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# Thermal comfort and perceived air quality (PAQ) using automatic ceiling fans in residential buildings

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ABSTRACT

In warm climates, resilient and low-energy methods for cooling building occupants are needed to ensure energy-efficient and adaptive thermal comfort. Air movement, particularly through ceiling fans, is an effective way to provide comfort in warm conditions, potentially minimizing or even avoiding the need for more energy-intensive air conditioning systems. This study aims to validate an algorithm for automatically adapting ceiling fan speed in residential settings based on room thermal conditions and focuses on subjective thermal satisfaction and perceived air quality (PAQ). An environmental chamber study was conducted with 30 participants across three different indoor air temperature conditions (27 °C, 29 °C, and 31 °C) over 2-hour sessions, testing four fan operational modes: Automatic (downward flow), Manual Direct (downward flow), Manual Reverse (upward flow), and Off. Subjective thermal satisfaction and PAQ were measured using standardized questionnaires on a 7-point Likert scale. Results showed that automatic operation maintained comparable thermal satisfaction levels to manual control, with no statistically significant differences ($p > 0.3$) across all temperature conditions, indicating that the automatic algorithm successfully provided comfortable environmental conditions comparable to user-controlled settings. Direct flow mode (downward) significantly outperformed reverse flow mode in thermal satisfaction, especially at higher temperatures (29 °C and 31 °C, $p < 0.05$). Air movement in direct flow improved perceived air quality compared to the no fan condition across all temperatures ($p < 0.05$). Automatic fan control showed no difference in PAQ satisfaction across all temperature conditions ($p > 0.2$), while manual and off modes showed decreased satisfaction, particularly from 27 °C to 31 °C ($p < 0.05$). These findings demonstrate that automatic ceiling fans can achieve equivalent comfort satisfaction to manual operation while enabling a more energy-efficient alternative to traditional air conditioning. The validated automatic control system provides a practical pathway toward resilient and personalized cooling strategies in residential buildings, contributing to both climate change mitigation and the achievement of plus-energy building goals.

## 1. Introduction

### 1.1. Background and context

Recent Intergovernmental Panel on Climate Change data show global temperatures rising faster since 1970 than in any 50-year period in the last 2000 years, with projections reaching 1.5 °C above pre-industrial levels by 2040 [1]. In these warm and hot climatic conditions, which are becoming increasingly more common worldwide, it is essential to ensure indoor thermal environments that can meet people's fundamental needs for comfort and health while minimizing the related energy consumption.

Passive and low-energy cooling solutions should be fostered not only for environmental reasons, but also for global equity motivations. Access

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to energy for space cooling is insufficient, especially in the developing countries. South Asia has the highest cooling energy gap, followed by Africa, and the demand continuously rises due to climate change, population growth and energy accessibility. High energy consumption in hot-humid regions, inhabited by 33 % of the global population, is also a major concern [2]. Since 1990, space cooling energy demand has tripled, primarily from window air conditioners and ductless mini splits [3], and is expected to triple by 2050 as forecasted by IEA, potentially accounting for 50 % of peak electricity demand in hotter regions [4]. According to the IEA's Net Zero Emissions Scenario, demand for space cooling is set to more than double by 2050 even with significant efficiency improvements, as cooled floor area increases substantially, particularly in emerging market and developing economies where around three-times more cooling degree days are experienced compared to advanced economies [5]. This escalating cooling need, driven by climate change and increasing wealth in developing countries, underscores the urgent requirement for sustainable cooling solutions. Promoting low-energy cooling solutions like ceiling fans can enhance thermal comfort in developing regions with limited electricity access, contributing to global equity by providing affordable and sustainable cooling options for a broader population, while minimizing energy consumption and emissions. Air movement is one of several solutions that can reduce energy consumption related to space cooling, as detailed in the following paragraph.

### 1.2. Principles and benefits of air movement for thermal comfort

Air conditioning is a widely adopted cooling option is the use of air conditioners, however, they typically maintain narrow and constant conditions that can affect occupants' thermal adaptability. Prolonged exposure to these tightly controlled environments diminishes both physiological and psychological adaptation mechanisms, making occupants more sensitive to minor deviations from setpoint temperatures [6]. This reduced adaptive capacity disconnects occupants from natural seasonal variations and weather patterns, whereas naturally ventilated spaces promote thermal adaptation and can provide more stimulating and pleasurable thermal experiences [7,8]. Air movement, within certain temperature ranges, can deliver the same level of comfort but with a considerably lower energy consumption. Devices such as fans are used to increase the rate at which the hot and humid near-body air is replaced by cooler and drier air, fastening both the convective and evaporative heat transfer coefficients at the skin surface, facilitating increased sensible and latent heat flux from the body to the environment, thereby reducing skin temperature and enhancing thermal comfort. Several studies suggested that air movement can be effectively used to provide cooling at temperature higher up to 34 °C [9].

In countries with warm and humid climates, the use of fans is very common, both as a standalone solution, and in mixed-mode operation where natural ventilation works in conjunction with mechanical systems [10,11]. Mixed-mode buildings strategically combine natural ventilation with mechanical cooling and fans to optimize both occupant comfort and energy efficiency [7]. Fans are more affordable and widely accessible due to the lower cost and easier maintenance, making them a practical option for many individuals and communities [12]. This hybrid approach allows buildings to adapt to varying environmental conditions while minimizing energy use. By optimizing the integration of fans with natural ventilation instead of relying solely on air conditioners, it is possible to reduce energy consumption, lower greenhouse gas emissions, mitigate the adverse effects of climate change while maintaining personal comfort, and avoid the installation of new air conditioning devices in climates where today it is not needed but it could be in the future [13,14]. In addition to the impact on thermal comfort, elevated airspeed positively impacts perceived air quality by enhancing convective cooling of the mucous membranes in the nasal cavity, particularly in the olfactory region [15]. This effect is achieved through two mechanisms: (1) disruption of the thermal plume around the face at airspeeds above 0.3 m/s, which helps dilute bio-effluents, and (2) enhanced convective and evaporative cooling in the respiratory tract [16]. Even minimal air movement that doesn't affect thermal perception can improve air quality perception by stimulating facial skin thermoreceptors, with greater benefits observed at higher temperatures and relative humidity levels [15].

### 1.3. Design issues and people's expectations

Despite having several benefits, the use of air movement as a means of providing comfort cooling presents challenges related to performance design predictions and users' expectations.

Firstly, fans generate non-uniform environments, both spatially and temporally, leading to more complex design requirements as compared to air conditioners. For this reason, there have been various studies on ceiling fans to quantify the air movements in the room, as well as thermal comfort [17,18,19,20,21,22]. Careful consideration should be given to air movement distribution, as research has shown that even under seemingly optimal conditions, occupants may find localized air movement uncomfortable [23]. While a relatively high number of studies have investigated the impact of ceiling fans on people's comfort, there remain some knowledge gaps. Previous experimental work in the literature focused on empty rooms or office-type settings [24,25,26], while significant knowledge gaps exist for residential configurations. Residential environments are of a different nature with some aspects lacking in literature [27], specifically (1) furniture arrangements – the impact of typical furniture layouts on fan-induced airflow patterns, (2) occupant behaviour patterns – the impact of typical residential activities on air movement effectiveness, and 3) spatial configurations – the influence of room geometry and fan placement on ventilation performance. Furthermore, the focus of previous studies has mainly been on airflow and thermal comfort, while the impact of ceiling fans on residential IAQ and occupant perception was only marginally addressed [27].

Secondly, while air conditioning, by definition, provides stable and uniform conditions (as the set-point is chosen by the user), to provide a stable level of comfort and hence consistently meet users' expectations, a fan should change its rotational speed according to the temporal variations in air temperature and relative humidity in the room. Automation in ceiling fans has the potential to address this issue and concerns about energy efficiency and comfort, offering benefits such as electricity savings through automated shutdown when not needed and providing remote and intelligent control for enhanced comfort [28]. Automatic control of ceiling fans can present several benefits: (1) it can enable real-time adjustment of fan speed in response to the variations in room temperature and humidity, ensuring optimal comfort without constant manual intervention, and preemptively managing thermal conditions before discomfort occurs; (2) it can improve energy efficiency through smart features like occupancy-based operation and automated shutdown when air movement is not needed, while freeing up occupants' time and cognitive resources for other tasks; and (3) it can facilitate integration with other cooling systems in the building, allowing for coordinated operation and optimized performance.

However, there might be further implications for occupants' thermal comfort related with the users' perception of control over the fan settings [29]: users can be given the choice of using an automatic system or not, and systems should maintain manual override options, or in larger rooms, to use fans only in certain portions of the room. This is relevant because the ability of occupants to control the thermal environment plays a key role in their overall thermal satisfaction: perceived control over systems and conditions translates into an improved thermal perception, and this is due to a psychological influence and not only to actual physical conditions [30,31]. Despite their potential benefits, automatically operated ceiling fans are not yet widely adopted, and their impact on occupant comfort at high temperatures requires further investigation, particularly regarding adaptive control algorithms and user interaction patterns.

### 1.4. Aim and research questions of this study

Within the Horizon 2020 project Cultural-E, the researchers are developing sets of technological solutions to achieve plus-energy multi-family buildings. Such an ambitious goal can be achieved only thorough a strong reduction of the energy demand, which is easily achievable in winter with passive solutions like highly insulated envelope, but managing summer comfort without excessive energy use remains challenging. A potential solution for summer conditions is the implementation of an energy-efficient strategy for thermal comfort that implement ceiling fans in combination with lighter use of air conditioning. In this study researchers investigated smart ceiling fans as a key component of an energy-efficient cooling strategy, examining their potential to delay and reduce air conditioning use through automated speed adjustment based on indoor temperature. However, implementing such systems faces several challenges, such as, initial costs and technical integration with existing building management systems, and resistance of occupants for automated control due to perceived loss of personal control. Additionally, successful implementation requires addressing user acceptance through careful interface design and maintaining manual override options.

This research evaluates these challenges while assessing the effectiveness of an automatic ceiling fan considering different operational mode (manual/automatic with smart algorithm) and flow direction (downward/upward) to answer the following research questions: (1) How occupants in residential buildings perceive thermal environment and IAQ on exposure to air movement and in different flow directions (up and down) at different temperatures?; (2) Do occupants perceive significant difference in comfort between automated ceiling fans as compared to manual control at different temperatures?

The rest of the paper is structured as follows: the methodology section details the prototype development, testing facility setup, preliminary thermal manikin tests, participant selection, survey questions, experimental procedures, monitoring approach, and data analysis methods. In the results section, both objective and subjective results are presented, examining thermal and indoor air quality satisfaction levels. It is followed by a discussion on the impact of air movement in residential settings and the effectiveness of the automatic control algorithm. Then, the limitations of the study along with the future research directions are discussed. The last section summarizes the key findings and implications for implementing smart ceiling fans in residential buildings aiming to achieve plus-energy performance.

## 2. Methods

The study evaluates thermal comfort and indoor air quality through controlled laboratory experiments with human subjects. The experiments were carried out at the Institute for Renewable Energy, Eurac Research in Bolzano, Italy, during summer 2022. Details are provided in the following sections.

### 2.1. Prototype description

The prototype comprises two main components, namely (i) a common ceiling fan that can be controlled remotely, and (ii) a remote control-unit that integrates temperature and relative humidity sensors, and the electronics to implement the algorithm developed by Eurac Research[1]. The system has two operational modes, namely Automatic and Manual control, and two directions of flow, namely Direct (downward blowing direction) and Reverse (upward blowing direction).

The algorithm was conceived[1] for automatically adapting a ceiling fan's rotational speed, and hence the generated air velocity, based on the air temperature and relative humidity values measured in the room, and the activity level chosen by the user (three possible levels). The algorithm was designed to ensure thermal comfort (90 % satisfaction) in warm and hot conditions (26 °C – 34 °C) for different activity levels. To achieve the 90 % satisfaction target, the algorithm calculates the speed corresponding to a Predicted Percentage Dissatisfied (PPD) value of 10 %, which is the same target reported in the EN16798-1 (T able B.1) for category II, typically chosen for residential buildings. It was developed for single-fan operation for Direct flow mode and implemented into a commercial residential ceiling fan. It is possible for the users to override the algorithm at any time, and use the fan in manual mode, thus controlling the flow direction (Direct or Reverse) and ceiling fan speed (as a percentage of the maximum available speed, from 0 to 100 % in a continuous way).

The prototype used in this study, shown in Fig. 1, is a DC-powered ceiling fan (30 W, 1.20 m diameter, 0.53 m ceiling-to-blade distance). The remote controller is equipped with temperature and humidity sensors and runs the control algorithm. The controller had a backlight 16 x 2 cm display which showed the operation mode, the flow direction and the fan speed and can be operated by the user through a membrane keyboard.

According to manufacturer specifications, the conversion of the fan speed (cf_Speed) from percentage (%) as displayed on the remote control, to fan speed in revolution per minute (RPM), is given by equation (1), except for 0 % fan speed which stops the fan motors, and the fan is off.

$$cf\_Speed(RPM) = \left( cf\_Speed(\%) \times \frac{(RPM\_max - RPM\_min)}{100} \right) + RPM\_min \tag{1}$$

The default values of the minimum and maximum fan speed in RPM for both the flow directions are reported in Table 1. The RPM values differ between direct and reverse modes due to the fan's design characteristics and mechanical constraints.

### 2.2. Testing facility

The experiments were carried out in Eurac Research's "Façade System Interactions Lab", located in Bolzano, Italy [32]. The facility comprises of two identical environmental chambers (each 4 m wide, 8 m deep and 3 m high) as shown in Fig. 2. Based on the experimental requirements, air and surface temperatures, relative humidity, and ventilation modes can be controlled independently in both chambers.

For these tests, the ceiling fan was suspended in both the chambers at a floor-to-blades distance of 2.2 m, and to simulate a residential environment, both chambers were equipped with typical household furniture: couch seats, a lounge table, a TV stand with a monitor display, a table with four chairs, an artificial plant, and curtains, as shown in Fig. 3. This served a crucial purpose, as these obstacles create a realistic air movement pattern, similar to what a user would experience in an actual residential setup. Moreover, by providing a familiar environment, the ecological validity of the study could be improved, allowing participants to respond more naturally and accurately to the indoor

[1] A detailed description of the algorithm is given in the deliverable "D2.3 – Fan/HVAC control strategies and integration guidelines" of H2020 4RinEU project. This report and the algorithm details are confidential and cannot be disclosed publicly for contractual obligation. For more information, both Eurac and Vortice must be contacted.


**Fig. 1.** Ceiling fan and remote control.

**Table 1**
Fan speed (rpm) default values.

| Flow direction | Minimum fan speed in RPM (RPM_min) | Maximum fan speed in RPM (RPM_max) |
|---|---|---|
| Direct | 50 | 235 |
| Reverse | 35 | 190 |

conditions they experienced.

The dimensions of the furniture used in the experiment are reported in the Table 2.

The fan remote controllers were placed on the lounge table, close to the participants for easy access, and the monitored air temperature and relative humidity were hidden from the display in order not to influence the participants' judgement.

To achieve the required indoor environment, the Air Handling Unit was set to 150 $m^3$/h supply and return airflow rate, with supply from the floor and return from ceiling. The radiant panels on the floor and ceiling only were turned on and set at the required temperature, while the radiant panels on the walls were left off. The overall configurations in both the chambers used were the same. In each chamber, only one subject was present at the time.

### 2.3. Preliminary test with thermal manikin for air speed characterization

For the same configuration of the laboratory, the air speeds were measured under the fan, in the area where the participants were seated, at four heights: 0.1, 0.6, 1.1, and 1.7 m, which represent ankle, abdomen and head level for a sitting and/or standing person, in compliance with EN ISO 7726:2001 [34]. A thermal manikin was also placed on the sofa to replicate the effect of air movement as would happen with a participant seated on the designated location, and the measurements were carried out at eight precise locations, as shown in Fig. 4. For both flow

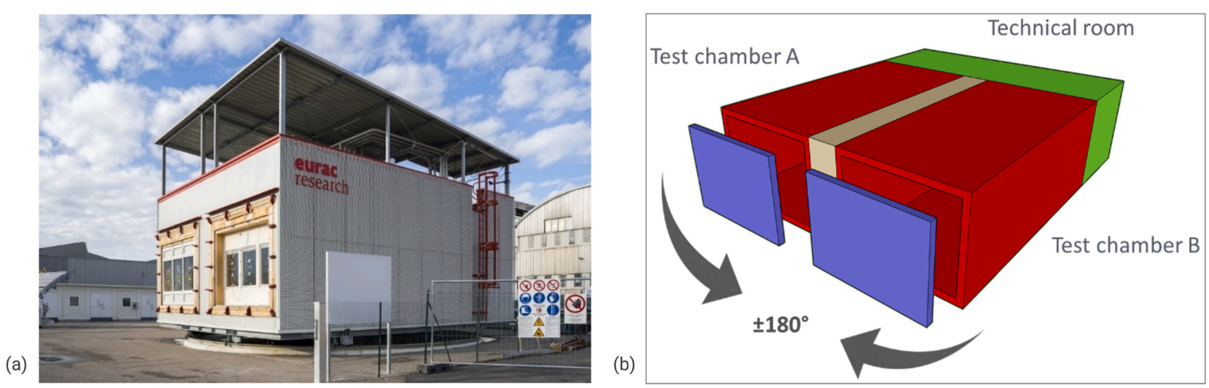


**Fig. 2.** Eurac Research's Facade system interaction lab (a) outdoor, (b) architecture (adapted from [33]).

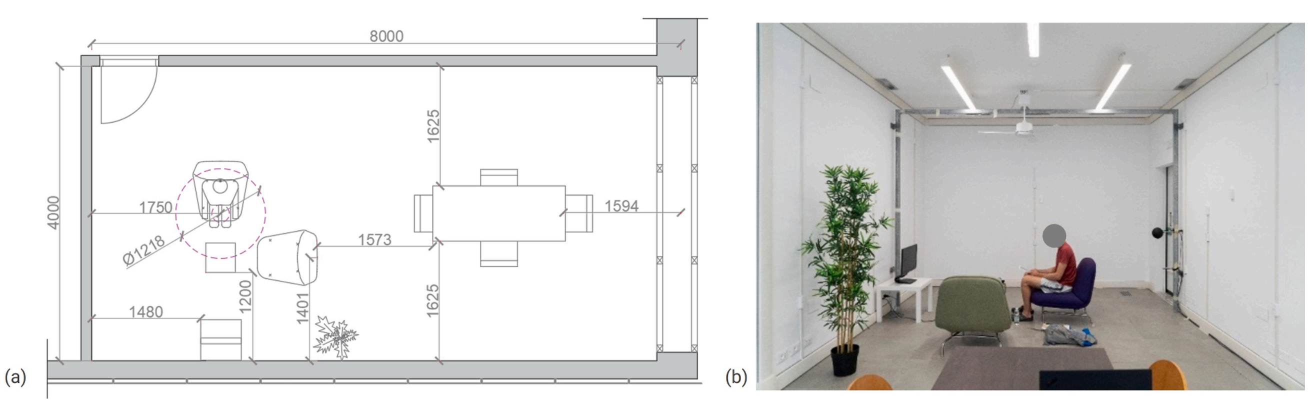


**Fig. 3.** Laboratory internal setup.

**Table 2**
Furniture used during the experiments in each chamber.

| Type | Dimensions (L x B x H cm) | Nr. |
|---|---|---|
| Couch seats | 81 x 74 x 78 | 2 |
| Lounge table | 40 x 40 x 45 | 1 |
| PC monitor | 55 x 46 x 8 | 1 |
| TV stand | 55 x 55 x 46 | 1 |
| Wooden table | 180 x 75 x 74 | 1 |
| Wooden chairs | 50 x 50 x 86 | 4 |
| Artificial plant | 22.5 x 22.5 x 180 | 1 |
| Curtains | 140 x 280 | |

**Table 3**
List of tests carried out with the different fan settings, and fan speed levels (with their corresponding RPM values as per manufacturer specifications).

| Test Name | Fan | Direction | Fan speed level | cf_Speed |
|---|---|---|---|---|
| **Off** | OFF | – | Off | 0 % (0 rpm) |
| **D_L1** | ON | Direct | Low (L1) | 33 % (111 rpm) |
| **D_L2** | ON | Direct | Medium (L2) | 66 % (172.1 rpm) |
| **D_L3** | ON | Direct | High (L3) | 100 % (235 rpm) |
| **R_L1** | ON | Reverse | Low (L1) | 33 % (86.15 rpm) |
| **R_L2** | ON | Reverse | Medium (L2) | 66 % (137.3 rpm) |
| **R_L3** | ON | Reverse | High (L3) | 100 % (190 rpm) |

directions, that is Direct (D) and Reverse (R), three different speed levels were monitored: low (L1, cf_Speed = 33 %), medium (L2, cf_Speed = 66 %), and high (L3, cf_Speed = 100 %), along with a baseline Off condition. These test conditions are reported in Table 3, along with their corresponding RPM values based on manufacturer specifications. The measurement at each of the eight points was carried out for 5 min, and the analysis was focused on the average of the final 180 s of the 5-minute period to ensure stability of the air speed.

Based on the above-mentioned tests, the average of the air velocities, at the eight points and the 4 specific heights were plotted, as shown in Fig. 5, along with the linear regression model. The figure also reports the equations for the direct and reverse flow direction, for calculating the air speed ($V_a$) at the different height planes (0.1, 0.6, 1.1, and 1.7 m) with respect to the ceiling fan speed (0–100 %).

The thermal manikin, dressed to match participant's clothing insulation level, was used to measure the heat flux required to maintain a constant skin temperature of 34 °C. The manikin was divided into 5 different body parts for the purpose of the analysis, namely Overall (full body), Face, Torso, Arms and Legs, as shown in Fig. 4. Fig. 6 demonstrates the linear relationship between fan speed and segmental heat flux for both direct and reverse flow directions, with direct flow showing notably higher heat flux particularly in the arms and face region.

## 2.4. Participants

A total of 30 adult participants were recruited (17 male and 13 female) between the ages of 20 and 60 years (mean BMI = 22.9, SD BMI = 3.2). The distribution of age and gender can be seen in Fig. 7. The recruitment was made based on specific criteria to only include adults with moderate consumption of coffee, energy drinks, and alcohol. Participants had no chronic diseases, hormonal disorders, cardiorespiratory problems, or metabolic conditions, maintained normal BMI, and engaged in moderate physical activity. They had no professional expertise in building thermal comfort, and mainly lived in the regions of and nearby the province of Bolzano (Trentino-Alto Adige, Italy), in order to ensure a homogeneous sample and ensure regional acclimatization [35]. These criteria ensured participants represented typical residential occupants while controlling for factors that could influence thermal comfort perception.

The study was approved by the Eurac Research's Prevention and Protection Service, in consultation with a Competent Physician, assessing the level of risk for the test participants as low. All participants were provided with a written informed consent before the tests.

## 2.5. Survey questions

The participants were asked to respond to three types of questionnaires, which were displayed on a portable tablet, using a commonly used online tool, that allowed an instant and direct individual feedback, while they remained in a relaxed and seated position.

The first questionnaire (**Q1 – basic information**) was filled once and investigated personal information (i.e., gender, age, weight, height, educational qualification, place of living) and habits potentially influencing thermal perception (e.g., consumption of energy drinks, consumption of caffeine and alcohol, sporting activity).

The second questionnaire (**Q2 – mood)** was filled in at the beginning of each experimental session and concerned the participants' mood in the week before the test and the current mood at the time of filling the questionnaire.

The third questionnaire (**Q3 – perception questionnaire**) was filled 7 times during each experimental session, and investigated the subjects' thermal comfort, air quality and air movement perception, and soundscape.

For the assessment of thermal comfort and perceived air quality, this paper analysed two questions taken from this extensive questionnaire, namely the Thermal Satisfaction Vote (TSatV) and Indoor Air Quality Satisfaction Votes (IAQSatV), both on a 7-point Likert scale (from "very dissatisfied" to "very satisfied"), which is commonly used in this type of evaluations [36,37].

Please, see Supplementary Material for the comprehensive questionnaires.

## 2.6. Experimental conditions and procedure

During the tests, the participants were asked to wear summer clothes, which consists of a t-shirt, shorts, underwear, slippers, and no socks. The intrinsic clothing insulation ($I_{cl}$) was estimated to be equal to 0.5 clo according to ISO 7730 standard [38]. The metabolic rate, for a relaxed

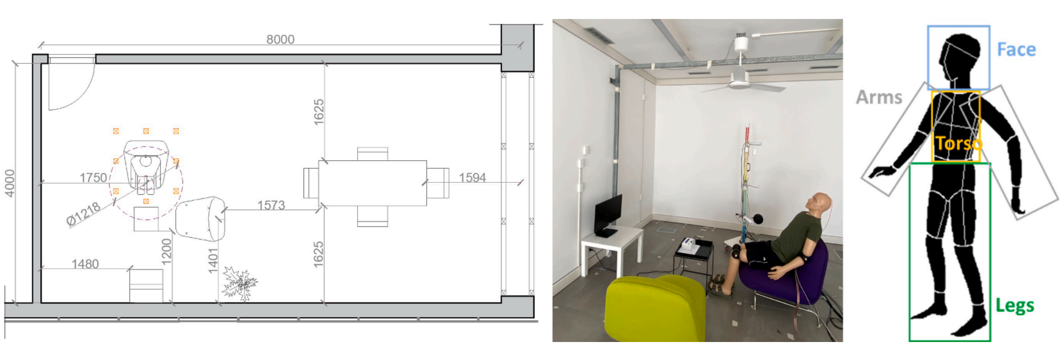


**Fig. 4.** Lab configuration for preliminary tests with thermal manikin.

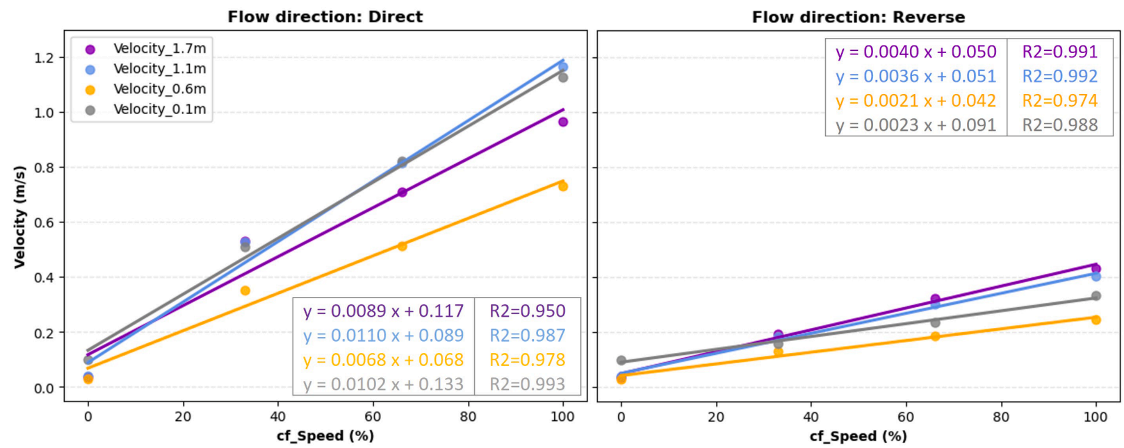


**Fig. 5.** The linear regression model of the average velocities at 4 height planes (1.7, 1.1, 0.6, and 0.1 m) for across fan speed (cf_Speed: 0–100 %), where 100 % corresponds to 235 RPM in Direct mode and 195 RPM in Reverse mode, reflecting the actual operational characteristics of each flow direction.

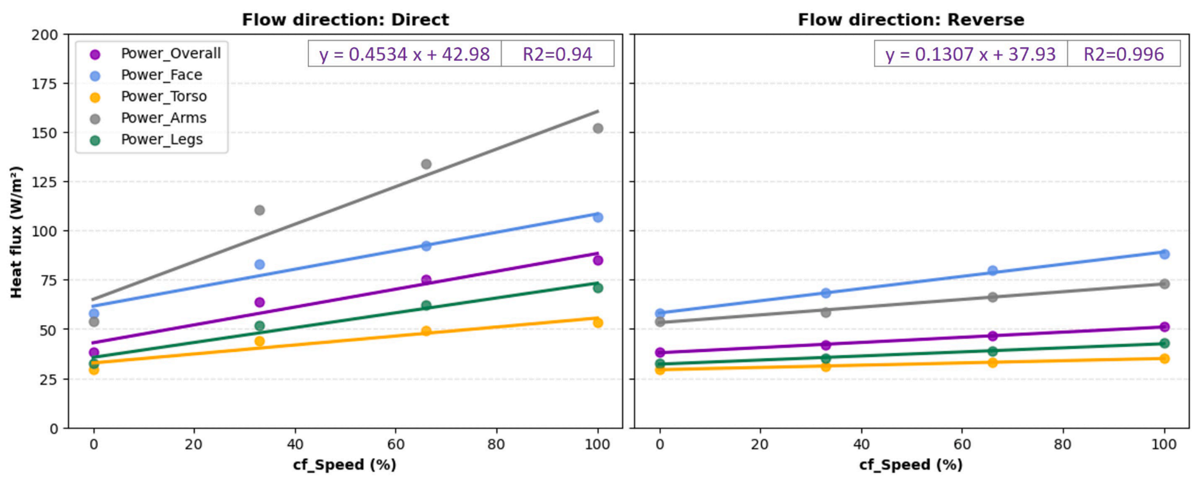


**Fig. 6.** The heat flux of the different parts of the thermal manikin for maintaining a constant skin temperature of 34 °C, for different fan speed (cf_Speed) in both flow directions: Direct and Reverse. The linear regression model for the overall body is also reported.

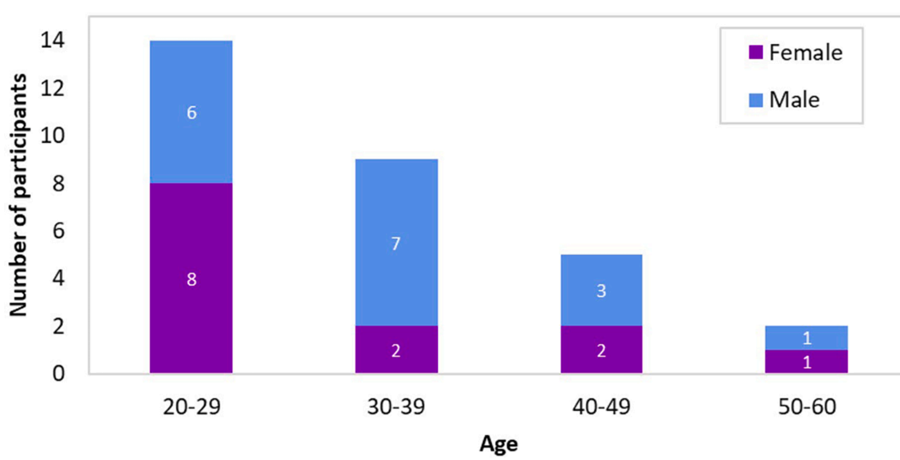


**Fig. 7.** Description of the participant sample age and gender.

person in a living room, was estimated to be equal to M = 1.1 met, according to ASHRAE Standard 55–2017 [37].

The fan settings based on the operation mode (Automatic or Manual) and flow direction (Direct or Reverse) were the following:

- Automatic (only in direct mode) – Auto
- Manual Direct – MD
- Manual Reverse – MR
- No fan – Off

Participants attended three separate sessions, during which they were exposed to different room temperatures: 27 °C, 29 °C, and 31 °C, scheduled on different days to avoid thermal fatigue. A typical schedule of a session is depicted in Fig. 8, each lasting 2 h and 30 min. During the first 15 min of the first session, participants provided informed consent, received an explanation of the experiment, and familiarized themselves with the fan's remote control. They then had 10 min to change their clothes, followed by a 30-minute acclimatization session when the fan was in Off mode, for the subjects to reach physiological and psychological stabilization [39]. At the end of this session, they completed the Q2 questionnaire. Then, the participant experienced the above-mentioned 3 fan settings with the fan On (i.e., Auto, MD, MR), which were randomised. During sessions with manual operation mode, the participants were informed that they could manipulate the fan speeds according to their preference. In between these conditions, every 15 min the participants were asked to fill in the Q3 and perform a light activity every 30 min. During the course of the experiment, participants were asked to imagine themselves relaxing in their homes, or in a lounge setting, and they could read books or access social media through their mobile phones.

### 2.7. Monitoring

The acquisition of the indoor parameters was done at a 20 s interval through a Keysight data logger. The air temperature, globe temperature, relative humidity, and $CO_2$ were monitored using the instruments presented in Table 4. Air temperature and relative humidity were measured at heights 0.6 and 1.1 m, globe temperature at 0.6 m and $CO_2$ at 1.1 m, behind the participant's head. The $CO_2$ concentrations were measured a proxy for IAQ evaluation. Participants' interactions with the fan remote controller for modifying the fan speed were continuously collected, using an interface developed using MODBUS, at a 5-second interval. The same interface was used for the switching of the fan operational modes and flow direction during the experiment. The status of the fan at the start of the survey was considered for the analysis.

### 2.8. Data processing

Indoor and outdoor thermal data were processed before being included as variables in the statistical models described in the following paragraph. For the indoor air temperature ($T_a$), an average of the air temperatures measured at 0.6 m and 1.1 m were taken, according to ASHRAE Standard 55 (seated person) [37]. The mean radiant temperature (MRT) was calculated using view factors [34] and considering the surface temperatures of the climatic chamber. The indoor operative temperature ($T_{op}$) was calculated as [34]:

$T_{op} = (T_a \bullet \sqrt{(10 \bullet V_a)} + MRT) / (1 + \sqrt{(10 \bullet V_a)})$ (2).

where $T_a$ is the air temperature, MRT is the mean radiant temperature and $V_a$ is the air velocity calculated as per the previous section 2.3. The indoor operative temperature was divided into three temperature bins (T_BIN) corresponding to the three test sessions, namely 27 °C, 29 °C, and 31 °C.

As regard to the outdoor environment, the running mean outdoor temperature ($T_{rmo}$) was calculated for the days of the experiment by considering the temperature measurements of seven prior days, calculated based on EN 16798–1 [40]:

$T_{rmo} = (1-\alpha) \bullet (T_{d-1} + \alpha T_{d-2} + \alpha^2 T_{d-3} + \alpha^3 T_{d-4} + \alpha^4 T_{d-5} + \alpha^5 T_{d-6} + \alpha^6 T_{d-7})$ (3).

where constant α is assumed to be 0.8, $T_{d-1}$ is the mean outdoor temperature of the prior day, $T_{d-2}$ the mean outdoor temperature for two days prior, and so on [41].

**Table 4**
Detailed information of the instruments.

| Measurement | Instrument | Range | Accuracy |
|---|---|---|---|
| **Air velocity** | SensoAnemo 51C0NSF transducer | 0.05 to 5 m/s | ±0.02 m/s, or ± 1.5 % of readings |
| **Air Temperature** | E + E EE060 | −40 to 60 °C | ±0.3 °C |
| **Relative Humidity** | E + E EE060 | 0 to 100 % | ±2.5 % |
| **$CO_2$** | EE872-M10HV2 | 0 to 5,000 ppm | ±50 ppm + 3 % measured value |

### 2.9. Statistical analysis

In the experiment, a repeated measure design was used. Thermal Satisfaction Votes (TSatV) and Indoor Air Quality Satisfaction Votes (IAQSatV) were therefore analysed using linear mixed models (LMM) in R (version 4.3.2) [42] with the lme4 package (version 1.1–35.1). This type of model is particularly useful in anthropocentric studies for analysing differences between observations with a repeated design [43]. All model assumptions were verified: linearity, normality and independence of residuals, homoscedasticity.

Two attributes were identified within the model: a fixed part responsible for the regression (independent variables in linear regression models) and a random part that considers the variability of the measurements, usually participants in anthropocentric measurements. The fixed part in the models included the ceiling fan operation mode (cf_operation_mode), operative temperature in bins (T_BIN), and the interaction between these two variables. Characteristics of the participants, such as age and gender, as well as the running mean outdoor temperature ($T_{rmo}$), were included as covariates. Participants were included as random intercepts.

We investigated the significance of the factors using the Car package (version 3.1–2) and performed post-hoc pairwise comparisons using the

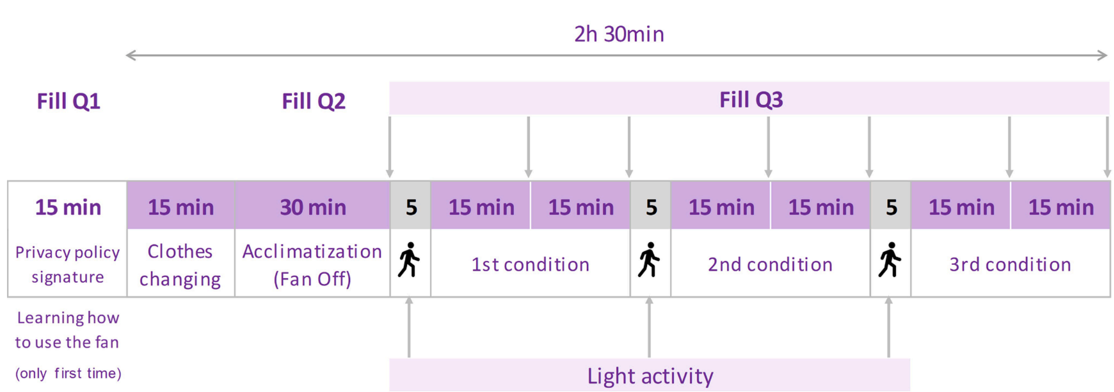


**Fig. 8.** Timeline of a typical session, showing schedule of the questionnaires' administration (Q1, Q2 and Q3) and the 3 fan conditions (randomised between Auto, MD and MR).

emmeans package (version 1.10.0), which were corrected with Bonferroni correction for multiple comparisons.

## 3. Results

### 3.1. Objective and subjective measurements

The boxplots of the important indoor and outdoor parameters during the experimental period are shown in Fig. 9. The indoor measurements were taken at occupant level, with sensors positioned at 0.6 m and 1.1 m heights behind the participant's head, and the measurements show natural variations due to occupant presence and air movement patterns. The mean indoor air temperature was equal to 27.36 °C, 29.36 °C and 31.70 °C for the first, second and third session, respectively. The mean relative humidity was within 50 ± 1 % despite reaching a minimum of 26.15 % and a maximum of 69.94 %, reflecting realistic residential conditions where occupant activity and air movement influences the microclimate. The mean operative temperatures calculated were 26.08 °C, 28.20 °C, and 30.57 °C for the three sessions respectively. The boxplots also show the running mean outdoor temperature ($T_{rmo}$), associated with each session. Measured values of $CO_2$ values were recorded in the range between 470 ppm to 800 ppm during the entire course of the experiment.

The means of the subjective responses, organized by temperature bins and ceiling fan operation mode, are reported in Table 5.

With increasing temperatures, the participants reported decreased satisfaction with both thermal environment and indoor air quality.

**Table 5**
Means of the subjective responses (vote) organized by Temperature Bin (T_BIN), 27, 29, 31, and the 4 ceiling fan operation modes used during the experiment: Auto (Automatic), MD (Manual Direct), MR (Manual Reverse) and Off.

| | Temperature Bins | | | Ceiling Fan Operation Mode | | | |
|---|---|---|---|---|---|---|---|
| | I Session [T_BIN 27] | II Session [T_BIN 29] | III Session [T_BIN 31] | Auto | MD | MR | Off |
| **TSatV** | 1.26 | 0.99 | 0.10 | 1.24 | 1.46 | 0.49 | −0.97 |
| **IAQSatV** | 1.59 | 1.27 | 0.61 | 1.46 | 1.60 | 0.99 | −0.07 |

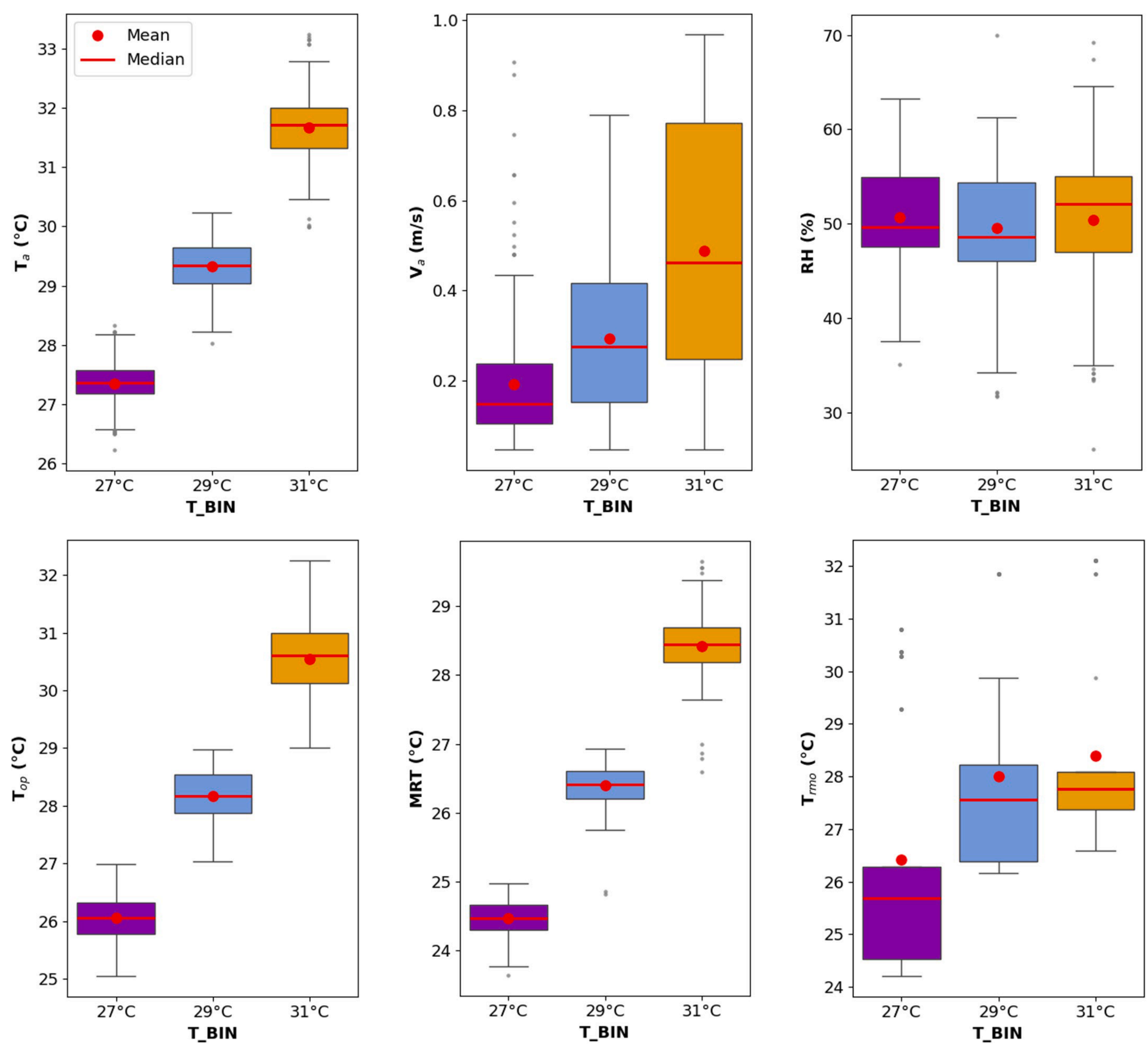


**Fig. 9.** Boxplots of the indoor and outdoor environmental parameters recorded during the experimental period.

Based on the ceiling fan operation mode, a clear trend of decreasing satisfaction can be noticed in the mean votes for both thermal satisfaction and IAQ satisfaction, with MD mode achieving the highest mean values, followed by Auto, MR and Off mode. Detailed analysis based on the temperature bins and the fan operation mode is reported in the subsequent sections.

### 3.2. Thermal satisfaction

The statistical analysis revealed that both the ceiling fan operation mode ($\chi^2(3) = 305.69$, $p < 0.001$) and the temperature bin ($\chi^2(2) = 91.48$, $p < 0.001$) had significant effects on thermal satisfaction, along with their interaction ($\chi^2(6) = 52.20$, $p < 0.001$). The analysis focused on the interaction between ceiling fan operation mode and temperature bin, as this interaction inherently includes their individual main effects.

Post-hoc comparisons at fixed temperature bins revealed that at all temperatures, thermal satisfaction in the Auto, MD, and MR modes was significantly higher than in the Off mode (*all ps* < 0.001). Additionally, satisfaction in the Auto mode was never significantly different from that in the MD mode (*all ps* > 0.3). At T_BIN = 27, there were no significant differences in satisfaction among the Auto, MD, and MR modes (*all ps* = 1). However, at T_BIN = 29 and T_BIN = 31 both the Auto and MD modes registered significantly higher satisfaction than MR mode (T_BIN = 29: Auto > MR; $p < 0.05$; MD > MR, $p < 0.001$; T_BIN = 31: Auto > MR, $p < 0.001$; MD > MR, $p < 0.001$). Table 6 provides detailed results of the pairwise comparisons of thermal satisfaction between the ceiling fan operation modes.

Post-hoc comparisons between temperatures at fixed ceiling fan operation modes showed that, for the MR mode satisfaction decreased as temperature increased (ceiling fan operation mode = MR: 27 > 29, $p = 0.008$; 27 > 31, $p < 0.001$; 29 > 31, $p < 0.001$). In the Auto mode, there were no significant differences in satisfaction across the different temperatures (*all ps* = 1). In MD mode, satisfaction decreased significantly at T_BIN = 31 compared to T_BIN = 29 (ceiling fan operation mode = MD: 29 > 31, $p < 0.001$). In the Off mode, satisfaction decreased significantly between T_BIN = 27 and T_BIN = 31 and between T_BIN = 29 and T_BIN = 31 (ceiling fan operation mode = Off: 27 > 31, $p < 0.001$; 29 > 31, $p = 0.01$), while there was no significant difference between 27 °C and 29 °C ($p = 0.1$). Table 7 provides detailed results of the pairwise comparisons of thermal satisfaction between the temperature bins.

Fig. 10 shows the boxplot of the thermal satisfaction votes given by the participants.

### 3.3. Indoor air quality satisfaction

The statistical analysis revealed that both the ceiling fan operation mode ($\chi^2(3) = 179.86$, p < 0.001) and the temperature bin ($\chi^2(2) = 72.82$, p < 0.001) had significant effects on IAQ satisfaction, along with their interaction ($\chi^2(6) = 21.27$, p = 0.002). The analysis focused on the interaction between ceiling fan operation mode and temperature bin, as this interaction inherently includes their individual main effects.

Post-hoc comparisons at fixed temperature bins revealed that at T_BIN = 27, satisfaction in Auto and MD modes was significantly higher than in Off mode (T_BIN = 27: Auto > Off, $p = 0.03$; MD > Off, $p < 0.001$), while there were no significant differences in satisfaction between MR and Off modes ($p = 0.08$). At T_BIN = 29 and T_BIN = 31, there was no difference in satisfaction between Auto and MD modes ($p = 1$); however, both Auto and MD modes showed higher satisfaction compared to MR and Off modes (*all ps* < 0.05). Additionally, at T_BIN = 29 and at T_BIN = 31, satisfaction in MR mode was higher than in Off mode ($p < 0.05$). Table 8 provides detailed results of the pairwise comparisons of IAQ satisfaction between ceiling fan operation modes.

Post-hoc comparisons between temperatures at fixed ceiling fan operation modes showed that In Auto mode, there was no difference in satisfaction across any temperature bins (*all ps* > 0.2). In MD mode, satisfaction decreased at T_BIN = 31 compared to the other two

**Table 6**
Pairwise comparison results of Thermal Satisfaction Votes. Comparisons between ceiling fan operation mode: Auto (Automatic), MD (Manual Direct), MR (Manual Reverse), and Off, at fixed temperature bins: 27 °C, 29 °C, and 31 °C. The columns show the pairwise comparison between the ceiling fan operation mode (mean value between brackets), the temperature bins, the value of the statistical test (*t* test), the p.value of the test (significance < 0.05) and the effect size calculated with Cohen's d only for significant comparisons.

| Pairwise comparison | Temperature bins | t | p. value | Effect size of Cohen's d |
|---|---|---|---|---|
| Auto (1.23) < MD (1.46) | 27 | −1.1 | 1 | – |
| Auto (1.23) < MR (1.38) | 27 | −0.73 | 1 | – |
| Auto (1.23) > Off (−0.13) | 27 | 5.29 | <0.001 | 1.18 *Large* |
| MD (1.46) > MR (1.48) | 27 | 0.33 | 1 | – |
| MD (1.46) > Off (−0.13) | 27 | 6.2 | <0.001 | 1.38 *Large* |
| MR (1.38) > Off (−0.13) | 27 | 5.75 | <0.001 | 1.32 *Large* |
| Auto (1.26) < MD (1.83) | 29 | −2.57 | 0.3 | – |
| Auto (1.26) > MR (0.55) | 29 | 3.31 | 0.03 | 0.63 *Medium* |
| Auto (1.26) > Off (−1.02) | 29 | 8.67 | <0.001 | 2.00 *Large* |
| MD (1.83) > MR (0.55) | 29 | 5.98 | <0.001 | 1.11 *Large* |
| MD (1.83) > Off (−1.02) | 29 | 10.93 | <0.001 | 2.48 *Large* |
| MR (0.55) > Off (−1.02) | 29 | 6.00 | <0.001 | 1.37 *Large* |
| Auto (0.87) > MD (0.83) | 31 | 0.25 | 1 | – |
| Auto (0.87) > MR (−0.69) | 31 | 7.41 | <0.001 | 1.38 *Large* |
| Auto (0.87) > Off (−2.12) | 31 | 11.39 | <0.001 | 2.63 *Large* |
| MD (0.83) > MR (−0.69) | 31 | 7.22 | <0.001 | 1.33 *Large* |
| MD (0.83) > Off (−2.12) | 31 | 11.24 | <0.001 | 2.58 *Large* |
| MR (−0.69) > Off (−2.12) | 31 | 5.41 | <0.001 | 1.25 *Large* |

**Table 7**
Pairwise comparison results of Thermal satisfaction Votes – Comparisons between temperature bins; 27 °C, 29 °C,31 °C, at fixed ceiling fan operation mode: Auto (Automatic), MD (Manual Direct), MR (Manual Reverse), and Off. The columns show the pairwise comparison between the different temperature bins (mean value between brackets), the ceiling fan operation mode, the value of the statistical test (*t* test), the p.value of the test (significance < 0.05) and the effect size calculated with Cohen's d only for significant comparisons.

| Pairwise comparison | Ceiling fan test mode | t | p. value | Effect size of Cohen's d |
|---|---|---|---|---|
| 27 (1.46) < 29 (1.82) | MD | −1.71 | 1 | – |
| 27 (1.46) > 31 (0.83) | MD | 2.85 | 0.1 | – |
| 29 (1.82) > 31 (0.83) | MD | 4.68 | <0.001 | 0.86 *Large* |
| 27 (1.23) < 29 (1.26) | Auto | −0.19 | 1 | – |
| 27 (1.23) > 31 (0.87) | Auto | 1.54 | 1 | – |
| 29 (1.26) > 31 (0.98) | Auto | 1.75 | 1 | – |
| 27 (1.38) > 29 (0.55) | MR | 3.67 | 0.008 | 0.73 *Medium* |
| 27 (1.38) > 31 (−0.69) | MR | 9.05 | <0.001 | 1.81 *Large* |
| 29 (0.55) > 31 (0.69) | MR | 5.78 | <0.001 | 1.08 *Large* |
| 27 (−0.13) > 29 (−1.02) | Off | 2.95 | 0.1 | – |
| 27 (−0.13) > 31 (−2.12) | Off | 6.47 | <0.001 | 1.74 *Large* |
| 29 (−1.02) > 31 (−2.12) | Off | 3.61 | 0.001 | 0.96 *Large* |

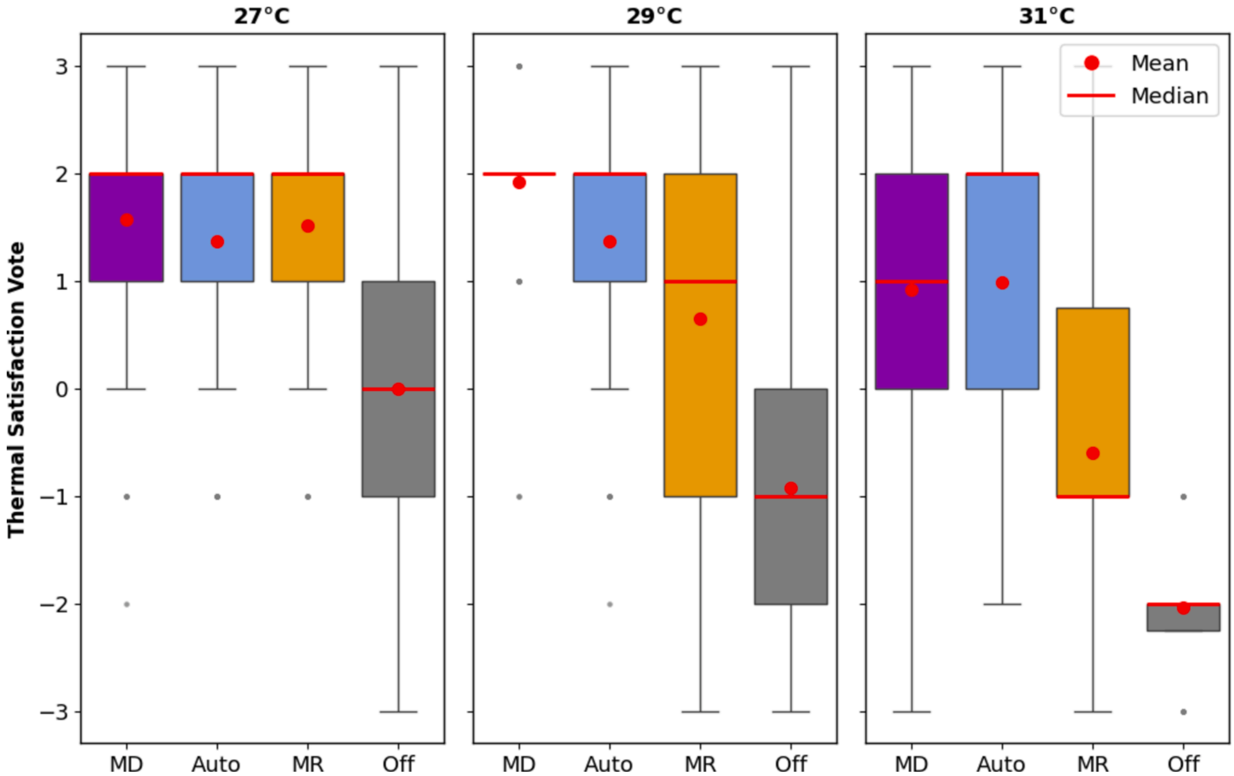


**Fig. 10.** Boxplot of the Thermal Satisfaction Votes for each Temperature Bin (T_BIN), 27, 29, 31 and ceiling fan operation mode used during the experiment: MD (Manual Direct), Auto (Automatic), MR (Manual Reverse) and Off.

**Table 8**
Pairwise comparison results of Indoor air quality satisfaction votes. Comparisons between ceiling fan operation mode: MD (Manual Direct), Auto (Automatic), MR (Manual Reverse), and Off, at fixed temperature bins: 27 °C, 29 °C, 31 °C. The columns show the pairwise comparison between the different ceiling fan test mode (mean value between brackets), the temperature bins, the value of the statistical test (*t* test), the p.value of the test (significance < 0.05) and the effect size calculated with Cohen's d only for significant comparisons.

| Pairwise comparison | Temperature bins | t | p.value | Effect size of Cohen's d |
|---|---|---|---|---|
| Auto (1.52) < MD (1.83) | 27 | −1.64 | 1 | – |
| Auto (1.52) > MR (1.48) | 27 | 0.24 | 1 | – |
| Auto (1.52) > Off (0.77) | 27 | 3.28 | 0.03 | 0.73 *Medium* |
| MD (1.83) > MR (1.48) | 27 | 1.81 | 1 | – |
| MD (1.83) > Off (0.77) | 27 | 4.62 | <0.001 | 1.03 Large |
| MR (1.48) > Off (0.77) | 27 | 3 | 0.08 | – |
| Auto (1.52) < MD (1.75) | 29 | −1.19 | 1 | – |
| Auto (1.52) > MR (0.85) | 29 | 3.41 | 0.02 | 0.65 *Medium* |
| Auto (1.52) > Off (−0.31) | 29 | 7.75 | <0.001 | 1.78 *Large* |
| MD (1.75) > MR (0.85) | 29 | 4.71 | <0.001 | 0.88 *Large* |
| MD (1.75) > Off (−0.31) | 29 | 8.85 | <0.001 | 2.01 *Large* |
| MR (0.85) > Off (−0.31) | 29 | 4.98 | <0.001 | 1.14 *Large* |
| Auto (0.98) < MD (0.98) | 31 | −0.04 | 1 | – |
| Auto (0.98) > MR (0.33) | 31 | 3.39 | 0.02 | 0.63 *Medium* |
| Auto (0.98) > Off (−1.01) | 31 | 8.45 | <0.001 | 1.95 *Large* |
| MD (0.98) > MR (0.33) | 31 | 3.45 | 0.02 | 0.64 *Medium* |
| MD (0.98) > Off (−1.01) | 31 | 8.51 | <0.001 | 1.95 *Large* |
| MR (0.33) > Off (−1.01) | 31 | 5.71 | <0.001 | 1.31 *Large* |

temperature bins ($p < 0.05$). In MR mode, satisfaction decreased at T_BIN = 31 compared to T_BIN = 27 ($p < 0.05$). In Off mode, there was a decrease in satisfaction between T_BIN = 27 and T_BIN = 29 ($p < 0.05$) and between T_BIN = 27 and T_BIN = 29 (p < 0.05), while there was no significant difference between T_BIN = 29 and T_BIN = 31 ($p = 0.3$). Table 9 provides detailed results of the pairwise comparisons of IAQ satisfaction between temperature bins.

Fig. 11 shows the boxplot of the IAQ satisfaction votes given by the participants.

## 4. Discussion

The experimental work reported in this paper provides insight into the effectiveness of the automatic ceiling fan system considering different operational mode (manual/automatic with smart algorithm) and flow direction (Direct or Reverse). The results are discussed below with reference to the two research questions of the study.

**Table 9**
Pairwise comparison results of Indoor air quality satisfaction votes – Comparisons between different temperature bins; 27 °C, 29 °C,31 °C, at fixed ceiling fan test mode: MD (Manual Direct), Auto (Automatic), MR (Manual Reverse), and Off. The columns show the pairwise comparison between different temperature bins (mean value between brackets), the ceiling fan test mode, the value of the statistical test (*t* test), the p.value of the test (significance < 0.05) and the effect size calculated with Cohen's d only for significant comparisons.

| Pairwise comparison | Ceiling fan test mode | t | p. value | Effect size of Cohen's d |
|---|---|---|---|---|
| 27 (1.83) > 29 (1.75) | MD | 0.39 | 1 | – |
| 27 (1.83) > 31 (0.98) | MD | 4.31 | <0.001 | 0.82 *Large* |
| 29 (1.75) > 31 (0.98) | MD | 4.06 | 0.002 | 0.75 *Medium* |
| 27 (1.52) > 29 (1.52) | Auto | 0.02 | 1 | – |
| 27 (1.52) > 31 (0.98) | Auto | 2.77 | 0.2 | – |
| 29 (1.52) > 31 (0.98) | Auto | 2.79 | 0.2 | – |
| 27 (1.48) > 29 (0.85) | MR | 3.05 | 0.07 | – |
| 27 (1.48) > 31 (0.33) | MR | 5.57 | <0.001 | 1.12 *Large* |
| 29 (0.85) > 31 (0.33) | MR | 2.73 | 0.2 | – |
| 27 (0.77) > 29 (−0.31) | Off | 3.98 | 0.002 | 1.06 *Large* |
| 27 (0.77) > 31 (−1.01) | Off | 6.49 | <0.001 | 1.75 *Large* |
| 29 (−0.31) > 31 (−1.01) | Off | 2.60 | 0.3 | – |

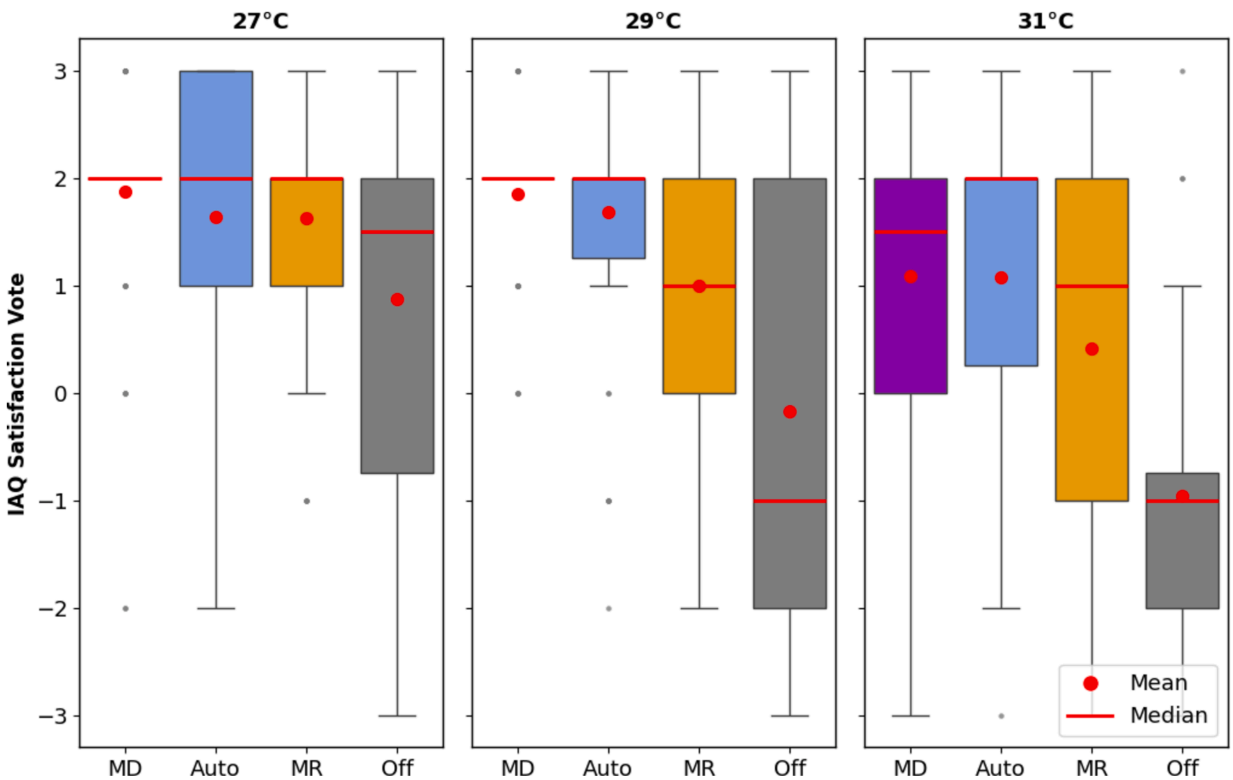


**Fig. 11.** Boxplot of the Indoor Air Quality Satisfaction Vote for each Temperature Bin (T_BIN), 27, 29, 31 and the ceiling operation mode used during the experiment: MD (Manual Direct), Auto (Automatic), MR (Manual Reverse) and Off.

### *4.1. Impact of air movement on thermal environment and PAQ in residential buildings*

Air movement can be an effective means to provide comfort cooling in warm environments as it increases the heat transfer from the human body to the environment [44]. To study the benefits of air movement, the satisfaction of the participants was assessed through questionnaires. For the domains of thermal environment, and perceived air quality, the thermal satisfaction vote (TSatV), and indoor air quality satisfaction vote (IAQSatV) were analysed.

For the overall experiment the thermal satisfaction votes were always higher for fan modes Auto, MD and MR, compared to no fan operation, as found in various previous studies [8,14,24], with this difference becoming more pronounced at higher temperatures, as found in a previous study [45]. Similarly, a higher overall IAQ satisfaction was noticed in the 3 modes when the fan was On (for Auto, MD and MR modes) as compared to the Off mode. This is likely due to enhanced convective and evaporative cooling [24] that reduces skin wettedness while improving evaporative efficiency, and the sensation of freshness [15] from reduced perception of stuffiness. Additionally, as previous studies have also demonstrated, there is a possible dilution of indoor air pollutants in the breathing zone, possibly due to the disruption of the thermal plume around occupants at airspeeds above 0.3 m/s, which helps dilute bio-effluents, enhance convective mixing and hence reduce their concentration [15,16,46]. However, while our study observed improved perceived air quality with fan operation, direct measurements of pollutant concentrations would be needed to quantify the actual dilution effects. There also appears to be a notable link between thermal satisfaction and perception of air quality. As thermal discomfort increases, particularly towards warmth, occupants tend to report lower air quality perception. This relationship underscores the interconnected nature of thermal and air quality satisfaction in indoor environments.

At fixed temperature bins, a significantly higher satisfaction was noticed in Auto and MD modes as compared to both MR and Off mode. However, between MR and Off mode a small difference was noticed suggesting that reverse flow generated only slight localized cooling as compared to no air movement situations.

For the 3 temperature bins, a low difference was noticed at 27 °C, but a significantly higher difference was noticed at higher temperatures, which is in line with previous studies showing pronounced benefits of air movement as temperature increases [24]. In the IAQ domain, MD mode showed a higher satisfaction compared to MR at higher temperatures, due to enhanced convective cooling and the refreshing sensation associated with direct air movement across the body.

Similarly, as far as the comparison between direct and reverse mode is concerned, comparing the MD and MR modes, the overall satisfaction was higher for MD mode. It can be concluded that reverse flow direction does not guarantee higher comfort as compared to direct flow directions at higher temperatures. This is likely because direct flow creates higher air velocities around the subject, which is crucial for body temperature regulation at higher temperatures. However, as discussed in previous studies, reverse flow can be beneficial at lower temperatures for destratification purposes, helping to mix air layers and redistribute warm air from the ceiling, potentially improving overall thermal comfort and energy efficiency during cooler periods [19,20,24].

### *4.2. Effectiveness of automatic algorithm for ceiling fan control*

To evaluate the effectiveness of the algorithm implemented in the fan, a comparison between Auto and MD mode was carried out, across various temperature conditions, assessing both thermal comfort and indoor air quality satisfaction. For the overall experiment, MD showed a slightly higher satisfaction for both thermal and IAQ, although results were not statistically significant. This suggests that the automatic algorithm can effectively maintain comfort conditions comparable to what occupants achieve through manual control.

These findings were consistent with the results of Park et al. [47] where the authors found comparable comfort between automated HVAC systems and manually controlled systems. However, the slight difference can be attributed to higher perceived control, since users feel more comfortable when they are aware of their ability to control their surrounding environment, which has been discussed in some recent studies like Hellwig et al. [48], Schweiker & Wagner [49], and Torriani et al. [29]. However, this difference is minimal, possibly because the automatic fan still allowed users to override the algorithm and switch to manual mode.

The results validate the conclusions of Kim et al. [50], that well-designed automated systems can match manual control performance in terms of occupant satisfaction. The findings demonstrate that automatic control can successfully provide comfortable environmental conditions, with satisfaction levels similar to those achieved through user-controlled operation under the same indoor conditions. The ability to maintain high comfort levels while removing the need for constant user intervention represents an advancement in residential cooling strategies. This balance between automation and user control suggests that smart ceiling fan systems can effectively contribute to energy-efficient cooling without compromising occupant satisfaction.

Limitations and future work.

While this controlled environment allows for standard measurement and accurate result interpretation, it may not fully replicate the diverse conditions that can be found in a real residential setup. Unlike laboratories, homes have variable occupancy patterns, diverse furniture arrangements, and multiple heat sources that can affect air distribution. The present work investigated air movement in a climatic chamber of specific dimensions with a fixed furniture arrangement. The baseline airflow patterns were not measured in unoccupied conditions, as the study focused on realistic scenarios with the thermal manikin present. Additionally, the air distribution will differ as the participant moves further from the fan centre. Similarly, the position of the fan and use of multiple fans, which is common in larger spaces, can also influence the air distribution in a room. Moreover, the algorithm in this study, adapts the fan speed based solely on measured environmental conditions, without automatically accounting for room size or occupancy patterns. Future development could incorporate smart sensing of room configurations and occupancy distribution, particularly for multi-fan scenarios where different zones may require independent control for optimal comfort conditions.

The study focused on specific temperature ranges, metabolic rates and clothing, factors that limit its applicability to the full spectrum of different possible scenarios. Comfort perceived by the participants may vary under different conditions, such as extreme temperatures, or other activity levels that residential occupants might have throughout the day. In addition, the duration of exposure to each fan mode in the study may not account for long-term adaptation effects, behavioural and psychological dynamics, or diurnal variations in comfort preferences that occur in real-world settings. These differences might affect both the effectiveness of automatic fan control and occupant satisfaction levels.

Linear mixed models assume that the dependent variable is measured on an interval scale, where the difference between any two consecutive points is equal. Likert scales, however, are ordinal scales, where the exact differences between points are not necessarily equal or known. However, prior research suggests that treating Likert scale data as interval data is acceptable when the scale has five or more points. This approach is commonly used in thermal comfort studies and can provide reasonably accurate results for the purposes of the analysis [51].

Lastly, while this study focused primarily on comfort perceptions, it may not fully address the energy efficiency implications of different fan modes. Future research could expand on these findings by incorporating a wider range of environmental conditions, longer exposure periods, and more diverse participant groups to provide a more comprehensive understanding of ceiling fan effectiveness in residential settings. Moreover, future field studies in actual residences could also complement the laboratory findings by capturing real-world variations and long-term adaptation patterns.

## 5. Conclusions

This study investigated ceiling fan efficacy using both manual and automatic control in residential settings under hot climate conditions. For this purpose, an experimental study was conducted within a building emulator with two realistic rooms involving 30 participants, with the main objective to evaluate the ceiling fan's effectiveness on thermal comfort and perceived air quality (PAQ). With reference to the two research questions, the main outcomes of this study are as follows:

1. Air movement significantly improves both thermal comfort and perceived air quality in residential environments. Air movement, due to the use of ceiling fans, enhance occupant satisfaction across various temperature ranges, especially in warmer conditions. The optimal flow direction depends on ambient temperature, with direct downward flow being more effective for providing satisfaction at higher temperatures.
2. The automatic algorithm performs comparably to manual operation in terms of resulting occupant satisfaction. Manual direct (MD) mode showed slightly higher satisfaction, which can be attributed to higher perceived control, but a well-designed automatic control systems can effectively predict and meet occupant's comfort needs, without compromising user satisfaction.

These findings contribute to the growing research on automation in environmental control systems and their impact on occupant's comfort, by carrying out thermal comfort and perceived air quality assessments using automated ceiling fans in residential settings, enabling energy-efficient operation. Smart ceiling fans represent a scalable, low-cost solution that can significantly reduce residential cooling energy use while maintaining occupant comfort. The practical implications are significant, as the findings quantify the relationship between air movement and occupant satisfaction using smart ceiling fans, providing a validated automatic control algorithm ready for implementation in residential building management systems. These findings directly support global efforts to reduce building energy consumption, particularly crucial as space cooling demands are rising with climate change.

In summary, this study's key contribution is establishing that automated ceiling fan control algorithms can match manual operation's comfort satisfaction levels in residential settings – a finding that fundamentally challenges the common assumption that direct user control is essential for optimal thermal comfort, while opening new possibilities for energy-efficient cooling strategies without compromising occupant satisfaction. Future research could explore long-term effects of automated systems on occupant behavior and adaptation strategies in real-world residential settings. Additionally, investigations into the interplay between perceived control, actual comfort, and energy saving benefits could provide valuable insights for optimizing residential comfort systems.

In conclusion, this study underlines the significant role of air movement in improving residential thermal comfort and perceived air quality. Considering the need for energy-efficient cooling solutions to achieve plus-energy buildings, meeting global climate goals, and the growing expectations for smarter systems, it also highlights the potential of automatic control systems to maintain high levels of occupant satisfaction, paving the way for more intelligent and energy-efficient residential environments.

## CRediT authorship contribution statement

**Akshit Gupta:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giulia Torriani:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Simone Torresin:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

**Lorenza Pistore:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Matteo Pellegatti:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Lucia Piazza:** Writing – review & editing, Investigation. **Fabrizio Miorin:** Writing – review & editing, Resources. **Wilmer Pasut:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Annamaria Belleri:** Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Roberto Lollini:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Francesco Babich:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Conceptualization.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115317.

## Data availability

Data will be made available on request.

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