A BIM-based approach towards personalized low-cost thermal comfort monitoring using digital twins

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Abstract. Heating, ventilation, and air conditioning (HVAC) systems help regulate indoor temperatures to maintain the comfort and productivity of building occupants. However, the global climate and energy crisis requires robust energy conservation measures to reduce electricity and heat consumption, particularly in HVAC-dominated building operations. To reduce energy consumption caused by building operations, the digital twin (DT) concept has focused on integrating new technologies and methodologies, such as the Internet of Things and building information modelling (BIM), for application in the field of thermal comfort and energy management. However, the adoption of digital twins faces limitations, including insufficient research on personalized thermal comfort models and a lack of consensus in the definition and design of digital twins. This study addresses the limitations by using a formal foundation to implement a BIM-based DT for personalized thermal comfort monitoring that integrates indoor environmental data and occupant feedback for analysis, visualization, and control of personalized thermal comfort in buildings.

Keywords: Personalized thermal comfort, smart monitoring, digital twins, Internet of Things (IoT), indoor environment.

1. Introduction

Energy consumption in the built environment has the potential to be reduced, particularly in buildings with heating, ventilation, and air conditioning (HVAC) systems, which account for 26 % of the global CO_2 emissions (IEA et al., 2023) . However, reducing the energy consumption in buildings may come at the cost of a comfortable indoor environment (Solano et al., 2021), jeopardizing the health and productivity of occupants in indoor environments, such as schools, university lecture halls, hospitals, or offices. The digital twin (DT) concept, which combines innovative technologies, including Internet of Things (IoT) technologies, wireless sensor systems, or building information modelling (BIM), has received increased attention in the field of civil and environmental engineering (Smarsly et al., 2024) Current research reveals a growing body of studies integrating BIM-based DTs, thermal comfort, and energy management with emphasis on optimization for HVAC systems (Hosamo et al., 2022). The International Energy Agency (IEA) is investigating energy efficiency in buildings, particularly focusing on standardizing *openBIM* methods for developing BIM-based digital twins for building energy management and thermal comfort simulations (Zucker, 2023).

Nevertheless, the adoption of DT concepts in the field of thermal comfort, although promising, has revealed certain limitations, such as insufficient research on personalized thermal comfort models, i.e. the assessment of thermal comfort for each individual occupant in an indoor space (Arakawa Martins et al., 2022). Moreover, research integrating thermal comfort and digital twins mostly focuses on monitoring air temperature and relative humidity, neglecting other important environmental parameters, such as mean radiant temperature and air velocity (Arowoiya et al., 2023). In addition, the majority of DT research focuses on project-specific implementations, and there is a lack of universal consensus on the definition and components of DTs (Sharma et al., 2022). A clear definition of DTs would facilitate (i) efficient communication between engineers and facility managers and (ii) enhance thermal comfort analysis to ensure the health and productivity of building occupants, while keeping the energy consumption of HVAC systems low.

This study builds upon a well-defined DT architecture based on a comprehensive study on digital twins for civil engineering (Al-Nasser et al., 2024), to facilitate the collection, analysis, and visualization of personalized thermal comfort data. In this paper, a thermal comfort monitoring system based on low-cost hardware components, IoT technologies, and digital twins to evaluate personalized thermal comfort, is presented. Wireless sensor nodes, or *thermal comfort stations*, whose development is described in more detail in Chillon Geck et al. (2023), are calibrated in a climate chamber and deployed in a decentralized fashion in an office environment. The thermal comfort stations collect indoor environmental data and automatically calculate the personalized predicted mean vote (PPMV), an enhancement of the predicted mean vote (PMV) thermal comfort index, newly proposed in this paper. The PPMV index is calculated by incorporating a digital thermal comfort survey that collects feedback from building occupants, including the clothing ensemble and the activity level. Moreover, the digital survey captures subjectively perceived thermal sensations and interactions with the built environment. The monitoring system integrates the data collected from the thermal comfort stations and the digital survey to calculate the PPMV index for each building occupant. The thermal comfort monitoring system is designed to be coupled to BIM-based digital twins where users can visualize real-time and historical thermal comfort data in a 3D environment. By interacting with the DT, users are enabled to act on the indoor environment, creating a bidirectional communication channel between the virtual and physical worlds.

The remainder of this paper is organized as follows. In the following section, the thermal comfort monitoring system is presented, including the hardware and software development of the monitoring system. Next, the calibration of the thermal comfort stations in a climate chamber to ensure the accuracy is explained. Then, the thermal comfort monitoring system is deployed in an office environment for which a BIM-based DT has been implemented, taking a formal architecture as a reference. The paper concludes with a summary of the key findings and a discussion of future research that may be conducted to further advance DTs for thermal comfort monitoring and energy-efficient buildings.

2. A personalized thermal comfort monitoring system based on digital twins

This section presents the architecture and the main elements of the monitoring system, developed to assess personalized thermal comfort. The monitoring system is built using low-cost hardware components and open-source software, designed to facilitate the collection of environmental data and occupant feedback for personalized thermal comfort. The monitoring system architecture, shown in Figure 1, comprises four integral elements, which are introduced in the following subsections:

1. *Thermal comfort stations*, including a microcontroller with IoT capabilities as well as sensors to measure air temperature (t_a), relative humidity (RH), mean radiant temperature (MRT), and air velocity (v_a).
2. A *portable main station* for data integration that handles (i) data storage and (ii) data communication between building occupants and the thermal comfort stations.
3. A *user interface* consisting of a digital thermal comfort survey to collect occupant feedback.
4. A *digital twin* that supports user control via bidirectional communication to visualize and retrieve real-time and historical thermal comfort data.

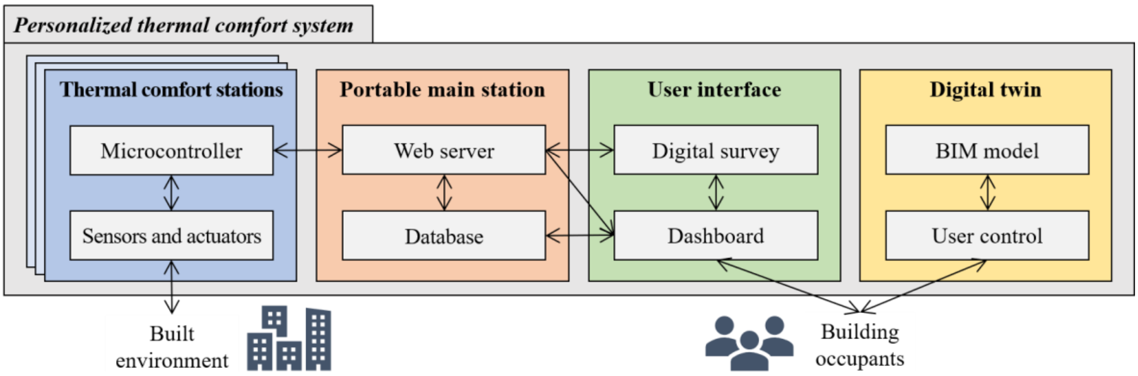
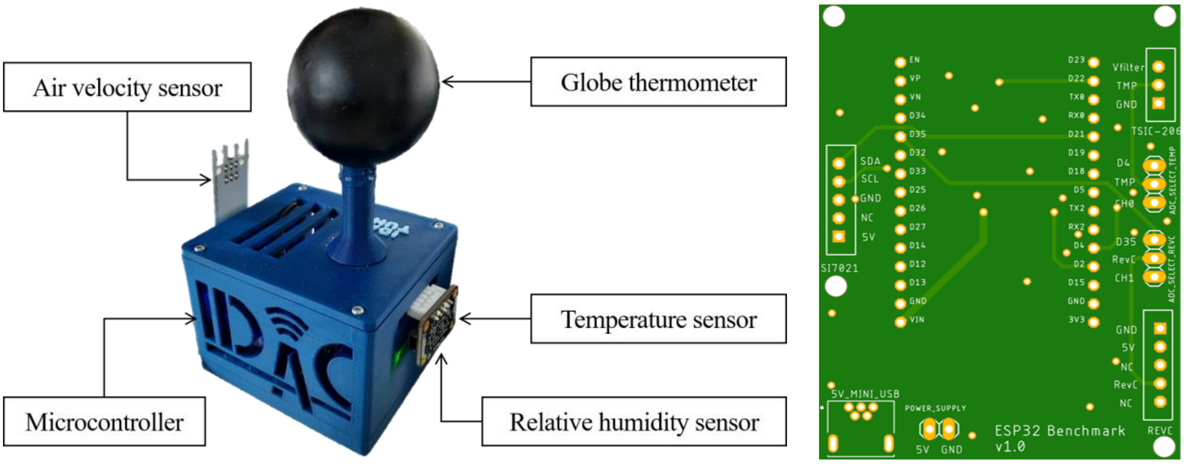


Figure 1: Monitoring system architecture

2.1 Thermal comfort stations

The thermal comfort stations include three low-cost sensors, (1) a combined sensor of the type Adafruit BME280 that measures the air temperature and RH, (2) an air velocity sensor, type Modern Device Rev. C, and (3) a temperature sensor, type B+B Sensors TSic 206-TO92, which is installed in a black-painted table tennis ball, forming a low-cost globe thermometer. The globe temperature is used with the air temperature and the air velocity to calculate the MRT. An ESP32 microcontroller, type Espressif WROOM-32, handles processing of the raw environmental data and periodically sends the data to the web server via Wi-Fi using the HTTP protocol. The microcontroller of the thermal comfort stations embeds the software application designed to collect sensor data and to exchange environmental and thermal comfort data with the main station. In addition, the software application is designed to calculate the PPMV onboard the microcontroller. The algorithm for calculating the PPMV index is implemented by adapting the pseudocode available in the ASHRAE Standard 55-2020 (ASHRAE, 2020). The output of the PPMV index corresponds to a value on a 7-point scale of the ASHRAE Standard 55-2020, where -3 represents cold sensation, +3 represents warm sensation, and an index of 0 expresses neutral thermal sensation. The hardware has been selected based on the following criteria: Low price, low power consumption, size, and operability at 5 V. The final price of a thermal comfort station is less than EUR 50. Figure 2a shows the final appearance of the thermal comfort station including the components. The components are wired to a printed circuit board (PCB) inside the thermal comfort station. The design of the PCB is shown in Figure 2b.



a) Final assembly

b) PCB design

Figure 2: Thermal comfort station

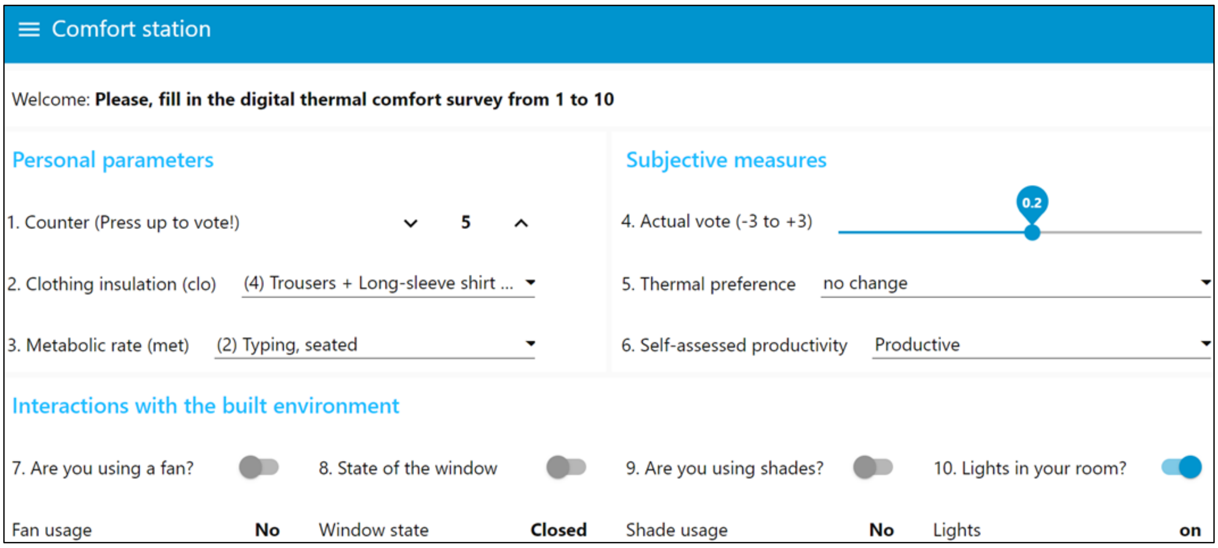
2.2 Portable main station

The portable main station consists of a Raspberry Pi (RPi) model 4B that hosts a web server supporting the monitoring system. The web server is built using the Node-RED framework. Node-RED is open source and compatible with the Raspbian operating system of the RPi. By using the Node-RED framework, programmers may implement web servers with a visual programming interface, creating flows consisting of predefined nodes. In Node-RED, flows are used to implement backend services, i.e. data communication and data management. *Flows* consist of interconnected nodes, which serve as basic building blocks performing computational actions on the data. *Nodes* in Node-RED are triggered by either receiving messages from the previous node in a flow, or by waiting for some external event, such as an incoming communication request. The nodes process the messages, or events, and then send a message to the next node in the flow. A node can have one input and as many outputs as the logic of the flow requires. In this work, the RPi-based web server receives the thermal comfort data, i.e. the environmental data and the PPMV index, from the thermal comfort stations. The price of a RPi used for the portable main station is EUR 52. The total price for a thermal comfort monitoring system with one thermal comfort station and one portable main station is EUR 100.

2.3 Digital thermal comfort survey

The digital thermal comfort survey is devised to collect feedback from building occupants. To collect the feedback, the building occupants use a personalized web application. The PPMV index is estimated using the environmental data collected by the thermal comfort stations and the feedback of the occupants, as required by international thermal comfort standards (ASHRAE, 2020; ISO, 2005) and dedicated literature (Nicol et al., 2012). The survey is displayed in the web application as shown in Figure 3, and comprises ten categories:

1. Personal parameters, which include (a) *clothing insulation* (I_{cl}), quantifying the clothing ensemble worn by an occupant and expressed in units of *clo*, and (b) *metabolic rate* (*MET*) quantifies the intensity of different types of office activity performed by a building occupant, measured in *met* units.
2. Subjective measures, including the (a) *actual vote*, describing how the building occupants feel on the ASHRAE 7-point thermal comfort scale, (b) *thermal preference,* which represents the preference of building occupants for the environment, and (c) *self-assessed productivity*, measuring the self-rated productivity in a qualitative scale.
3. Interactions with the built environment, which collect information on the usage of fans, windows, shades, and lights.



Welcome: **Please, fill in the digital thermal comfort survey from 1 to 10**

Personal parameters

1. Counter (Press up to vote!) 5
2. Clothing insulation (clo) (4) Trousers + Long-sleeve shirt ...
3. Metabolic rate (met) (2) Typing, seated

Subjective measures

4. Actual vote (-3 to +3) 0.2
5. Thermal preference no change
6. Self-assessed productivity Productive

Interactions with the built environment

7. Are you using a fan?
8. State of the window
9. Are you using shades?
10. Lights in your room?

Fan usage **No**

Window state **Closed**

Shade usage **No**

Lights **on**

Figure 3: Prototype of the digital thermal comfort survey, as part of the web application

2.4 Digital twin

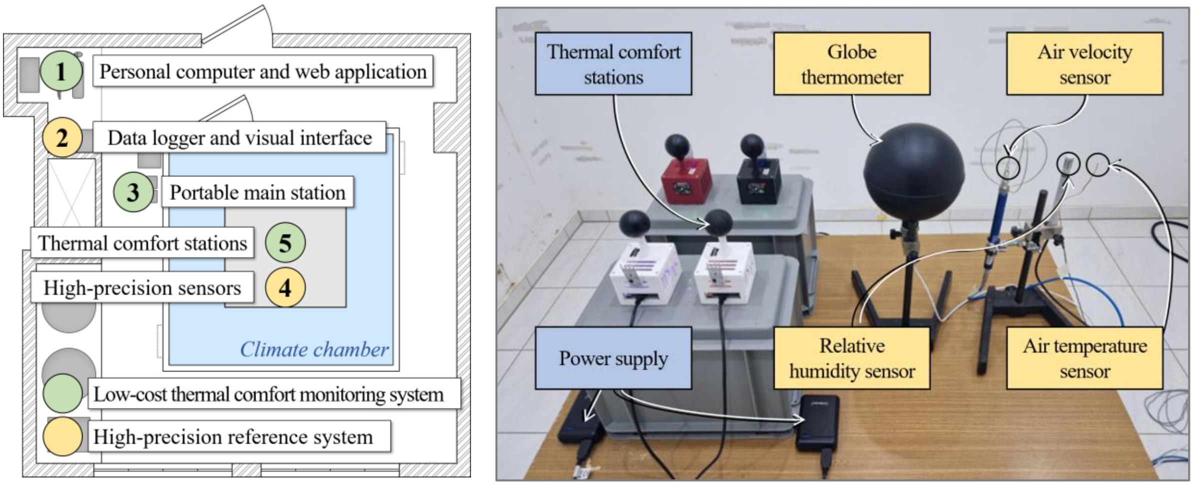
The design of the DT architecture is based on a formal architecture for digital twins in civil engineering, proposed by Al-Nasser et al. (2024). The implementation of the DT is adapted to personalize thermal comfort and to include the sensor data and the feedback from the building occupants, integrated in the web server of the system. Regarding the software implementation, Rhino (TLM, inc) is used to create BIM models of indoor environments, including geometric and semantic information, while Grasshopper is used to connect BIM models with data provided by wireless sensor nodes. Specifically, Grasshopper interfaces connect via Wi-Fi to the Node-RED framework, which forwards the sensor data collected from the thermal comfort stations via Wi-Fi to Grasshopper. The data can be visualized by users in real-time and in the 3-dimensional BIM models. In addition, users may query the DT to visualize and retrieve historical thermal comfort data by using interfaces created with the add-on Human UI (NBBJ).

3. Calibration of the thermal comfort stations

Before being deployed in a real-world office environment, the sensors of the thermal comfort monitoring system are calibrated in a climate chamber using high-precision sensors as a reference, as shown in Figure 4 (blue) and listed in Table 1. Four thermal comfort stations (CS_1 to CS_4) and the high-precision sensors, are placed on a table next to each other to measure the air temperature, the globe temperature, the RH, and the air velocity. For calibration, the four walls, the floor, and the ceiling of the climate chamber are set to different temperatures, to obtain calibration curves by measuring the environmental parameters at different stationary and transient temperatures.

Table 1: Reference sensors used in the calibration procedure in the climate chambers.

Parameter	**Reference sensor**	**Accuracy**	**Resolution**	**Range**	**Low-cost sensor**
t_a	NTC type N	±0.2 K	0.01 K	-20°C to 100°C	Si7021
RH	Capacitive sensor	±0.2 K	0.01 K	5 % to 98 %	Si7021
MRT	150 mm black globe with Pt100 element	±(0.3+0.005|T|) K	0.01 K	-40°C to 200°C	TSic 206-TO92
v_a	Omnidirectional thermo-anemometer	±(1 % of final value + 3 % of measured value + 2 digits)	0.001 m/s	0.01 m/s to 1 m/s	Rev. C

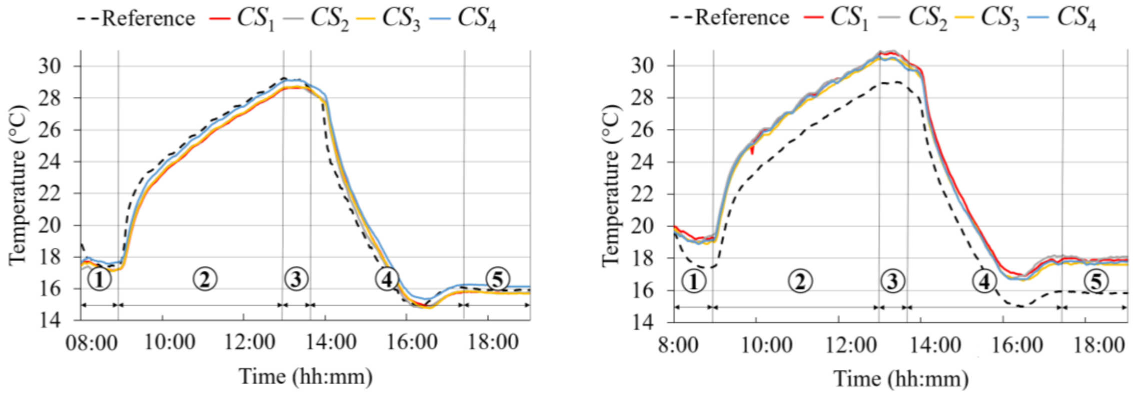


a) Ground plan

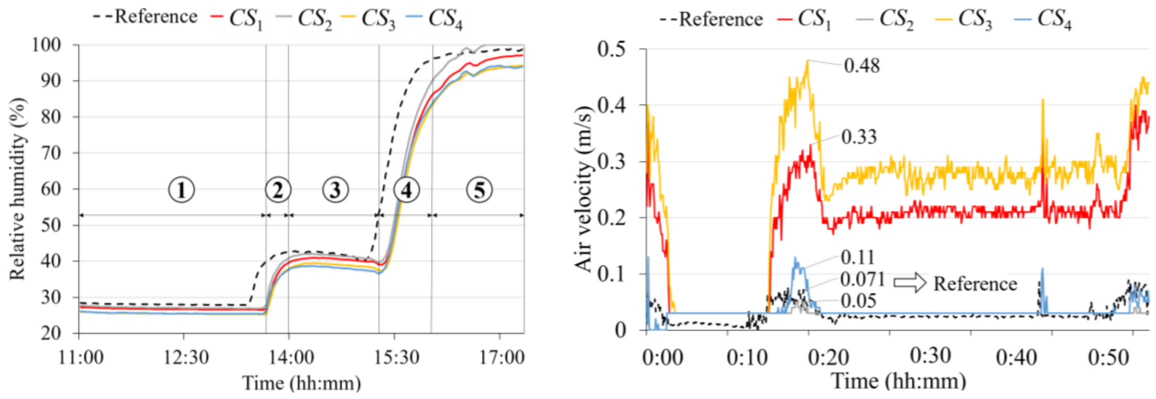
b) Setup of the low-cost sensors (blue) and the high-precision reference sensors (yellow)

Figure 4: Setup of the calibration tests in the climate chamber

The results of the calibration procedure for the thermal comfort stations (CS_1 to CS_4) are shown in Figure 5. In Figure 5a and Figure 5b, the results of calibrating the air and globe temperature sensors using are depicted, with the different phases of the calibration procedure indicated as follows. The climate chamber is set to stationary temperatures of 18 °C (phase 1), 28 °C (phase 3), and 16 °C (phase 5); and to two transient phases, phase 2 (from 18 °C to 28 °C) and phase 4 (from 28 °C to 16 °C). The calibration of the humidity sensor is conducted using a humidifier device. The RH is measured first without influence of the humidifier (to obtain a reference value) and then under increasing humidity conditions until reaching saturation, i.e. $RH = 100$ %, as illustrated in Figure 5c. The air velocity sensor is compared to a high-precision omnidirectional anemometer calibrated for air velocities between $v_a = 0$ m/s and $v_a = 1$ m/s. The results of the test of the low-cost air velocity sensors are shown in Figure 5d.



a) Air temperature b) Globe temperature



c) Relative humidity d) Air velocity

Figure 5: Results of the calibration procedure of the thermal comfort stations

The data collected during the calibration procedure implies that the offset of the values of the low-cost air temperature sensors is smaller than the offset observed in the globe thermometers. The average offset of the air temperature sensors during the calibration experiments corresponds to $\bar{t}_{\mathrm{a}}$ = 0.221 °C, and the average offset of the globe temperature is $\bar{t}_g$ = -1.86 °C. The offsets of both the low-cost air temperature sensor and the globe thermometer affect the value of the PPMV, and are thus corrected by adjusting the offset in the software embedded in the thermal comfort stations. The four low-cost sensors capture the same changes in air velocity as the high-precision sensor, as can be seen from the simultaneous peaks in the figure. However, two of the low-cost sensors, CS_1 and CS_3 measure air velocities with an average offset value of v_a = +0.25 m/s. After calibration, the thermal comfort stations are validated in an office environment, described in the next section.

4. Field validation test

To validate the capability of the low-cost system to monitor occupant thermal comfort, a four-week field test is conducted during the month of April in a moderate continental climate in the spring season, with average temperatures of 9 °C. The field test is conducted in an office environment during regular office activities under real-world conditions. For the field test, the four thermal comfort station plus a fifth one, constructed and calibrated as the four original stations, are placed in five offices. The field test is conducted in the five office rooms to collect data from four environmental parameters, i.e. t_{a}, RH, v_{a}, and t_{g} (to calculate the MRT) at 5-second intervals during three minutes, before sending an average for each parameter. Each station collects data for 4 weeks, 7 days a week, 24 hours a day, at a sampling rate of 20 data points per hour, i.e. for a total of 13,440 data points. In addition, each person taking part in the field test is assigned a dashboard to complete the digital survey. An IoT gateway establishes a local network, in which the thermal comfort stations and the digital survey are connected to the web server hosted in the portable main station. The locations of the thermal comfort stations placed in the office environment, as well as the portable main station and the IoT gateway, are shown in Figure 6. All participating offices have a similar size and the same orientation, rendering the results comparable.

Figure 7 compares the average PPMV index and the average actual vote calculated by each thermal comfort station for the corresponding building occupant. As can be seen from Figure 7, the actual vote corresponds to the vote on the subjective thermal sensation on the 7-point scale entered by the building occupants (O_1 to O_5) via the digital survey. The PPMV index, also expressed on the 7-point scale, is calculated by the thermal comfort stations and averaged over two weeks, in which the building occupants voted 272 times. The low-cost thermal comfort monitoring system aggregates and integrates the PPMV index and the actual vote, facilitating the comparison of the two values. By comparing the two average values, the suitability of the PPMV index to assess thermal comfort is examined. The absolute difference between the pair of values depicted in the figure are $O_1 = 0.45$, $O_2 = -0.38$, $O_3 = -0.08$, $O_4 = 0.18$ and $O_5 = -0.16$, respectively, indicating that thermal comfort is perceived uniquely by each occupant. In Figure 8, the digital twin is exemplarily shown, together with the user interface that enables occupants to select real-time or historical data. In the figure, the colors represent the PPMV value on the 7-point scale calculated for each office. The visualizations indicate that occupants of different offices have different PPMV values.

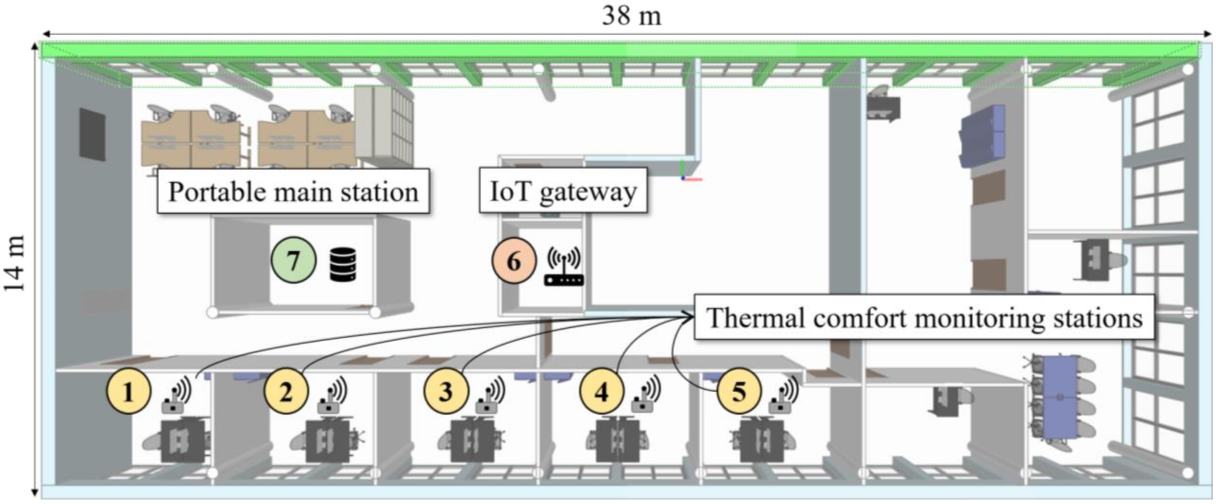


Figure 6: Setup of the validation test including the thermal comfort stations (1 to 5), the IoT gateway (6), and the portable main station (7)

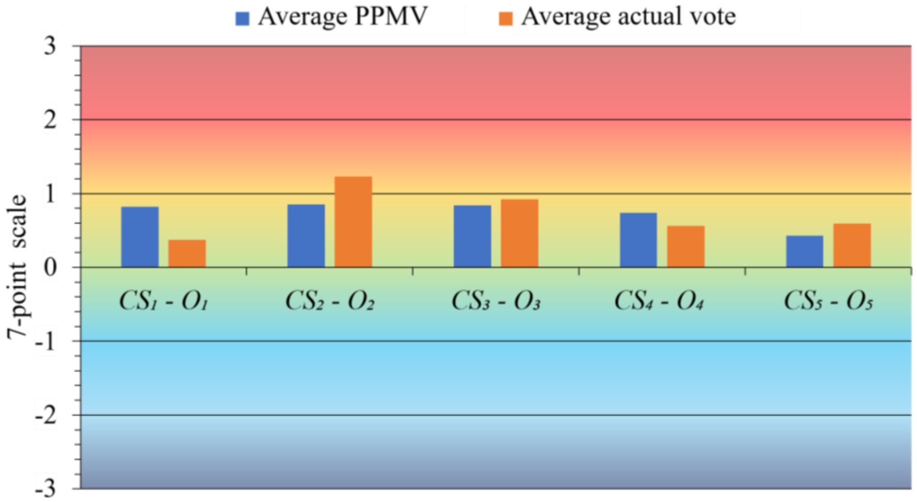


Figure 7: Comparison of the personalized PPMV index and the actual vote for all building occupants

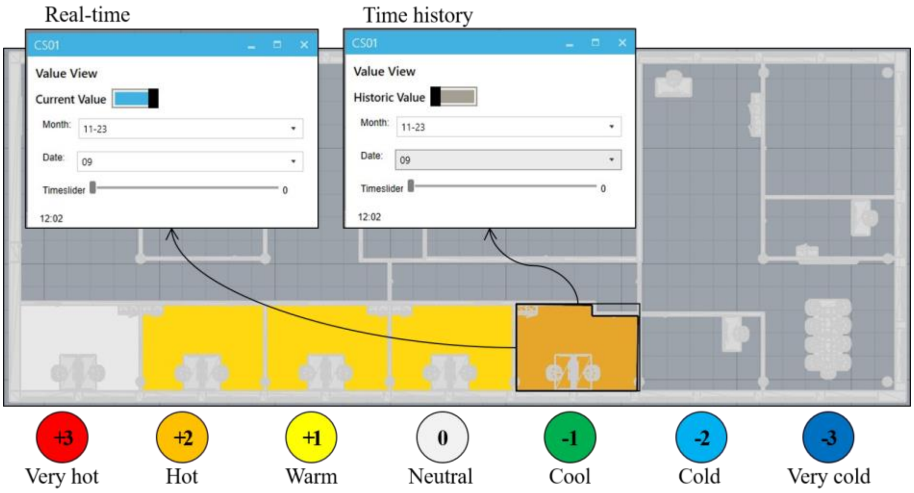


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Figure 8: Digital twin of the office environment and user interface

5. Summary and conclusions

The results of the field validation test demonstrate the potential of the thermal comfort monitoring system to collect and analyze personalized thermal comfort data. By integrating a DT into the monitoring system, the participation of building occupants through feedback collection is reinforced, and the visualization of thermal comfort data is enhanced. The system is capable of personalizing the PPMV model by comparing feedback on thermal sensation and thermal preferences of building occupants. It is expected that, with personalized thermal comfort, the conditions of indoor environments are maximized in terms of thermal comfort, health, and productivity of building occupants, whilst minimizing the energy consumption of HVAC systems. In conclusion, this work addresses the evolving needs of the built environment amidst global climate challenges by engineering sustainable smart buildings. In future research, the thermal comfort monitoring system may be used in large-scale thermal comfort surveys. Due to the bidirectional communication enabled by the DT, the system can modularly be deployed with additional actuators to control personal comfort systems, such as heating or cooling devices.

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