey was personally approached by a researcher and asked to fill out a short survey on a tablet. Occupants filled out the survey themselves while the researcher took a step back. In this case, the occupants were asked to take the current day into consideration when answering. The surveys were always performed in the afternoon, between 2 and 4 p.m. Survey questions are summarized in Appendix A.

5.2.4. *Focus group interviews*

A focus group interview was performed at the end of the experiment in Building 1 (with 3 occupants) and in Building 2 (with 5 occupants). The intention of the focus interviews was to record occupant opinions and recommendations that could only be obtained through open questions. The focus group interview in Building 3 has not yet been performed as the experiment was suspended due to the COVID pandemic. It might be performed at a later point, should the experiment start again. The participants were selected by inviting all occupants in the room and letting those who were present and available at the planned time to join in the interview - thus the respondents are not a statistically representative sample of the office population. The outcomes of the focus group interviews could therefore be biased as those more “interested” in the project or the indoor climate may have been more inclined to participate (see Table 4).

5.3. *Results and discussion from field tests*

5.3.1. *Presentation of collected data*

A graphical overview of the experiment data collected during the three field tests is given in Figs. 8–10 below. Main data quantities from the feedback system are given in Table 3 and Fig. 11 (see also Table 6 in Appendix).

The main collected data from the experiments is presented in Figs. 8–10 (see Fig. 12). The top plot in each figure displays the daily temperature variation between all sensors, plotted with geom_boxplot. The lower and upper hinges correspond to the first and third quartiles (the 25th and 75th percentiles). The whiskers extend 1.5 times the interquartile range. Data beyond the end of the whiskers are not plotted. The second plot displays the mean daily SPS satisfaction score, and

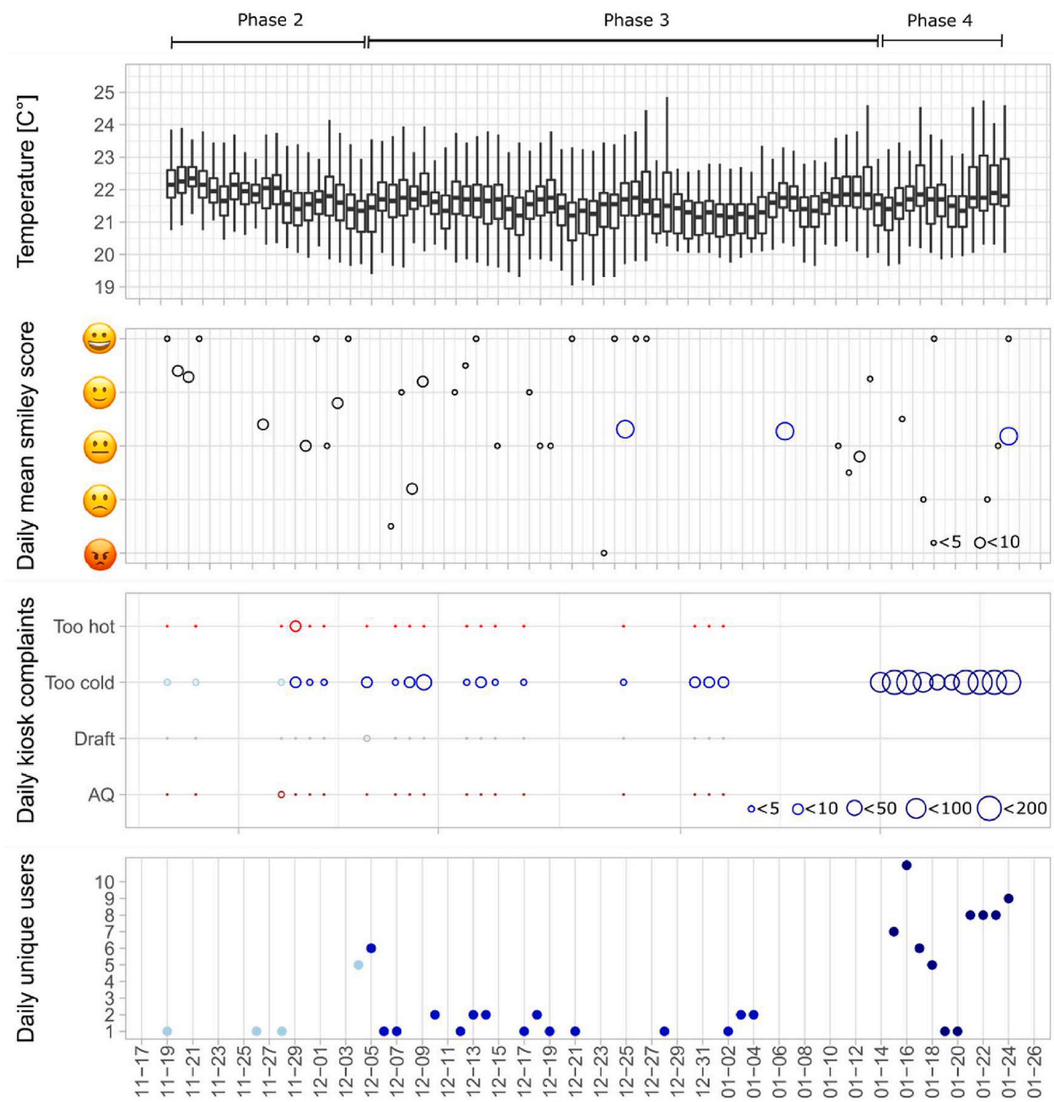

Fig. 8. General presentation of results from Building 1. Top chart displays temperature distribution from all sensors in the space per day. Second chart displays SPS daily mean score (size of dot renders number of votes on that day) and mean of the SPS question survey (blue). Third chart displays daily number of complaints via SPS page two, organized horizontally and by color. The bottom chart displays the number of daily (unique) users using the heater.

equivalent score on surveys (blue). Small black bubbles are a mean daily score containing <5 votes while the larger the bubbles, the higher the number of votes, meaning that larger bubbles should be given more weight. The third chart displays the number of complaints made via the QR code or SPS complaint page (depending on version), as well as heater use (counted as "too cold"). The bottom plot displays number of daily unique users voting on the QR complaint solution or using the heater. (see Fig13)

Survey results relevant for the occupant's perception of the feedback system are shown in Appendix C. Relevant quotes from the focus group interviews are cited in Appendix B.

5.3.2. *Systems for occupant complaints (level 1)*

5.3.2.1. Data collection. The SPS complaint function (Version 2) collected more complaints (1.6 per day) than the QR complaint function (Version 1) without heater (0.6 and 1.1 per day). In Fig. 10 it can be seen how more Version 2 SPS "Too cold" complaints were collected in Building 3 during the intervention with reduced room temperature, indicating that the occupants use the system as intended. Fig. 9 shows how the same phenomenon occurred with the Version 1 QR complaint function in Building 2. Fig. 13 shows an example from two rooms in Building 2 during a time span of 40 days where two temperature interventions were made to reduce the room temperature by approximately 1–1.5 °C. There was however no effect of the second temperature intervention in one of the rooms (Room 1). Each blue dot is a "Too cold" complaint made by an occupant. During the first intervention there was no heater connected to the complaint (Phase 2). The visualization shows that more complaints were made during the temperature interventions than during normal temperatures.

5.3.3. *Occupant opinions*

In the focus group interviews, occupants in both Building 1 and 2 expressed that they had not used the QR complaint option much, as they found it impractical, time consuming and they found no motivation to use it. Several users reported having trouble with, or did not know how to, use a QR code with their Smartphone. Although the QR solution was a very effective way of linking feedback information to a particular location in the building and user ID, it turned out that the technical threshold of using QR codes was too high for some of the occupants. This resulted in the solution collecting lower volumes of data than the other solutions.

5.3.3.1. Technical performance. There were some minor IT-technical

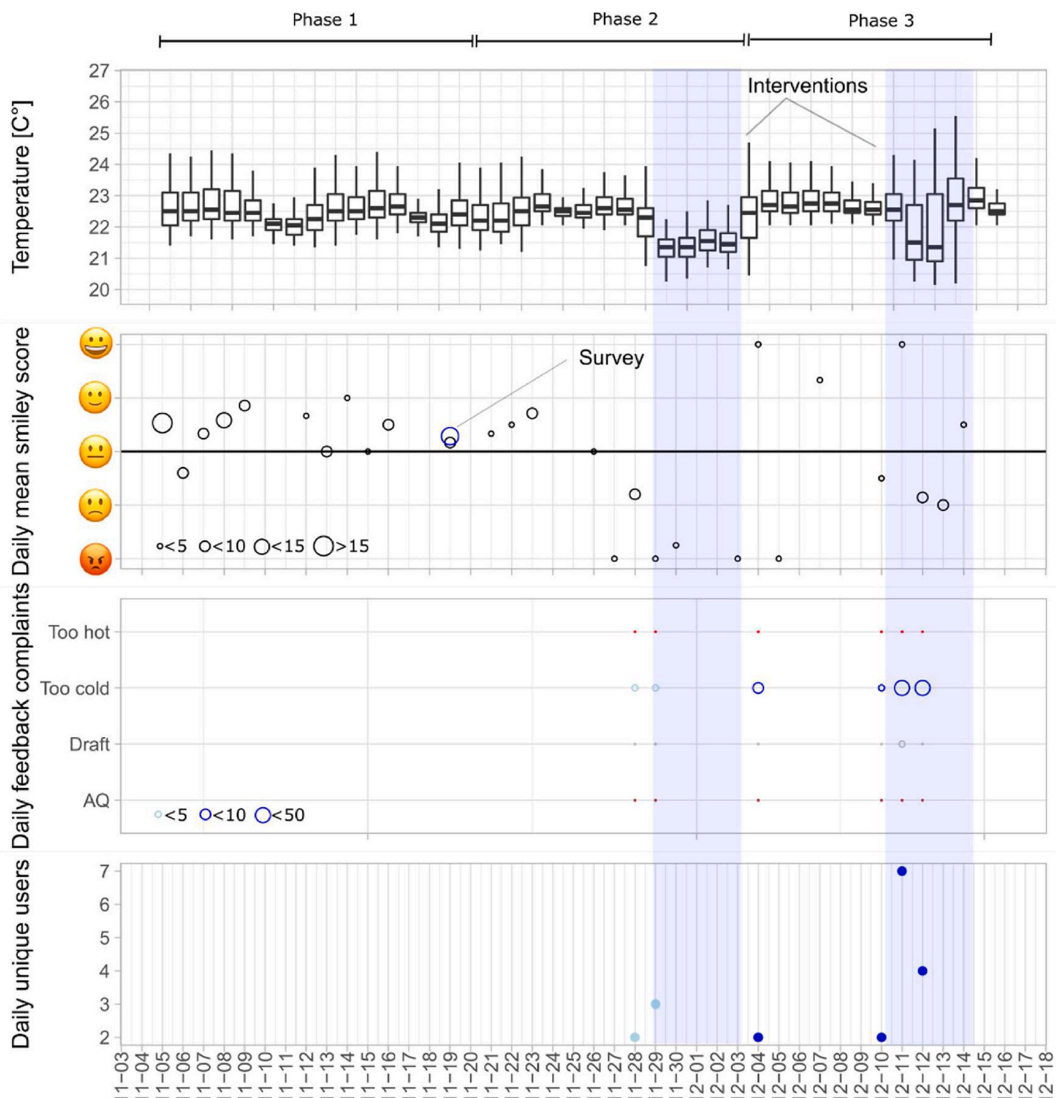

Fig. 9. General presentation of results from Building 2. Top chart displays temperature distribution from all sensors in the space per day. Second chart displays SPS daily mean score (size of dot renders number of votes on that day) and mean of the SPS question survey (blue). Third chart displays daily number of complaints via SPS page two, organized horizontally and by color. The bottom chart displays the number of daily (unique) users using heater in manual mode. Blue shaded areas mark days with deliberate temperature reduction. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

issues with the Version 1 QR complaint function, but these were quickly resolved.

5.3.4. Systems for occupant control actions (level 2)

5.3.4.1. Data collection. In Fig. 13 we see how the occupant complaint solutions (Version 1 and 2) collected much fewer data points than the occupant control solutions where there was a heater response. Many of the heater responses are however repeat responses after the heater had shut off after 30 min. The number of unique users can be seen in the bottom plots of Figs. 8–10, and we see that the number of unique users also clearly increased when heater was connected in Building 1 and 2. Fig. 13 shows the same effect in Building 2, where more “Too cold” complaints were entered during the second intervention where there was a heater connected. When the heater was connected to a manual control button, the user activity increased by almost 20 times in Building 1 (although these were not fully true control actions as heaters could be left on). However, Building 3 also had a similarly high number of control actions with manual heater control.

5.3.4.2. Occupant opinions. In Building 1 and 3, occupants reported in the survey to have a higher degree of control in Phase 4, where they had manual control over personal heaters. In Building 1 the increase in perceived control between Phase 2 and 4 was statistically significant. Through the focus group interviews, occupants in both Building 1 and 2 expressed strong opinions about the control and feedback interfaces as they preferred manual and direct control options. They also clearly expressed a wish for direct and immediate responses to their control actions. Occupants in both buildings showed an impressive ability to take matters into their own hands to achieve the form of control they wanted (overriding the smartphone control for personal heaters in Building 1 and disconnecting the remote control over radiators in Building 2). Occupants in both buildings, especially those who reported being cold, were very happy about having a personal heater at their space.

5.3.4.3. Technical performance. In Version 1, the QR connection to heater (via IoT platform) did not always work as some heaters were far from the gateway and had poor reception. Heaters were attached to

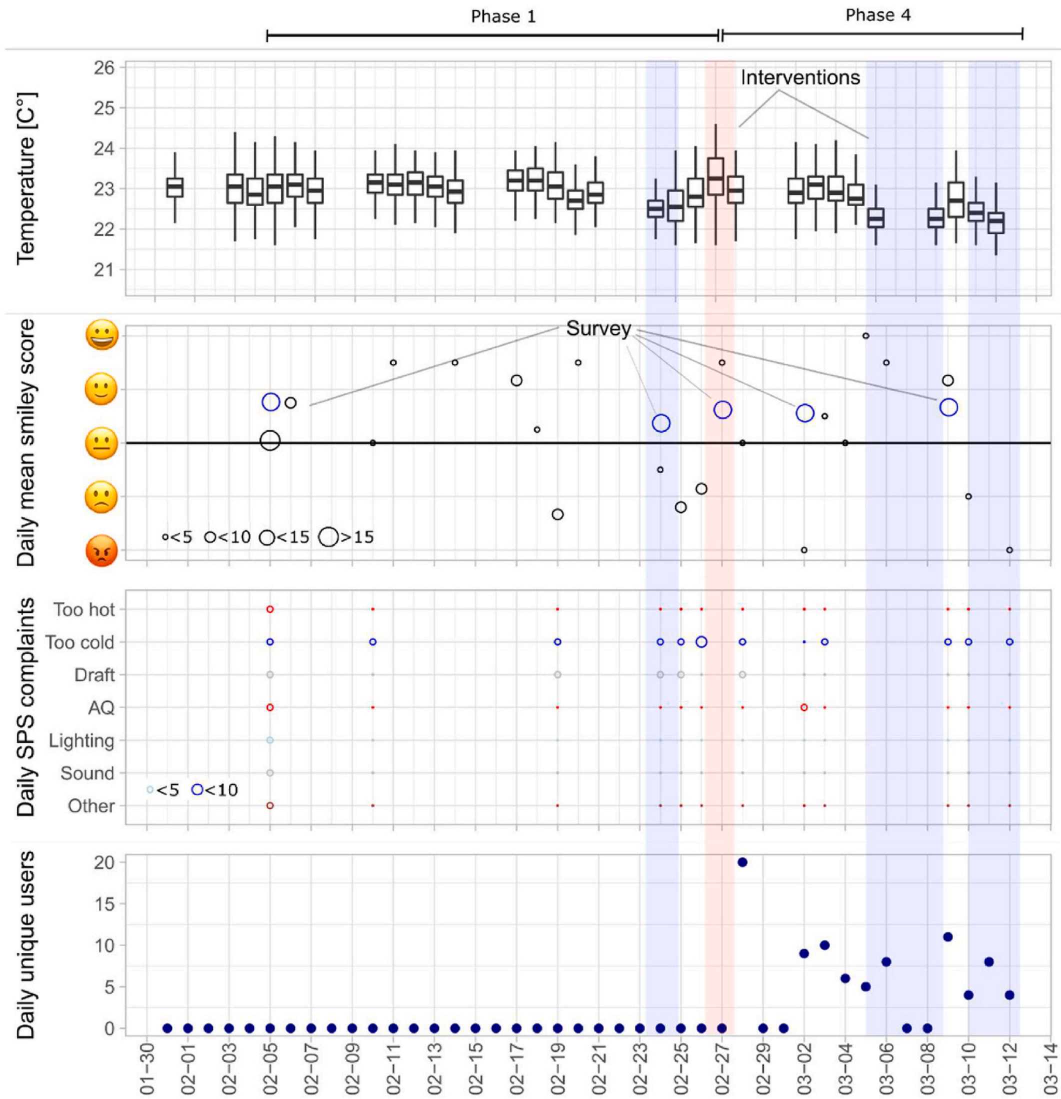

Fig. 10. General presentation of results from Building 3. Top chart displays temperature distribution from all sensors in the space per day. Second chart displays SPS daily mean score (size of dot renders number of votes on that day) and mean of the SPS question survey (blue). Third chart displays daily number of complaints via SPS page two, organized horizontally and by color. The bottom chart displays the number of daily (unique) users using heater in manual mode. Blue and red shaded areas mark days with deliberate temperature reduction (blue) and increase (red). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

desks with adhesive, leading to some heaters falling down during the experiment. In Version 2, direct radio communication (rather than via cloud) from the heater switch to the heater eliminated the problems with bad reception and internet connectivity. Heaters were attached with screws and brackets to the desks rather than adhesive, eliminating the installation problems.

5.3.5. System for total occupant satisfaction data collection (level 3)

5.3.5.1. Data collection. The SPS satisfaction solution collected more votes than the complaint solution, as seen in Fig. 11. It is unknown why the SPS in Building 2 recorded close to three times as many votes per day as in Building 1, but this could be related to the fact that the occupants of Building 2 were young IT professionals with a natural interest in such systems, or perhaps the fact that the SPS in Building 2 was located next to a large info-screen displaying other kinds of office-related information. Fig. 13 displays a smoothed graph of the number of votes received per day divided by the population of each building. The results show that Building 2 and Building 3 experienced a decline in voting frequency during the first 10–15 days. After this, the voting frequency stabilized. These results are similar to results obtained in another study on the SPS [48]. In Building 1 the frequency was constantly lower during the whole period. All buildings experienced relatively large day to day variations in voting frequency.

5.3.5.2. Occupant opinions. Between 42% and 70% of the occupants in each building reported in the survey to have used the SPS. The most prominent reasons given in the survey for not using the SPS were "It's not working", "I have not noticed it", "I don't know" and "Other". Occupants reported in focus group interviews that they were satisfied with the SPS and said that they thought it had collected a lot of data. See Appendix B and Appendix C for results.

5.3.5.3. Technical performance. In Version 1, there was some downtime on SPS due to poor internet connection or power loss when cleaning personnel disconnected the power source. It was a problem that researchers were not informed when the SPS was down, leading to the problem of not being fixed promptly. Kiosk mode in browser on SPS did not work perfectly, as occupants could use some functions (such as zoom

Table 3
Main feedback data quantities.

	Building 1	Building 2	Building 3
Population	26	12	28
Number of experiment days (working days)	88 (60)	42 (30)	37 (25)
SPS votes collected	97	124	90
Average number of SPS responses per working day	1.5	4.1	3.6
QR/SPS feedback complaints recorded	10	5	41
QR/SPS feedback complaints recorded per working day	1.1	0.6	1.6
QR control actions collected	79	54	NA
QR control actions collected per day	4.0	6.0	NA
Number of manual control actions collected (total time heaters were left on, divided by one half hour for building 1)	899	NA	445
Number of manual control actions per day	69†	NA	49
Total survey Reponses	40	7	97
Average response rate on surveys	51%	58%	65%

† *The heaters could be left on. Number shown is total heater use time within work hours divided by 30 min.*

in on the page). In Version 2, a designated application for kiosk mode on the SPS was used leading to better stability and usability. There was some downtime on the SPS due to power and connectivity losses, but researchers were alerted by the system when this happened so the effective downtime was minimal. The connectivity issues and downtime for the SPS and QR complaint function in Version 1 may have caused the occupants to lose interest in the system. Occupants in focus interviews reported that there had been technical problems but did not name this as a reason for not using system. 28% of those who reported on the survey in Building 1 that they had not used the SPS selected "Not working" as a reason.

5.3.6. Limitations

This paper does not focus on the validity or accuracy of the data, i.e. whether the collected feedback data is representative of the opinion of the entire building population. This aspect will be analysed in a more comprehensive and robust analysis for a larger dataset in a dedicated article using logistic regression in multivariate random effects models to compare collected feedback data to survey data with other input (such as building, response rate or temperature) as explanatory variables. The decision to have a 30-min time limit on heaters makes it impossible to directly compare control actions to complaints, as control actions were repeated.

6. Lessons learned

6.1. Research panorama

The literature study revealed that some existing studies on CSOF focus on the data collection method itself, while other studies have a control- or modelling oriented approach focusing on the further use of occupant feedback. Smartphone apps are used in most studies, while several also use intelligent thermostats. A few studies use polling stations, or interactions with personal comfort systems. Relatively few of the studies focus on the data collection methods themselves, or on how the occupants receive them. In relation to the research panorama, the study presented in this paper tackles CSOF in a way that is not entirely covered by any of the above-mentioned studies, as none of them distinguish clearly between *occupant data* and *subjective occupant feedback*. The difference between the two aspects, in short, lies in the level of human consciousness involved in the feedback or data. Subjective feedback will always involve a conscious thought process (such as performing an evaluation to give a score, or deciding to make a control action), while occupant data may be all types of objective or subjective data (also involving physical data such as presence, heart rate, skin temperature, etc.). Few of the studies compare or question how one should collect data best or question the validity of the collected data if compared to traditional survey methods. There is a lack of critical reflection about how different data collection methods may result in conceptually different data being collected, or how the different collection methods relate to each other.

6.2. System design

We were able to design a simple system with off-the-shelf products

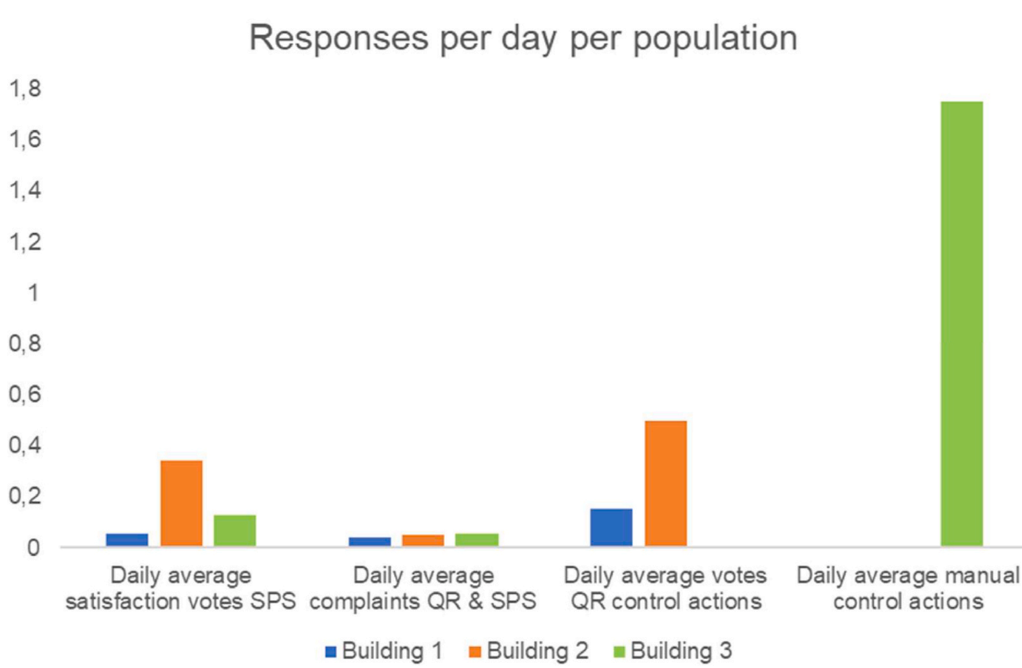

Fig. 11. Quantities of collected data from each system and building, presented as responses per day per building population. Manual heater data from Building 1 has been removed as it was not considered representative as the heaters could be left on.

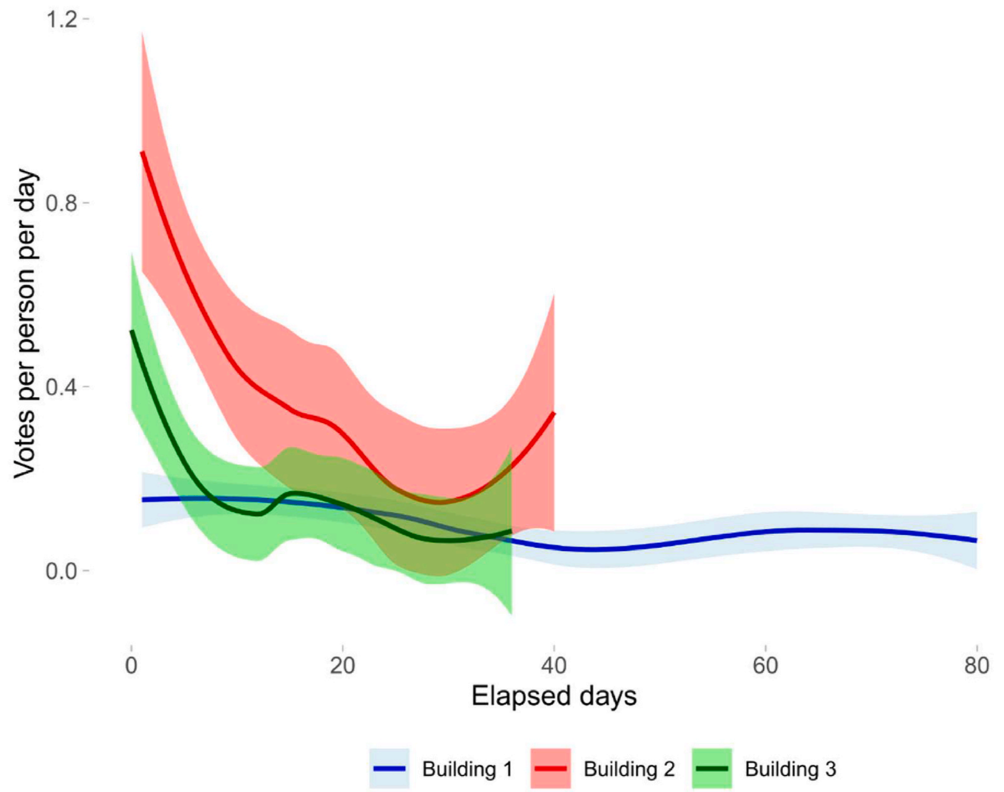

Fig. 12. Smoothed graph showing SPS usage over experiment duration for all three buildings, presented as responses per day per building population. Shaded areas represent 5% and 95% confidence intervals.

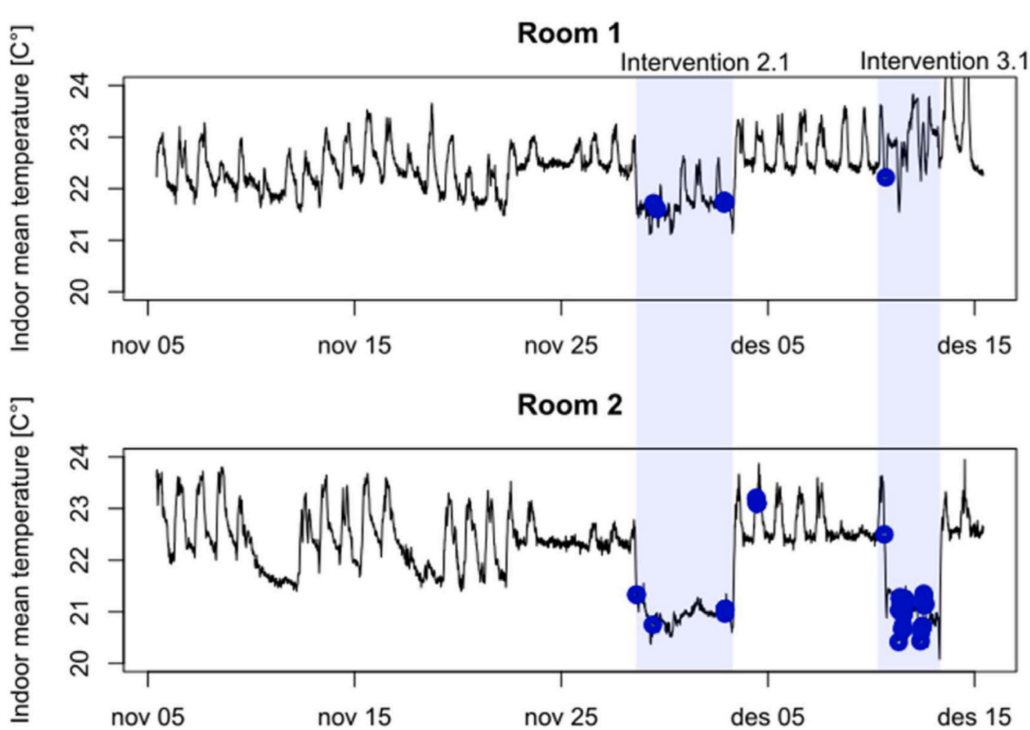

Fig. 13. Example of time correlation plot for temperature and QR/heater use in two rooms of Building 2 during temperature swings. Each blue dot is a "Too cold" complaint made by an occupant. Second temperature swing in Room 1 did not have any effect as occupants had disconnected the radiator control cable. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

which was taken into use by the occupants. There were some technical and usability related issues, which were addressed in Version 2 of the system. The occupants showed an unexpected will and ability to manipulate the heater control system in Version 1 when they found it to be too complicated or unreliable. Stability and robustness are found to be crucial in order to have a well-functioning system, since downtime and functionality errors both cost time for operators and may lead users to lose confidence in the system. The simpler system used in Version 2 was promising, as it was more reliable, flexible and more intuitive in use. Future systems of this type should be as simple and intuitive as possible and as far as possible address the wishes of the occupants, to ensure that the potential data collection is maximized with as little as possible bias from personal differences (i.e. technical competence, comfort level etc.) among the occupants.

6.3. Occupant's response and data collection

The occupants provided useful data to the system through their daily interaction with it. The decline in intensity lasted only for the first 15 days before stabilizing for the remaining duration of the experiment. The average usage frequency of the SPS varied significantly between the three buildings. Causes are unknown, but presentation, visibility, information, demographics or climate differences may have contributed to cause the differences. It should be noted that the systems were in use only for a short period during winter season, and climatic causes for SPS usage cannot be ruled out. Details of SPS usage (climatic influence, biases and recommended applications) have been further studied in a separate study by the authors [48]. There were also large individual differences in how people used the SPS, complaint function and heater. The results indicate that occupants provided more data when the complaint function was on the SPS than when occupants had to use the QR code and smartphone. Results also indicate that occupants perform many more control actions when they have manual control over the personal heater as opposed to using their smartphone.

In this paper we do not investigate explicitly the validity or quality of the data collected, nor how it may be used, as our research questions focus on how occupants respond to a system in field tests in terms of interest and feedback. We can however see some tendencies in the data that should be investigated further. The SPS mean daily score has large variations from day to day. This is likely to be due to the low number of votes per day and the large difference in people's opinions. As many do not vote, and some vote several times per day, this may imply that this data is highly biased. Figs. 8, Figure 9, and Fig. 10 show indications of thermal complaints and control actions being correlated in time with temperature interventions, indicating that the feedback is rooted in the actual climate conditions on that same day (see Table 7).

Results from focus interviews and surveys show that occupants prefer feedback systems that are simple, intuitive and give an immediate response when used. Table 5, Figs. 8, Fig 9, Figs. 10 and 11 show that the heater in manual control mode collected far more data than the other solutions. Survey results in Table 6 show that occupants also experience a significantly higher level of control over their environment when they have manual control over the heater.

Two different survey methods were used in the experiments: one traditional email survey and one survey where occupants were approached by a researcher with a tablet with questions. The tablet survey method was successful in increasing the response rate from ~50% to ~70%, as well as giving the researchers better control over the exact response rate as they could see how many people were in the office at the time of survey. A change was also made in asking occupants to answer for their experience for that given day rather than for the entire week, which also made survey answers more comparable to the feedback. The tablet-based, individual survey method with a person visiting the test location and asking each occupant to fill the survey is also recommended for further studies.

7. Conclusions

In this paper, we highlight some of the current knowledge gaps for the field of continuous subjective occupant feedback. We have designed a system where we made explicit the different types of occupant data that can be collected, and in our implementation we cellected three levels of information, namely *occupant complaints, occupant control actions,* and *occupant satisfaction evaluations*. We proved it possible to make a system collecting occupant feedback on three levels by using off-shelf products and a relatively simple ICT architecture. The cost for installing such a system in a high-quality office buidling is a fraction of the construction costs, and thus shuold be considered as a low-cost solution to involve occupants in the loop. Occupants made use of the system and provided data that, after a qualitative preliminary analysis, seems to reveal the ability of the system to collect meaningful feedback. They had a far higher usage frequency of the solutions that had an accessible and intuitive usage interface and provided the user with an immediate response to the feedback. The results indicate that a simple feedback system may be enough to gather useful information for building tuning, automation, benchmarking, and learning, provided that the system offers a sufficient level of usability and offers an immediate and meaningful response to the user. They also indicate that it can be beneficial to the total value of collected data to collect less detailed data if this can result in simpler occupant interfaces (i.e. use manual buttons rather than smartphone for heater control). Further investigations will be necessary to assess on a quantitative basis the validity and robustness of the collected data. The SPS is a promising solution, but we need to make further investigations to uncover the effect and magnitude of non-response bias and sensitivity to environmental changes, as we have begun addressing in another study [48]. We also need to investigate how response rates can be improved. The complaint function is promising when incorporated in the SPS. The heater control actions are a promising method of collecting feedback, which also gives significant benefits to the occupants in form of increased level of perceived control.

Declaration of competing interest

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

Acknowledgements

This study has been performed with the financial support of the Research Council of Norway, within the project "Methods for real-time user involvement of indoor climate in smart buildings" (project number: 277048). The support provided by the Research Council of Norway, Skanska Norway, KnowIt, Avantor, Asplan Viak and the Norwegian University of Science and Technology is gratefully acknowledged. The authors would also like to thank Judy Lomax for contributing to the readability of this research.

Appendix A

Table 4
Survey questions buildings 1 and 2, translated to English from Norwegian language.

Question	Response alternatives
Q1 – How satisfied are you with the indoor climate at your workplace today?	[5 smiley face buttons]
Q2 – On a 7-point scale, how satisfied are you with the indoor climate at your workplace today?	[7-point slider from "Very dissatisfied" to "Very satisfied"]
Q3 – How acceptable did you find the temperature of your workspace during the period?	[Acceptable/Barely acceptable/Barely unacceptable/Unacceptable]
Q4 – How acceptable did you find the air quality of your workspace during the period?	Acceptable/Barely acceptable/Barely unacceptable/Unacceptable]
Q5 – How do you feel about the temperature of your workspace?	[Hot/Warm/Slightly warm/Neither/Slightly cool/Cool/Cold]
Q6 – Have you experienced it to be colder than what you think is acceptable during the period?	[Yes/No]
Q7 – Have you experienced it to be warmer than what you think is acceptable during the period?	[Yes/No]
Q8 – Have you experienced being so cold it interfered with you work tasks during the period?	[Yes/No]
Q9 – Have you experienced being so warm it interfered with you work tasks during the period?	[Yes/No]
Q10 – Which level of control you perceive to have over your indoor climate?	[No control/Little control/Some control/Much control]
Q11 – Have you used the heater that is mounted under your desk during the period?	[Yes/No]
Q12 – If not, what was the reason for not using the heater?	[I am content – I have no need for extra heat/I was not aware that it was there/I don't understand how it works/I find it too cumbersome to use/It's not working/I don't know/Other]
Q13 – Have you used the smiley-face kiosk located by the entrance during the period?	[Yes/No]
Q14 – If not, why?	[I don't think it works/I find it too time consuming/I don't understand the point of giving feedback/I don't know]
Q15 – Would you, on a regular basis, prefer more information regarding your indoor climate (for instance information about temperature and air quality on a screen by the entrance)?	[Yes/No/Other]
Q16 – Please submit other comments if you wish.	[Text]

Table 5
Survey questions building 3, translated to English from Norwegian language.

Topic	Question	Response alternatives
Metadata (inserted by researcher)	Q1 - Workplace ID	[Text]
	Q2- Approximate age	[Years, binned]
	Q3 - Sex	[Male/Female]
	Q4 – Workplace type	[Open plan, cubicle, single office, Team office]
	Q5 – Workplace comments	[Text]
	Q6 – Other comments	[Text]
SPS questions	Q7 – How satisfied are you with the indoor climate at your workplace today?	[5 smiley face buttons]
	Q8 – Help us pinpoint the problem (if dissatisfied)	[Too hot/Too cold/Draft/Air quality issues/Sound issues/Lighting issues/Other
	Q9 – Please specify the problem(s) (if chosen Other)	[Text]
POE questions	Q10 – How satisfied are you with the temperature of your workspace today?	[Very satisfied/Satisfied/Somewhat satisfied/Neither satisfied nor dissatisfied/Somewhat dissatisfied/Dissatisfied/Very dissatisfied]
	Q11 – How satisfied are you with the air quality of your workspace today?	[Very satisfied/Satisfied/Somewhat satisfied/Neither satisfied nor dissatisfied/Somewhat dissatisfied/Dissatisfied/Very dissatisfied]
	Q12 – How do you feel about the temperature of your workspace?	[Hot/Warm/Slightly warm/Neither/Slightly cool/Cool/Cold]
SPS voting habits	Q13 – How often do you vote at the smiley kiosk?	[Never/Once since it was introduced/A few times sporadically/Regularly each week/Regularly once per day/regularly several times per day]
Perceived control	Q14 – Which level of control you perceive to have over your indoor climate?	[No control/Little control/Some control/Much control]

Appendix B

Relevant quotes from focus interviews and questions from semi-structured interviews. Translated from Norwegian.

Building 1

- "Many of us use the heater all the time"
- "I love the heater! Can I keep it?"
- "Half an hour duration is way too short."
- Many people don't know how to use a QR code with their smartphone.
- "I have disconnected the heater from the QR controlled smart plug and use the manual control. I have helped several others do the same, so you don't have to use your smartphone on the QR code and get restricted to half an hour of heat at a time."
- "I had to remove my heater because a sharp corner of it made holes in my pants."
- "All of us wear wool sweaters, even in the summer. It's very cold here."
- "My heater never worked, but I never needed it anyway. I am never cold."
- "I use the SPS, but I have a feeling that I use it more when I am satisfied."
- "I see many people using the SPS, I think you got a lot of data."

- “Some of us sit for long periods at a time, while others move more around to meeting etc. I think they complain less about the indoor climate.”
- “I think you could have a second question at the SPS, so you can see what those dissatisfied are complaining about.”

Building 2

- “I don’t like the way the personal heater radiates heat on my thighs. It would have been better if pointed toward the feet.”
- “I want the possibility to control the temperature in the office. There should have been a screen on the wall for this or something like that.”
- “I have disconnected the regulator on the radiator in my office. This way I can override the central thermostat control.”
- “I want to see a correlation between the knob I am turning and a change in the environment.”
- “Light and solar shading is a big problem. We need more zones on the automated external sun shading system.”
- “People are messing with the SPS and zooming in at one smiley face and so on.”
- “Maybe it would be better to use simple grades or dice/star ratings instead of the smiley faces.”

Interview questions (building 1 & 2)

The interview questions used to drive the discussion of the semi-structured interview were:

1. Have you used the QR codes/personal heater? If not, why?
2. What do you think of the solution with QR code/personal heater?
3. Have you used the SPS? If not, why?
4. What do you think of the SPS solution for collecting feedback?
5. What could be done better?

Appendix C

Table 6
Relevant survey results Corresponding to $p > 0.05$ – ns (non-significant), $0.01<p < 0.05$ *, $0.01<p < 0.001$ **, $p < 0.0001$ ***. AIntervention, 1.5 °C cooler. BIntervention, 1.0 °C warmer. Statistical analyses were performed as two-sample single sided *t*-test.

		Phase 1 – SPS only		Phase 2 - QR	Phase 4 – Manual Heater	
		Survey 1.1	*Survey 1.2*	*Survey 2.1*	*Survey 4.1*	*Survey 4.2*
Number of respondents	Building 1	16		12	12	
	Building 2	7				
	Building 3	19	21		18	18
Percent dissatisfied (all domains) Smiley [Q1/Q7]	Building 1	25%		25%	17%	
	Building 2	14%				
	Building 3	21%^{A}	14%^{B}		6%	17%^{A}
Percent dissatisfied (thermal domain) Smiley [Q2/Q8]	Building 1	25%		25%	17%	
	Building 2	14%				
	Building 3	21%^{A}	14%^{B}		6%	17%^{A}
Percent dissatisfied temperature/unacceptable temperature [Q3/Q10]	Building 1	25%		33%	25%	
	Building 2	0%				
	Building 3	32%^{A}	29%^{B}		22%	33%^{A}
Perceived control (mean score) [Q10/Q14]	Building 1	0,64		0,42	1,08*	
	Building 2	0,71				
	Building 3		0,38^{B}		0,61	
Percentage who report to have used the SPS [Q13]	Building 1			70%	42%	
	Building 2					
	Building 3	55%			61%	
Reasons for not using the SPS [14] – Building 1 Survey 2.1 and 4.1 only	Building 1	Don’t know: 67% Too time consuming: 33%			Not working: 28% Don’t know: 14% Too time consuming: 14% Don’t see the point: 14% Other: 29%	
Reasons for not using the SPS [14] – Building 3 survey 1.1, 4.1 only	Building 3	Not noticed it: 67% Other: 33%			Not noticed it: 14% Other: 86%	

Appendix D

Table 7
Study sequences with dates.

		Building 1	Building 2	Building 3
PHASE 1	START Phase1	November 05, 2018	November 04, 2018	February 05, 2020
	SPS installed	November 05, 2018	November 04, 2018	February 05, 2020
	Survey 1.1 distributed	November 16, 2018	November 16, 2018	February 24, 2020
	Survey 1.1 closed	November 19, 2018	November 19, 2018	February 24, 2020
	Intervention 1.1	NA	18.11–November 24, 2018 (0.5 °C cooler)	24–25.02.2020 (1.5 °C cooler)
	Survey 1.2 distributed	NA	NA	February 27, 2020

(*continued on next page*)

Table 7 (*continued*)

		Building 1	Building 2	Building 3
	Survey 1.2 closed	NA	NA	February 27, 2020
	Intervention 1.2	NA	NA	February 27, 2020 (1.0 °C warmer)
PHASE 2	START Phase 2	November 19, 2018	November 20, 2018	NA
	QR codes installed	November 19, 2018	November 20, 2018	NA
	Survey 2.1 distributed	November 30, 2018	NA	NA
	Survey 2.1 closed	December 03, 2018	NA	NA
	Intervention 2.1	NA	28.11–December 03, 2018 (1.5 °C cooler)	NA
PHASE 3	START Phase 3	December 04, 2018	December 03, 2018	NA
	Under desk heaters installed for code control	December 04, 2018	December 03, 2018	NA
	Intervention 3.1	NA	10.12–December 14, 2018 (1.5 °C cooler)	NA
PHASE 4	START Phase 4	January 14, 2019	NA	February 27, 2020
	Manual heater control enabled/QR removed	January 14, 2019	NA	February 27, 2020
	Survey 4.1 distributed	January 23, 2019	NA	March 02, 2020
	Survey 4.1 closed	January 24, 2019	NA	March 02, 2020
	Intervention 4.1	NA	NA	06–09.03.2020 (1.5 °C cooler)
	Survey 4.2 distributed	NA	NA	March 09, 2020
	Survey 4.2 closed	NA	NA	March 09, 2020
	Intervention 4.2	NA	NA	11–12.03.2020
	Focus group interview	January 10, 2019	December 12, 2018	NA
	END	February 02, 2019	December 16, 2018	March 12, 2020†

† *Experiment is suspended due to COVID pandemic and restart of the experient is currently unknown because of vigent regulations.*

References

[1] J.D. Lucas, An Integrated BIM Framework to Support Facility Management in Healthcare Environments, 2012.

[2] P.X.W. Zou, X. Xu, J. Sanjayan, J. Wang, Review of 10 years research on building energy performance gap: life-cycle and stakeholder perspectives, Energy Build. 178 (2018) 165–181, https://doi.org/10.1016/j.enbuild.2018.08.040.

[3] M. Ornetzeder, M. Wicher, J. Suschek-Berger, User satisfaction and well-being in energy efficient office buildings: evidence from cutting-edge projects in Austria, Energy Build. 118 (2016) 18–26, https://doi.org/10.1016/j.enbuild.2016.02.036.

[4] P.A. Jensen, Knowledge transfer from facilities management to building projects: a typology of transfer mechanisms, Architect. Eng. Des. Manag. 8 (2012) 170–179, https://doi.org/10.1080/17452007.2012.669131.

[5] H. Knudsen, R. Andersen, A. Hansen, House Owners' Interest and Actions in Relation to Indoor Temperature, Air Quality and Energy Use Proc. Clima., 2016. http://vbn.aau.dk/files/234609590/Paper_Clima2016_hnk.pdf.

[6] J.K. Day, W. O'Brien, Oh behave! Survey stories and lessons learned from building occupants in high-performance buildings, Energy Res. Soc. Sci. 31 (2017) 11–20, https://doi.org/10.1016/j.erss.2017.05.037.

[7] R.J. Cole, Z. Brown, Reconciling human and automated intelligence in the provision of occupant comfort, Intell. Build. Int. 1 (2009) 39–55, https://doi.org/10.3763/inbi.2009.0007.

[8] S. Karjalainen, Should it be automatic or manual - the occupant's perspective on the design of domestic control systems, Energy Build. 65 (2013) 119–126, https://doi.org/10.1016/j.enbuild.2013.05.043.

[9] J.K. Day, L.L. Heschong, Understanding behavior potential: the role of building interfaces. ACEEE Summer Study Energy Effic, Build., 2016, 2016, https://www.researchgate.net/publication/308141281.

[10] A.C. Boerstra, Personal Control over Indoor Climate in Offices Impact on Comfort, Health & Productivity, Eindhoven University of Technology, 2016.

[11] A. Leaman, B. Bordass, Productivity in buildings: the "killer" variables, Build. Res. Inf. 27 (1999) 4–19, https://doi.org/10.1080/096132199369615.

[12] A.C. Boerstra, M. Te Kulve, J. Toftum, M.G.L.C. Loomans, B.W. Olesen, J.L. M. Hensen, Comfort and performance impact of personal control over thermal environment in summer: results from a laboratory study, Build. Environ. 87 (2015) 315–326, https://doi.org/10.1016/j.buildenv.2014.12.022.

[13] N. Baker, M. Standeven, Thermal Comfort for Free-Running Buildings, Energy Build, 1996, https://doi.org/10.1016/0378-7788(95)00942-6.

[14] M. Kwon, H. Remøy, A. van den Dobbelsteen, U. Knaack, Personal control and environmental user satisfaction in office buildings: results of case studies in The Netherlands, Build, Environ. Times 149 (2019) 428–435, https://doi.org/10.1016/j.buildenv.2018.12.021.

[15] M.A. Humphreys, J.F. Nicol, Understanding the adaptive approach to thermal comfort, Build. Eng. (1998) 1–14.

[16] R.T. Hellwig, Perceived control in indoor environments: a conceptual approach, Build. Res. Inf. 43 (2015) 302–315, https://doi.org/10.1080/09613218.2015.1004150.

[17] J.Y. Park, M.M. Ouf, B. Gunay, Y. Peng, W. O'Brien, M.B. Kjærgaard, Z. Nagy, A critical review of field implementations of occupant-centric building controls, Build. Environ. (2019) 106351, https://doi.org/10.1016/j.buildenv.2019.106351.

[18] W. Jung, F. Jazizadeh, Human-in-the-loop HVAC operations: a quantitative review on occupancy, comfort, and energy-efficiency dimensions, Appl. Energy 239 (2019) 1471–1508, https://doi.org/10.1016/j.apenergy.2019.01.070.

[19] D.S. Khan, J. Kolarik, P. Weitzmann, Design and application of occupant voting systems for collecting occupant feedback on indoor environmental quality of buildings – a review, Build. Environ. (2020) 107192, https://doi.org/10.1016/j.buildenv.2020.107192.

[20] Smart Buildings Center, Keeping Employees Productive through Thermal Comfort the Value of Thermal Comfort in the Workplace, vol. 9, 2015, pp. 1–4.

[21] J. Berquist, M. Ouf, W. O'Brien, A method to conduct longitudinal studies on indoor environmental quality and perceived occupant comfort, Build. Environ. 150 (2019) 88–98, https://doi.org/10.1016/j.buildenv.2018.12.064.

[22] Y. Peng, Z. Nagy, A. Schlüter, Temperature-preference learning with neural networks for occupant-centric building indoor climate controls, Build. Environ. 154 (2019) 296–308, https://doi.org/10.1016/j.buildenv.2019.01.036.

[23] J. Kim, Y. Zhou, S. Schiavon, P. Raftery, G. Brager, Personal comfort models: predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning, Build. Environ. 129 (2018) 96–106, https://doi.org/10.1016/j.buildenv.2017.12.011.

[24] M. Pritoni, K. Salmon, A. Sanguinetti, J. Morejohn, M. Modera, Occupant thermal feedback for improved efficiency in university buildings, Energy Build. 144 (2017) 241–250, https://doi.org/10.1016/j.enbuild.2017.03.048.

[25] S.K. Gupta, S. Atkinson, I. O'Boyle, J. Drogo, K. Kar, S. Mishra, J.T. Wen, BEES: real-time occupant feedback and environmental learning framework for collaborative thermal management in multi-zone, multi-occupant buildings, Energy Build. 125 (2016) 1–13, https://doi.org/10.1016/j.enbuild.2016.04.084.

[26] A.T. Alan, M. Shann, E. Costanza, S.D. Ramchurn, S. Seuken, It is too hot: an in-situ study of three designs for heating. Conf. Hum. Factors Comput. Syst. - Proc., Association for Computing Machinery, 2016, pp. 5262–5273, https://doi.org/10.1145/2858036.2858222.

[27] D.A. Winkler, A. Beltran, N.P. Esfahani, P.P. Maglio, A.E. Cerpa, FORCES: feedback and control for occupants to refine comfort and energy savings. UbiComp 2016 - Proc. 2016 ACM Int. Jt. Conf. Pervasive Ubiquitous Comput., Association for Computing Machinery, Inc, 2016, pp. 1188–1199, https://doi.org/10.1145/2971648.2971700.

[28] K. Konis, L. Zhang, Occupant-aware energy management: simulated energy savings acheivable through application of temperature setpoints learned through end user feedback. ASHRAE IBPSA-USA SimBuild 2016 Build. Perform. Model. Conf., 2016, pp. 283–289. www.ashrae.org.

[29] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, User-led decentralized thermal comfort driven HVAC operations for improved efficiency in office buildings, Energy Build. 70 (2014) 398–410, https://doi.org/10.1016/j.enbuild.2013.11.066.

[30] Q. Zhao, Y. Zhao, F. Wang, Y. Jiang, F. Zhang, Preliminary study of learning individual thermal complaint behavior using one-class classifier for indoor environment control, Build. Environ. 72 (2014) 201–211, https://doi.org/10.1016/j.buildenv.2013.11.009.

[31] M. Rittenbruch, J. Donovan, Y. Santo, Evaluating the use of ambient and tangible interaction approaches for personal indoor climate preferences. UbiComp 2014 - Adjun. Proc. 2014 ACM Int. Jt. Conf. Pervasive Ubiquitous Comput., Association for Computing Machinery, Inc, 2014, pp. 159–162, https://doi.org/10.1145/2638728.2638755.

[32] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, Human-building interaction framework for personalized thermal comfort-driven systems in office buildings, J. Comput. Civ. Eng. 28 (2014) 2–16, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000300.

[33] A. Hang-yat, D. Wang, Carrying my environment with Me : a participatory-sensing approach to enhance thermal comfort. BuildSys '13, 2013, https://doi.org/10.1145/2528282.2528286.

[34] S. Purdon, B. Kusy, R. Jurdak, G. Challen, Model-free HVAC control using occupant feedback, in: Proc. - Conf. Local Comput. Networks, LCN, 2013, pp. 84–92, https://doi.org/10.1109/LCNW.2013.6758502.

[35] F. Jazizadeh, A. Ghahramani, B. Becerik-Gerber, T. Kichkaylo, M. Orosz, Personalized thermal comfort driven control in HVAC operated office buildings, Comput. Civ. Eng., 2013, pp. 218–225, 218.

[36] B. Balaj, H. Teraoka, R. Gupta, A. Yuvraj, ZonePAC: zonal power estimation and control via HVAC metering and occupant feedback bharathan, in: BuildSys '13, ACM, 2013.

[37] K.S. Konis, Leveraging ubiquitous computing as a platform for collecting real-time occupant feedback in buildings, Intell. Build. Int. 5 (2013) 150–161, https://doi.org/10.1080/17508975.2013.781499.

[38] V.L. Erickson, A.E. Cerpa, Thermovote: participatory sensing for efficient building HVAC conditioning. BuildSys '12 Proc. Fourth ACM Work. Embed. Sens. Syst, . Energy-Efficiency Build., 2012, pp. 9–16.

[39] F. Jazizadeh, B. Becerik-Gerber, Toward adaptive comfort management in office buildings using participatory sensing for end user driven control, in: Buildsys'12 (Ed.), ACM, 2012, pp. 1–8.

[40] T. Sood, M. Quintana, P. Jayathissa, M. Abdelrahman, C. Miller, The SDE4 Learning Trail: crowdsourcing occupant comfort feedback at a net-zero energy building, J. Phys. Conf. Ser. 1343 (2019), https://doi.org/10.1088/1742-6596/1343/1/012141.

[41] P. Jayathissa, M. Quintana, T. Sood, N. Nazarian, C. Miller, Is your clock-face cozie? A smartwatch methodology for the in-situ collection of occupant comfort data, J. Phys. Conf. Ser. 1343 (2019), https://doi.org/10.1088/1742-6596/1343/1/012145.

[42] T. Sood, P. Janssen, C. Miller, Spacematch: Using Environmental Preferences to Match Occupants to Suitable Activity-Based Workspaces, 2020, https://doi.org/10.3389/fbuil.2020.00113.

[43] W. O'Brien, M. Schweiker, J.K. Day, Get the picture? Lessons learned from a smartphone-based post-occupancy evaluation, Energy Res. Soc. Sci. 56 (2019), https://doi.org/10.1016/j.erss.2019.101224.

[44] S. Purdon, B. Kusy, R. Jurdak, G. Challen, Model-free HVAC control using occupant feedback. Proc. - Conf. Local Comput. Networks, LCN, 2013, https://doi.org/10.1109/LCNW.2013.6758502.

[45] L.R. Rabbitt, J.A. Hasselgren, C. Cook, Y.B. Sirotin, Measuring satisfaction with standard survey instruments and single-button responses on kiosks, Proc. Hum. Factors Ergon. Soc. Annu. Meet. (2018), https://doi.org/10.1177/1541931218621325.

[46] N. Lassen, T. Josefsen, Experimental setup and testing of an in-field system for real-Time occupant feedback, IOP Conf. Ser. Mater. Sci. Eng. (2019), https://doi.org/10.1088/1757-899X/609/4/042045.

[47] N. Lassen, Case study of personal heaters in a Plus energy building – simulations of potential energy savings and results from a field test, in: 1st Nord, Conf. Zero Emiss. Plus Energy Build. IOP Conf. Ser. Earth Environ. Sci. 352 (2019) 1–8, https://doi.org/10.1088/1755-1315/352/1/012051.

[48] N. Lassen, F. Goia, S. Schiavon, J. Pantelic, Field investigations of a smiley-face polling station for recording occupant satisfaction with indoor climate, Build. Environ. 185 (2020), 107266, https://doi.org/10.1016/j.buildenv.2020.107266.

[49] J. Kim, R. de Dear, C. Cândido, H. Zhang, E. Arens, Gender differences in office occupant perception of indoor environmental quality (IEQ), Build, Environ. Times (2013), https://doi.org/10.1016/j.buildenv.2013.08.022.