# Indoor thermal comfort analysis for developing energy-saving strategies in buildings

***Panayiotis M. Papadopoulos**
Energy, Environment, and Water Research Center
The Cyprus Institute
Nicosia, Cyprus
*p.papadopoulos@cyi.ac.cy

**Ioanna Kyprianou**
Energy, Environment, and Water Research Center
The Cyprus Institute
Nicosia, Cyprus
i.kyprianous@cyi.ac.cy

**Muhammad Salman Shahid**
Univ. Grenoble Alpes, CNRS
Institute of Engineering Univ. Grenoble Alpes G2Elab, 38000,
Grenoble, France
Muhammad-Salman.Shahid@g2elab.grenoble-inp.fr

**Silvia Erba**
Department of Architecture and Urban Studies
Politecnico di Milano,
Milan, Italy
silvia.erba@polimi.it

**Frédéric Wurtz**
Univ. Grenoble Alpes, CNRS
Institute of Engineering Univ. Grenoble Alpes, G2Elab, 38000
Grenoble, France
frederic.wurtz @g2elab.grenoble-inp.fr

**Benoit Delinchant**
Univ. Grenoble Alpes, CNRS
Institute of Engineering Univ. Grenoble Alpes G2Elab, 38000
Grenoble, France
benoit.delinchant@g2elab.grenoble-inp.fr

**Peter Riederer**
Centre Scientifique et Technique du Bâtiment
290 Rte des Lucioles, 06904 Sophia Antipolis, France
peter.riederer@cstb.fr

***Mohammadreza Aghaei**
Department of Ocean Operations and Civil Engineering, Norwegian University of Science and Technology (NTNU), Alesund, Norway
*mohammadreza.aghaei@ntnu.no

**Salvatore Carlucci**
Energy, Environment, and Water Research Center
The Cyprus Institute
Nicosia, Cyprus
s.carlucci @cyi.ac.cy

2023 International Conference on Future Energy Solutions (FES) | 979-8-3503-3230-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/FES57669.2023.10183297

***Abstract***

Humans spend most of their time indoors, whether in their place of residence or work, with large amounts of energy consumed to create comfortable living conditions. Buildings are, therefore, accountable for a considerable proportion of global energy demand; within them, heating, ventilation, and air-conditioning systems constitute major energy drains. Traditionally, these systems are controlled by conventional, mainly static set points, but research has shown that substantial energy savings can be achieved by applying adaptive ones. This work aims to showcase the lower energy consumption achievable when employing adaptive over static approaches, using empirical data from a non-residential living lab. Assessments of rational and adaptive thermal comfort indices over the energy used in HVAC systems are provided, and the energy-saving potential of adaptive thermal comfort models in the design of HVAC control algorithms is estimated. The findings of this work highlight that controlling indoor setpoint temperature according to the adaptive comfort model can achieve energy savings from 15% up to 33%, compared to the rational one, while providing a satisfactory thermal environment.

***Keywords—ASHRAE Likelihood of dissatisfaction, energy savings, smart buildings, thermal comfort***

## I. INTRODUCTION

### A. *Motivation*

Buildings, from their nature, are designed to provide a safe, secure, and pleasant environment for humans to live, work, study, etc. On the other hand, to serve their role, they require a vast amount of energy that can reach around 40% and 37% of the primary energy sector in the USA and Europe, respectively, according to [1]. It is well known and recognized that indoor environment control (i.e., heating, cooling, and ventilation) dominates the annual energy use of a building (in both residential and commercial sectors) since in the USA, it constitutes more than 50% of the total primary energy in buildings [1]. Nowadays, energy crises and climate change are the main challenges people are facing on a global scale, and buildings are among the main responsible. It has been seen in the press that Germany's energy minister called people to set their heating systems to lower temperatures [2]. In addition, on 29 April 2023, the Italian Government promulgated Law n. 34, which implements the Italian plan to "immediately make savings useful at the European level to prepare for possible interruptions in gas supplies from Russia". Among the measures envisaged a reduction of 1 ºC for the space heating of buildings, from 17 with plus or minus 2 ºC of tolerance for buildings used for industrial, craft, and similar activities, from 19 with plus or minus 2 ºC of tolerance for all other buildings. Furthermore, "the operating limits of the heating systems are reduced by 15 days as regards the operation period (postponing the start date by 8 days and bringing forward the end date by 7 days) and by 1 hour as regards the daily switch-on time". The Law does not apply to hospitals and nursing homes, or rather "sensitive users" [3]. Moreover, France introduced public holidays during predicted extreme weather periods to compensate for the effects of gas shortage. Generally, indoor environmental conditions are regulated by heating, ventilation, and air-conditioning (HVAC) systems. Most HVAC systems emphasize thermal comfort by regulating the indoor air temperature, while more advanced ones offer control of indoor air quality (IAQ) by regulating relative humidity, $CO_2$ concentration, and other variables for specified uses.

### B. *Background*

Indoor environmental quality (IEQ) refers to indoor environmental conditions in a building related to the health and comfort of its occupants. IEQ includes thermal, visual, and acoustic comfort, as well as indoor air quality. These aspects are all linked to each other and are strongly related to the energy performance of a building [4]–[7]; therefore, they should be incorporated into the building design and its operation.

Thermal comfort is defined as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” [8]. Conventionally, there are two main approaches reflected in standards that provide methods to assess the expected thermal response of people to given indoor hygro-thermal conditions. The first approach, usually referred to as the rational approach, is based on the assumption that a person’s thermal satisfaction with respect to the thermal environment can be modeled with a steady-state energy balance of the human body. According to this approach, comfort levels are predicted based on laboratory-based experiments and people's ratings of the thermal condition to which they are exposed. The most common energy balance model is the one proposed by Fanger [9], which expresses thermal sensation as a function of four environmental variables (air temperature, mean radiant temperature, relative humidity, and airspeed) and two personal variables (metabolic activity and clothing level). The second approach, known as adaptive thermal comfort, acknowledges that humans actively manage their thermal environment to ensure comfort rather than being passive with regard to it. Thus, it is possible to think of thermal comfort as a self-regulating system that considers not only the heat transfer between a person and their environment but also the physiological, behavioral, and psychological responses of the person as well as the control opportunities provided by the building's design and construction [10]. The adaptive approach has been incorporated into two standards, the ASHRAE 55 and the EN 16798-1, and its adoption is restricted to “naturally ventilated buildings” and “buildings without a mechanic cooling system”, respectively. However, an adaptive control algorithm (ACA) based on the principles of the adaptive comfort theory of Nicol and Humphreys was developed in the SCATs project and used to create a new control system for air-conditioned buildings [11].

## C. *Literature review*

More recently, following this tendency, research on the use of the two schools of thermal comfort models suggests that designing buildings according to comfort ranges recommended by adaptive models generally requires lower energy use as long as convenient, responsive, and effective means for occupants to improve their environment, like operable windows, are available [12]–[14].

Likewise, HVAC system control strategies often rely on steady-state assumptions, resulting in oversized system sizing estimations to meet buildings' energy demands. Strategies to reduce the energy consumption of HVAC systems include mechanical interventions in the individual components of the systems, as well as smart-enabled approaches [15], [16]. By adopting smart control approaches for HVAC systems can provide energy savings estimated around the half of the energy use in residential and office buildings [13], [17]. For instance, a simulation study estimated up to 60% energy savings from optimized use of HVAC in US office buildings [18] and a retrofitted HVAC system in Hong Kong has shown an energy reduction of 50% while improving indoor air quality [19]. HVAC systes can affect all aspects of IEQ and provide health, satisfaction, and productivity for building occupants [20]. Implications of the trade-offs between energy savings and occupant comfort were identified in early studies of HVAC control design with modified setpoint temperatures, where a static and adaptive strategy was implemented in Australian office buildings. The study aimed to improve comfort and increase energy savings, and, although daily HVAC electricity consumption was reduced similarly under both strategies, occupant discomfort also marked an increase on both occasions [21]. This and subsequent studies argue that the theoretical and achievable potential for energy savings is considerable, without reducing satisfaction levels [19], [22]. However, the human factor needs to be accounted for, and this is where smart control systems, enriched with occupant feedback, are essential. Although it has been established that an appropriate HVAC system specification, operated under an adaptive approach, benefits both the comfort of occupants and the energy savings of buildings, difficulties still remain in translating this principle into design practice [10].

## D. *Contribution*

The contribution of this paper is to provide a comparative study based on in-field data that shows the energy-saving potential of adopting adaptive thermal comfort models in the design of HVAC control algorithms. In particular, data from indoor environmental monitoring devices and the building management system installed in a living lab were gathered and analyzed to assess the thermal comfort over the HVAC energy use.

# II. METHODOLOGY

This section presents the methodology followed to show the potential of energy savings by using the adaptive thermal comfort approach (i.e., ASHRAE adaptive comfort model) to define the setpoint temperature instead of the steady-state rational approach (i.e., Fanger’s comfort model) in the development and design of building control strategies. The methodology involves the calculation of the predicted dissatisfaction level based on the aforementioned thermal comfort models using actual field data and the comparison of the results with respect to energy use. In the following sections, we present the mathematical formulation of the thermal comfort indices, the description of the site, and the description of the dataset used for the analysis.

## A. *Equations*

The Predicted Percentage of Dissatisfied (PPD) is a thermal comfort index developed by Fanger model and proposed for application in mechanically conditioned buildings. PPD is expressed as a function of the Predicted Mean Vote (PMV) through the following equation (1):

$$PPD_{Fanger}^{ISO}(PMV) = 100 - 95e^{-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2} \in (5, 100) \tag{1}$$

The PMV predicts the mean value of the thermal sensation votes of a large group of people, and it is a function of the dry-bulb air temperature (ºC), mean radiant temperature (ºC), average air speed (m/s), relative humidity (%), metabolic activity (met), clothing insulation (clo) and external work (met). The calculation of the PPD and PMV is performed using *pythermalcomfort*, “a Python package that allows users to calculate the most common thermal comfort indices in compliance with the main thermal comfort standards” [23].

The ASHRAE Likelihood of Dissatisfaction (ALD) is developed by Carlucci et al. [24] to assess the likelihood of dissatisfaction according to the ASHRAE adaptive comfort model. The expression to compute ALD is in equation (2):

$$ALD(\Delta T_{op}) = PPD(\Delta T_{op}) = \frac{e^{-3.057+0.419\Delta T_{op}+0.007\Delta T_{op}^2}}{1+e^{-3.057+0.419\Delta T_{op}+0.007\Delta T_{op}^2}} \quad (2)$$

where $\Delta T_{op} = |T_{op,in} - T_{c,ASHRAE}|$ is the offset from the ASHRAE optimal operative temperature $T_{c,ASHRAE}$ (°C), which is derived from the prevailing mean outdoor air temperature $t_{pma(out)}$ and that is calculated as presented in equation (3):

$$T_{c,ASHRAE} = 0.31 \cdot t_{pma(out)} + 17.8 \quad (3)$$

For calculating the $t_{pma(out)}$, weather data from the *Meteostat* python library are used [25] using the data from the nearest meteorological station to the pilot building for period under study, i.e., 17-30/03/2023.

### B. *Dataset description*

As described in Section A, the calculation of the selected indoor thermal comfort indicators requires a collection of field measurements. For this, both legacy equipment (i.e., BMS) and indoor environmental monitoring devices (i.e., temperature, relative humidity, and IAQ data logger named Sphensors and built by the *LSI LASTEM* company) installed for the COLLECTiEF project were used to collect measurements for HVAC power use, and the indoor environmental quality. However, since some of the input information or data were difficult to get (e.g., require specialized equipment, user input), the following assumptions were considered for calculation purposes:

- The mean radiant temperature is assumed to be equal to the dry-bulb air temperature measured by the Sphensor devices with a time resolution of 1 minute,
- Relative humidity (%) is assumed constant and equal to 60 %,
- Metabolic activity is assumed equal to 1.0 met, corresponding to the “Seated, quiet” item of ASHRAE 55,
- and clothing insulation is assumed equal to 0.6 clo corresponding to the 'casual' item of ASHRAE 55,
- Average airspeed is considered constant, with v = 0.01 m/s,
- External work is set to 0 met.

The data collection period corresponds to the heating season, starting from 17/03/2023 and ending on 30/03/2023. The power use of the HVAC system is calculated at the room level as a function of the water inlet/outlet temperature and the water flow of the hydronic system installed on the ceiling of each room.

### C. *Pilot site description*

The proposed methodology is evaluated in a living lab with advanced BMS. This living lab is situated in the Grenoble Electrical Engineering Lab (G2ELab), which is accommodated in the GreEn-ER building that stands for the Teaching and Research on Energy in Grenoble. Inaugurated in 2015, the GreEn-ER building brings in research, academia, and creativity in the domain of sustainable energy within an environment, having students and researchers under one roof. It is an energy-efficient building constructed in conformity with the French thermal regulation of 2012 and is managed under a public-private partnership. The purpose of a living lab is to realize cross-domain research while keeping humans in the loop where user engagement and feedback serve to perform research to support the energy transition [26], [27].

The building is partially energy self-sufficient due to photovoltaic (PV) panels installed in the premises of the building (i.e., 183 $kW_p$ on the rooftop and 22 $kW_p$ on the roof of the bicycle stand for a total of 205 $kW_p$). In addition, electric vehicle charging stations are also available within the building premises, which provide free charging at the expense of the building energy consumption (four plugs of 7 kW and four plugs of 22 kW). The total primary energy consumption of the building is less than 2200 MWh/year, corresponding to 110 $kWh/m^2$ [28]. Fig.1 presents the location of the living lab in the GreEn-ER building.

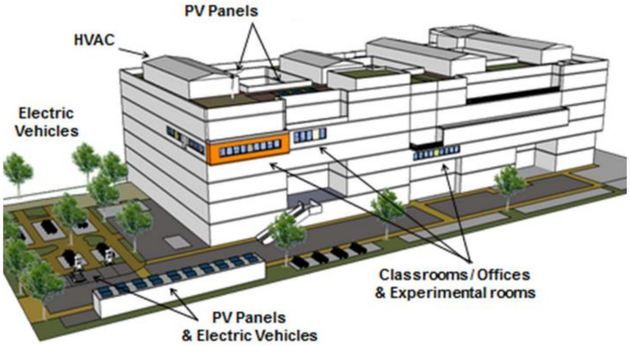

Fig. 1. Living Lab situated in GreEn-ER building [26]–[28]

The BMS of GreEn-ER is connected to a number of sensors. These sensors are implemented top-down, whereby they measure different variables at the building and room levels and trickle down to measuring energy consumption at the plug level. The living lab is a part of G2ELab, which consists of some offices, a classroom, and a laboratory (as illustrated in Figure 1). Fig. 2 presents the top view of the living lab. BMS data are collected for the following variables of interest from all rooms using the pre-installed sensors.

- Room temperature (°C),
- HVAC thermal power consumption (W),
- Thermal energy consumption (kWh),
- Water flow in the HVAC circuit ($m^3/h$),
- Supply and return water temperature in the circuit of each room (°C),
- Ventilation damper opening (%) and room inlet temperatures (°C)
- Plug-level electricity consumption (kWh),
- Lighting consumption (kWh),
- $CO_2$ concentration except in 4A013 (ppm),

Note that the sampling period of the variables depends on the kind and the resolution of each sensor, but the typical interval is in the order of minutes.

The thermal condition can be modulated by modifying the air-temperature set points of the rooms (except 4A013 and 4A017). These room-level setpoints include: (a) $CO_2$ concentration setpoint, (b) Hot temperature setpoint (implementable during winter season), and (c) Cold temperature setpoint (implementable during summer season). These setpoints can either be modified by the LCD screen installed in each room, or they can be changed by using the web interface of the BMS. However, the experiment requires hourly modification of setpoints done by an automatic code.

Fig. 2. The drawing of rooms in the Living Lab

Due to data privacy and cyber-security concerns, it is not allowed to give external researchers to G2ELab direct access to the BMS. Therefore, an intermediate platform is used to share the collected data and get the new setpoints for each room to outside certificated and identified users (typically partner researchers). Through an automated code, both actions have been executed on an hourly basis. The intermediate platform is known as SG-InterOp (acronym of Smart-Grid Inter-Operability). The objective of this platform is to do cross-sectional research on the inter-operability of the smart grid, ranging from (but not limited to) the electricity production from hydraulic turbines, energy storage, and energy flexibility at the end-user level [29]. Fig.3 presents the schematic diagram of data sharing and automatic remote control via SG-InterOp.

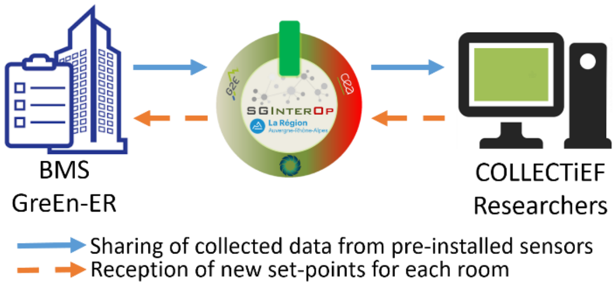

Fig. 3. Schematic diagram of data sharing and reception of new setpoints using SG-InterOp

Besides the data of pre-installed sensors, the experiment also benefits from specific sensors with higher resolution. These sensors are commercially known as “Sphensors” and have a data retrieving resolution of 1 minute. The sensors are placed in each room at an optimal location, from where the data is transferred to the dedicated server of the experiment. Table I presents the surface area and variables measured by the Sphensors in each room

TABLE I. THE VARIABLES MEASURED BY THE SPHENSORS IN EACH ROOM

| Room Id | Type of Room | Surface area (m2) | Variables measured by Sphensors |
|---|---|---|---|
| 4A013 | Laboratory | 63,5 | Sphensor 1: Room temperature, relative humidity, luminosity<br>Sphensor 2: CO2 Concentration, Volatile organic compound, Particulate Matter (1, 2.5, 4, 10) |
| 4A014 | Office | 42,0 | Room temperature, relative humidity, luminosity |
| 4A015 | Office | 25,0 | Room temperature, relative humidity, luminosity |
| 4A016 | Office | 18,5 | Room temperature, relative humidity, luminosity |
| 4A017 | Office | 19,0 | Room temperature, relative humidity, luminosity |
| 4A018 | Office | 18,5 | Room temperature, relative humidity, luminosity |
| 4A019 | Office | 27,5 | Room temperature, relative humidity, luminosity |
| 4A020 | Classroom | 78,5 | Sphensor 1: Room temperature, relative humidity, luminosity<br>Sphensor 2: CO2 Concentration, Volatile organic compound, Particulate Matter (1, 2.5, 4, 10) |

## III. RESULTS

This section presents the potential of the application of adaptive thermal comfort models to develop energy-saving control strategies without compromising indoor thermal comfort.

Fig. 4 presents a comparative analysis of the percentage of dissatisfaction (%) generated by the PPD and ALD indices with respect to HVAC power use per zone. Specifically, each dot corresponds to a specific time interval of 1 hour in which the calculated index, along with the instantaneous HVAC power use, is measured. The blue and orange lines show the linear regression of the data points for PPD and ALD indices, respectively. From the experimental data, it can be shown that the adaptive thermal comfort model, which is expressed by the ALD index, can provide additional energy savings or more room for energy flexibility without affecting the perceived thermal comfort of the building users. Specifically, it can be observed that with the same amount of HVAC power, we can achieve significantly reduced thermal dissatisfaction with the ALD with respect to the PPD since the orange line is for all rooms below the blue line. Table II shows the calculated percentage of indoor thermal comfort improvement per room by computing the minimum and maximum error between the blue and orange lines.

TABLE II. PERCENTAGE OF THERMAL COMFORT IMPROVEMENT PER ROOM

| Room ID | Range of indoor thermal comfort improvement |
|---|---|
| 4A015 | 5-38% |
| 4A016 | 10-33% |
| 4A018 | 15-33% |
| 4A019 | 15-40% |

Considering a linear relation between thermal comfort and power use, the adoption of the adaptive thermal comfort approach in the design of control strategies could provide energy savings estimated to be between 15% and 33% without compromising the thermal sensation perceived by the occupants.

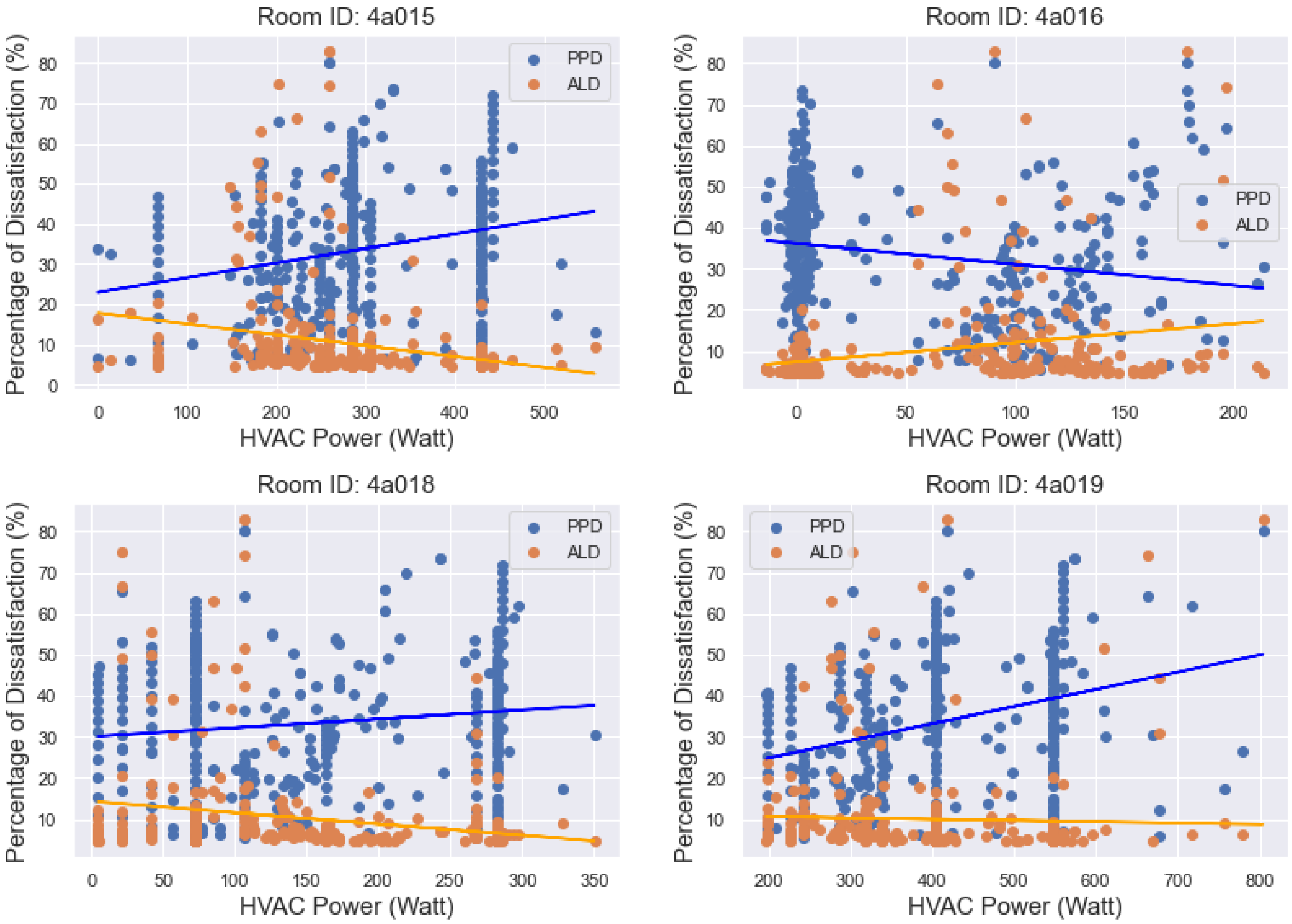

Fig. 4. Comparative analysis of the percentage of dissatisfaction for PPD and ALD with respect to HVAC power use per zone of the G2Elab living lab. The blue and orange lines show the linear regression of the data points for the PPD and ALD, respectively.

## IV. CONCLUSIONS

This work proposes the use of adaptive thermal comfort models in the design of HVAC control algorithms with regards to the state-of-practice rational models for reducing buildings energy use.

Based on field data, it is shown that, during winter season in Grenoble, France, adaptive comfort models can reduce significantly discomfort conditions than the rational ones, with same HVAC power use. This implies to significant energy savings by adopting adaptive temperature set points in the design of HVAC control algorithms.

Future work could be the testing and evaluation of an adaptive temperature set point in real a physical environment based on occupants' feedback (i.e., questionnaires).

## ACKNOWLEDGMENT

This work has been supported by the COLLECTiEF project, which has received research funding from European Union's Horizon 2020 research and innovation program under Grant Agreement No. 101033683. Special thanks to *LSI LASTEM* for providing the indoor environmental monitoring equipment i.e., Sphensor devices, and *Energy@Work* and *CETMA* for establishing the communication and remote access of field data.

The views and opinions expressed are those of the authors and do not reflect the views of the European Union.

## REFERENCES

[1] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information,"

*Energy Build.*, vol. 40, no. 3, pp. 394–398, 2008.

[2] K. Connolly, "Germany approves limits on heating public buildings to save energy," *The Guardian*, 24-Aug-2022.

[3] "Gazzetta Ufficiale." [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2022/04/28/22G00048/SG. [Accessed: 21-Apr-2023].

[4] S. D'Oca, T. Hong, and J. Langevin, "The human dimensions of energy use in buildings: A review," *Renew. Sustain. Energy Rev.*, vol. 81, no. August 2017, pp. 731–742, Jan. 2018.

[5] G. K. Oral, A. K. Yener, and N. T. Bayazit, "Building envelope design with the objective to ensure thermal, visual and acoustic comfort conditions," *Build. Environ.*, vol. 39, no. 3, pp. 281–287, Mar. 2004.

[6] A. M. Omer, "Energy, environment and sustainable development," *Renew. Sustain. Energy Rev.*, vol. 12, no. 9, pp. 2265–2300, Dec. 2008.

[7] J. Mardaljevic, L. Heschong, and E. Lee, "Daylight metrics and energy savings," *Light. Res. Technol.*, vol. 41, no. 3, pp. 261–283, Sep. 2009.

[8] ASHRAE, "Standard 55 – Thermal Environmental Conditions for Human Occupancy," 2020.

[9] P. O. Fanger, *Thermal comfort. Analysis and applications in environmental engineering.* Copenhagen: Danish Technical Press., 1970.

[10] R. T. Hellwig *et al.*, "A framework for adopting adaptive thermal comfort principles in design and operation of buildings," *Energy Build.*, vol. 205, p. 109476, Dec. 2019.

[11] K. J. McCartney and J. Fergus Nicol, "Developing an adaptive control algorithm for Europe," *Energy Build.*, vol. 34, no. 6, pp. 623–635, Jul. 2002.

[12] R. Tällberg, B. P. Jelle, R. Loonen, T. Gao, and M. Hamdy, "Comparison of the energy saving potential of adaptive and controllable smart windows: A state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies," *Sol. Energy Mater. Sol. Cells*, vol. 200, no. June, p. 109828, Sep. 2019.

[13] L. Yang, H. Yan, and J. C. Lam, "Thermal comfort and building energy consumption implications – A review," *Appl. Energy*, vol. 115, pp. 164–173, Feb. 2014.

[14] M. K. Singh, S. Mahapatra, and S. K. Atreya, "Adaptive thermal comfort model for different climatic zones of North-East India," *Appl. Energy*, vol. 88, no. 7, pp. 2420–2428, Jul. 2011.

[15] G. Barone, A. Buonomano, C. Forzano, G. F. Giuzio, A. Palombo, and G. Russo, "A new thermal comfort model based on physiological parameters for the smart design and control of energy-efficient HVAC systems," *Renew. Sustain. Energy Rev.*, vol. 173, p. 113015, Mar. 2023.

[16] V. Vakiloroaya, B. Samali, A. Fakhar, and K. Pishghadam, "A review of different strategies for HVAC energy saving," *Energy Convers. Manag.*, vol. 77, pp. 738–754, Jan. 2014.

[17] W. Jung and F. Jazizadeh, "Human-in-the-loop HVAC operations: A quantitative review on occupancy, comfort, and energy-efficiency dimensions," *Appl. Energy*, vol. 239, pp. 1471–1508, Apr. 2019.

[18] S. Papadopoulos, C. E. Kontokosta, A. Vlachokostas, and E. Azar, "Rethinking HVAC temperature setpoints in commercial buildings: The potential for zero-cost energy savings and comfort improvement in different climates," *Build. Environ.*, vol. 155, pp. 350–359, May 2019.

[19] W. W. Che *et al.*, "Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system," *Energy Build.*, vol. 201, pp. 202–215, Oct. 2019.

[20] Wenqi Guo and Mengchu Zhou, "Technologies toward thermal comfort-based and energy-efficient HVAC systems: A review," in *2009 IEEE International Conference on Systems, Man and Cybernetics*, 2009, pp. 3883–3888.

[21] A. C. Roussac, J. Steinfeld, and R. de Dear, "A preliminary evaluation of two strategies for raising indoor air temperature setpoints in office buildings," *Archit. Sci. Rev.*, vol. 54, no. 2, pp. 148–156, May 2011.

[22] T. Hoyt, E. Arens, and H. Zhang, "Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings," *Build. Environ.*, vol. 88, pp. 89–96, Jun. 2015.

[23] F. Tartarini and S. Schiavon, "pythermalcomfort: A Python package for thermal comfort research," *SoftwareX*, vol. 12, p. 100578, Jul. 2020.

[24] S. Carlucci, S. Erba, L. Pagliano, and R. de Dear, "ASHRAE Likelihood of Dissatisfaction: A new right-here and right-now thermal comfort index for assessing the Likelihood of dissatisfaction according to the ASHRAE adaptive comfort model," *Energy Build.*, vol. 250, p. 111286, Nov. 2021.

[25] C. S. Lamprecht, "Meteostat Python." .

[26] N. K. Twum-Duah, M. Amayri, S. Ploix, and F. Wurtz, "A Comparison of Direct and Indirect Flexibilities on the Self-Consumption of an Office Building: The Case of Predis-MHI, a Smart Office Building," *Front. Energy Res.*, vol. 10, no. 10, p. 874041, Jun. 2022.

[27] F. Wurtz and B. Delinchant, "'Smart buildings' integrated in 'smart grids': A key challenge for the energy transition by using physical models and optimization with a 'human-in-the-loop' approach," *Comptes Rendus Phys.*, vol. 18, no. 7–8, pp. 428–444, Sep. 2017.

[28] B. Delinchant, F. Wurtz, S. Ploix, J. L. Schanen, and Y. Marechal, "GreEn-ER living lab : A green building with energy aware occupants," in *SMARTGREENS 2016 - Proceedings of the 5th International Conference on Smart Cities and Green ICT Systems*, 2016, pp. 316–323.

[29] A. Labonne, "Méthodes et Outils pour la simulation et la validation expérimentale temps-réel des réseaux intelligents ou 'Smart Grids,'" Nov. 2022.