Thermo-Hygrometric Comfort Analysis in a Real Public Conference Room to Support a Digital-Twin Targeted to Parametric Investigations

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Abstract

In this paper, the efficient use of a building-plant system in terms of thermal comfort conditions for a real conference room was verified in the summer by its digital twin. A DesignBuilder model was calibrated by experimental data concerning the indoor air temperature, average radiant temperature, relative humidity and CO_2 concentration. Different situations for people's well-being were studied by varying emitter typology, control strategies, subjective parameters and internal loads. The EMS tool was used to simulate high-level control strategies. It was found that radiant ceilings in continuous operation could promote situations of undercooling, whereas a predicted plant operation is appropriate with intermittent functioning. People's metabolism affects comfort conditions more than internal loads, determining an increase of about 3 degrees in indoor air and mean radiant temperature. Inlet temperature variations in fan coils modify comfort conditions marginally. However, these emitters interact worse with internal loads than radiant ceilings. Aside from the Fanger PMV, discomfort indices following EN 15251 were also evaluated. However, in prevision of the implementation of predictive control strategies, the degree hour approach is not recommended because it does not consider clothing resistance properly.

1. Introduction

Recent studies confirm how the implications of thermal comfort in human activities are increasingly relevant, from energy management to ensuring energy efficiency, up to contexts linked to environmental impact and economy (Abdelrahman et al., 2022). People, indeed, spend up to 90 % of their lives in buildings, therefore proper management of indoor spaces is required, also to have a positive impact on people's productivity (Asadi et al., 2017). Recently, targeted investigations have shown that, beyond the subjective parameters involved in ISO 7730, a sort of dependence on gender, age, lighting, CO2 concentration and noise occurs (Crosby & Rysanek, 2021). How-ever, also the more updated thermal comfort models produce accuracy in results of less than 33 % when compared with measured data (Li et al., 2018). In the light of this, the procedures based on the development of a tuned digital twin of the building plant systems could improve the reliability of the result. Moreover, predictive control strategies can be developed to attain simultaneously well-being and energy savings when significant parameters change dynamically. Despite the elevated potential, also to favor the intuitive visualizations of the monitored data in appropriate dashboards, digital twins have rarely been studied for thermal comfort evaluation. A vector-based spatial model, called Build2Vec, for predicting spatial-temporal occupants' indoor environmental preferences was studied in (Abdelrahman et al., 2022), showing a 14 %–28 % accuracy improvement. In (Zhang et al., 2022) a web-based digital twin platform combined with IoT allowed real-time control of the relative humidity level of underground heritage sites to promote preservation to be achieved. A system architecture for the live PMV/PPD calculation based on ASHRAE 55 and enrichment of BIM-based representations of building spaces in virtual reality environments, with live IoT-enabled monitoring data, was proposed in (Shahinmoghadam et al., 2021). In this paper, referring to a real conference room lo-

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cated at the University of Calabria, experimental data of indoor air temperature, relative humidity, CO_2 concentration and mean radiant temperature were used to calibrate the digital twin developed in the DesignBuilder environment (DesignBuilder Software Ltd, 2018), a user interface based on an EnergyPlus engine (Berkeley et al., 2019). In this study, the model was employed to determine the influence of different parameters on thermal comfort indices. This work is targeted for the successive implementation of predictive control strategies that assure appropriate thermal comfort conditions in transient regimes. So, the real-time monitoring associated with IoT will be able to intervene by apposite actuators in order to maintain comfort indices within a suitable range.

2. Materials and Methods

Indoor microclimatic measurements were carried out from 11 on 19 July 2019 to 11 on 22 July 2019 using the BABUC control unit (*LSI - Babuc System*, 2022). The aim was to obtain experimental data necessary for validating a dynamic model in DesignBuilder and then proceed to further parametric analyses. In Figure 1, the conference room monitored is shown in blue. The variables strictly related to people, such as metabolism and clothing thermal resistance, were changed related to the different seasons following UNI EN ISO 9920 (Italian Unification Institution, 2009). Environmental parameters refer to the UNI EN ISO 7726 (Italian Unification Institution, 2001).

2.1 The Building-Plant System

The experimental site is located at the University of Calabria (Southern Italy, 39°19'58"80N - 16°11'6"72 E) with typical Mediterranean climatic conditions, defined as subtype CSa following the Köppen climate classification (Peel et al., 2007).

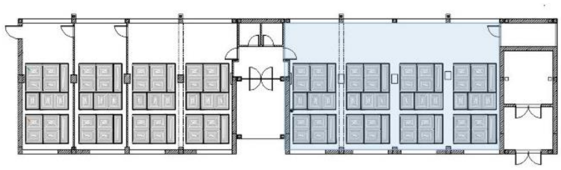

Fig. 1 – Ground floor plane and highlighted monitored area

Table 1 – Layers of the vertical walls

Layer	T [m]	TC [W m^{-1} K^{-1}]	SH [J kg^{-1} K^{-1}]	D [kg m^{-3}]
Plaster	0.02	0.900	800	1400
Hollow brick	0.30	0.157	1000	1250
Plaster	0.02	0.900	800	1400

Table 2 – Layers of the ground floor

Layer	T [m]	TC [W m^{-1} K^{-1}]	SH [J kg^{-1} K^{-1}]	D [kg m^{-3}]
Tiles	0.005	1	1000	2000
Light concr.	0.050	2	800	900
EPS	0.090	0.035	800	55
Stru. element	0.140	2. 2	1000	2600

Table 3 – Layers of the ceiling deck

Layer	T [m]	TC [W m^{-1} K^{-1}]	SH [J kg^{-1} K^{-1}]	D [kg m^{-3}]
Tiles	0.005	1	1000	2000
Light concr.	0.050	2	800	900
EPS	0.090	0.035	800	55
Stru. element	0.140	2. 2	1000	2600
Plaster	0.020	0.9	800	1400

The structure is made of reinforced concrete with transparent surfaces located in the South and North. Stratigraphies of vertical and horizontal opaque walls are listed from Tab. 1 to Tab. 3 with thickness (T), Thermal conductivity (TC), Specific heat (SH) and density (D), all derived from material datasheets.

Highly efficient technological solutions were implemented inside the building, with a control system capable of optimizing renewable energy resources. Two air-water heat pumps in master/slave functioning with a rated thermal power of 5 kW and cooling capacity of 3.8 kW each, connected with a 4 kW_P PV generator, provided heating and cooling by an 800-litre storage tank, configured as a sui-generis electrical storage system to manage PV surpluses. A cogenerative biomass boiler with a Stirling engine (14 kW of thermal power, 1 kW of electric load) was used as an integration system. Emitters consisted of radiant ceilings in mineral fibre, thermally decoupled from the structure, installed in a false ceiling, with an active radiant surface of 124.8 m² distributed in eight independent sectors (see Fig. 1). The main novelty lay in the management of the experimental set-up: while integrating different systems and devices, the system carries out checks on a single decision-making level to rationalize and manage resources in the best possible way by creating an electrical island grid-independent.

2.2 Measurement System

The BABUC instrument line consists of an assembly of instruments, sensors, accessories and software programs for acquisition, display, storage and processing purposes. Different sensors adopting different physical principles can be connected simultaneously to BABUC, and those employed are listed in Tab. 4. All the probes were positioned in the centre of the conference room.

2.3 Simulation Model

DesignBuilder is based on an EnergyPlus calculation engine and allows for managing the degree of detail with which it intends to set envelope and technological aspects, internal loads, occupancy scenarios, clothing and others.
Climatic data were provided by an *.epw file on an hourly basis using the real values acquired by the weather stations located at the University of Calabria (external air temperature, relative humidity, atmospheric pressure, global horizontal irradiation, beam and diffuse components). Schedules were set for light activity with a metabolism of 1.2 met and a summer clothing factor of 0.5 clo. Air infiltration was set following EN 12831 and it was evaluated as a discriminating element for the calibration of the model. On the other hand, natural ventilation was neglected.

Table 4 – Probes employed for room monitoring

Code	Probe	Measured parameter
BSU102	Psychrometer	Dry bulb temperature (°C) Wet Bulb Temperature (°C) Relative Humidity (%) Dew point temperature (°C) Enthalpy (J)
BST131	Globe Thermometer	Globe temperature (°C) Mean radiant temperature (°C)
BSO103.1	CO_2 sensor	CO_2 concentration (ppm)
BSR001	Lux meter	Illuminance (lux)

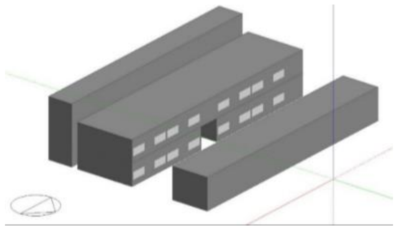

Fig. 2 – Reference building model in DesignBuilder

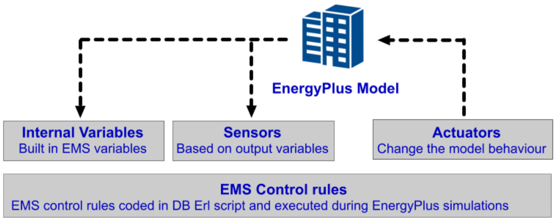

Fig. 3 – Scheme of operation of an EMS control

The HVAC system assumed an ideal setting with unlimited power to attain a setpoint of 22 °C. An EMS (Energy Management System) was employed to carry out an advanced control of the CO_2 concentration. This tool is one of the high-level control methods available in EnergyPlus. An EMS script can access a wide variety of “sensor” data to direct various types of control actions. The EMS uses the concept of sensors to obtain information from elsewhere to use in control calculations. Actuators determine changes in the model and these commands will be used in future studies for the evolution of the model and for the control of air flows to control CO_2 levels by adding control logic following the scheme of Fig. 3

3. Results

3.1 Experimental Data and Validation

The microclimatic surveys for the validation of the model were carried out considering the presence of nine people on 19 July from 14:00 to 18:30 and on 20 July from 9:00 to 14:00, following the real occupation profile. Calibration was carried out by considering closed windows and non-activated shading devices. In order to tune the results, in the model the specific heat and the density of the layers (from Tab. 1 to Tab. 3), the infiltration flow rate and the optical properties of the transparent surfaces were varied. After a fair number of attempts, the temperature profiles of the indoor air matched, with a slight temporal shift between the experimental and modeled trends (imperfect tuning of the building thermal mass), as depicted in Fig. 4. This aspect is more evident with the indoor mean radiant temperature (Fig. 6). Instruments do not record variations of the relative humidity in the presence of occupants, while the simulation returns a sudden increase (Fig. 5). It can be assumed that real ventilation produces a considerable lowering of humidity ratio in the indoor environment, without affecting the indoor relative humidity. A good match can be observed also for the CO_2 concentration (Fig. 7). Validation was analytically confirmed by statistical indices: mean square error (RMSE), mean bias error (MBE) and correlation factor "r", listed in Tab. 5. It can be appreciated, as temperature and CO_2 concentration are met quite well; relative humidity is slightly underestimated, as indicated by the negative MBE value.

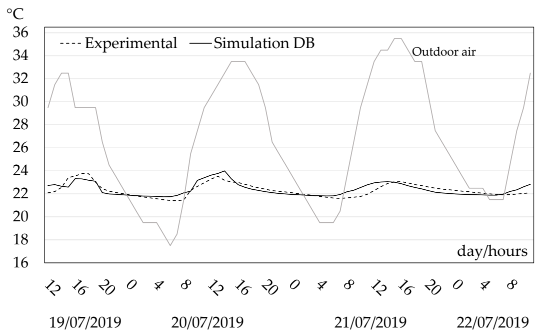

Fig. 4 – Experimental and modeled indoor air temperature

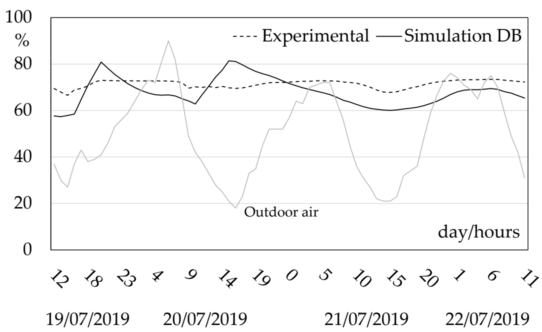

Fig. 5 – Experimental and modeled indoor relative humidity

Table 5 – Some statistical indices for the validation procedure

	RMSE	r	MBE
Indoor air temperature	0.37	0.8	0.00004
Relative humidity	6.61	0.41	-0.00068
Mean radiant temperature	0.48	0.66	0.00014
CO_2	272.17	0.92	-0.00170

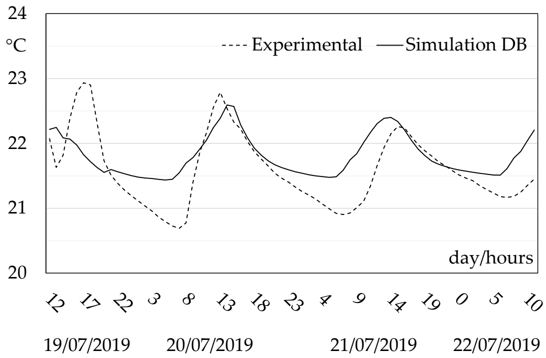

Fig. 6 – Experimental and modeled mean radiant temperature

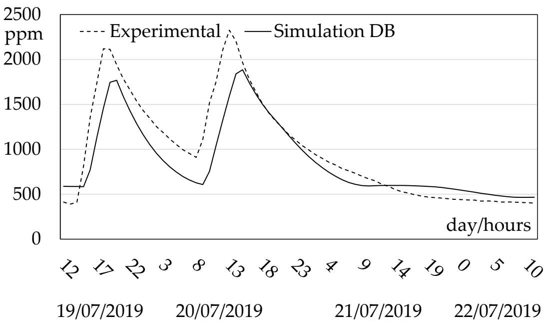

Fig. 7 – Experimental and modeled indoor CO_2 concentration

3.2 Thermal Comfort Evaluation

After validation, the model results were used to proceed with parametric studies for thermal comfort evaluation inside the conference room. Initially, the use of fan-coils and radiant ceilings (both installed in the conference room, with fan-coils provided mainly for dehumidification purposes) and the variation of the inlet temperature was considered by referring to the whole month of July and 9 to 18 users from Monday to Friday (with an hour and a half of lunch break from 13:00 to 14:30). Lightings (dimming LED system with 5 W of electric power each) were scheduled with the same profile relating to user presence. The cases listed in Tab. 6 were considered.

Table 6 – Cases considered for the thermal comfort evaluation

	Emitter	Cooling time	Clothing/ Metabolism
Case 1	Radiant ceiling 15 °C	7-18 Mo- Fr	0.5 clo/1.2 me
Case 2	Radiant ceiling 15 °C	24h Mo- Fr	0.5 clo/1.2 me
Case 3	Fan coil 15 °C	7-18 Mo- Fr	0.5 clo/1.2 me
Case 4	Fan coil 7 °C	7-18 Mo- Fr	0.5 clo/1.2 me

Regarding the plant operation, two modes were envisaged: the first follows the occupation profile starting one hour earlier. The second mode provides continuous functioning for weekdays to overcome the issues related to the inertia of the radiant ceilings. The Fanger PMV, the Pierce PMV SET, the PMV ET and the operative temperature, as described in the EN 15251 standard, were determined. For the latter, assuming a category II, an operative temperature range is recommended in summer at 23 ÷ 26 °C. The Degree Hours criterion, which defines the time during which the operative temperature exceeds the comfort range by the weight factor w_f, was also calculated. It can be noticed that a continuous functioning regime of radiant ceilings allows for the best result (-5.03 °C/month), followed by the intermittent functioning (+119.4 °C/month), whereas fan-coils always involve a worsening of the operative temperature due to the prevalent convective exchange inside the indoor environment (422.11 and 324.08 °C/month, respectively, for Cases 3 and 4). The daily average comfort indexes obtained by DesignBuilder confirmed Case 2 as the situation that allows for achieving values falling within the comfort range with the greatest frequency, while fan coils produce marked overheating conditions.

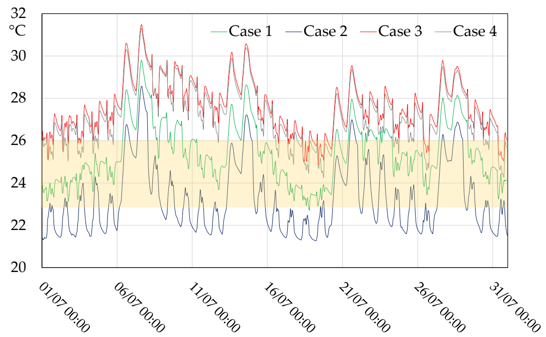

Fig. 8 – Operative temperature in July for the cases considered

Case 2 often guarantees thermal neutrality, but sometimes also a slight undercooling, confirmed both by the w_f index and by the Fanger PMV, whereas the other indices denote a position closer to a slightly warm condition. In Case 1, a slight overheating is detected, meaning that a proper activation in advance is needed to attain adequate comfort. Fan coils supplied at 7 °C guarantee better comfort conditions than Case 4. However, similar comfort indices were obtained, meaning that the inlet temperature is not suitable for regulating thermal comfort when these emitters are employed.

3.3 Parametric Studies

For cases 1, 2 and 4, the role of some parameters on the thermal comfort conditions was evaluated. Case 3 was not considered because it produced the worst scenario. The situation VAR1 involves an increase of internal loads by adding 10 computers supplying 100 Watts each of sensible load. VAR2, instead, considers an increase in 10 people suppling 2 met, whereas in VAR3, a change in clothing insulation to 0.72 clo was implemented. Table 7 highlights how the three situations affect the operative temperature values in Case 1. An evident similarity was detected between the base case and VAR 3, because the indoor air and the mean radiant temperature are the same by changing the clothing thermal resistance. Conversely, a considerable increase was observed in VAR 1 and VAR 2. In particular, 10 people suppling 2 met led to an indoor air temperature growth of 3.6 °C, and the average radiant temperature increased up to 3.4 °C. The weight factor w_f increases in VAR 1 and VAR 2, with the latter affecting results more than the addition of 10 computers (2 met per person for a body area of 1.8 m² corresponds approximately to 200 W following Dubois). It can be appreciated that the mean and maximum temperatures slightly vary, the minimum temperature is almost constant, whereas the degree hour criterion shows considerable worsening with people's metabolism increase.

Table 7 – Operative temperatures with variations in Case1

Base Case	VAR 1	VAR 2	VAR 3
Mean = 25.4 °C	Mean = 26 °C	Mean = 26.9 °C	Mean = 25.5 °C
Max = 29.8 °C	Max = 30 °C	Max = 30.7 °C	Max = 29.8 °C
Min = 22.8 °C	Min = 23.4 °C	Min = 23.6 °C	Min = 22.7 °C
w_f = 119.4	w_f = 179.43	w_f = 347.57	w_f = 119
°C/month	°C/month	°C/month	°C/month

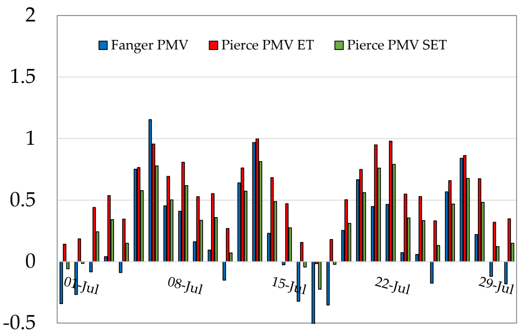

Fig. 9 – Some comfort indices for July 2012, Case 1-base case

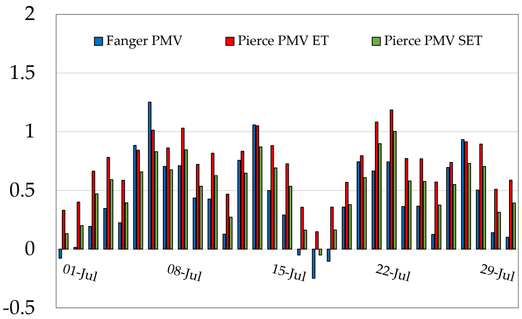

Fig. 10 – Some comfort indices for July 2012, Case 1-VAR1

It can be appreciated that, in the base case, the mean daily Fanger PMV allows for remaining frequently in the desirable range -0.5/+0.5, whereas both Pierce PMV ET and PMV SET produce a situation with slight overheating. In particular, the latter are majorly affected by people's metabolism increase, therefore the use of these indices has to be evaluated carefully because it is more sensitive than Fanger PMV. In accordance with the w_f index, the PMV also records the greatest discomfort in VAR 2. For VAR 3, on the other hand, the PMV indices highlight an exceeding of the comfort threshold, nevertheless offering more consistency than the w_f index.

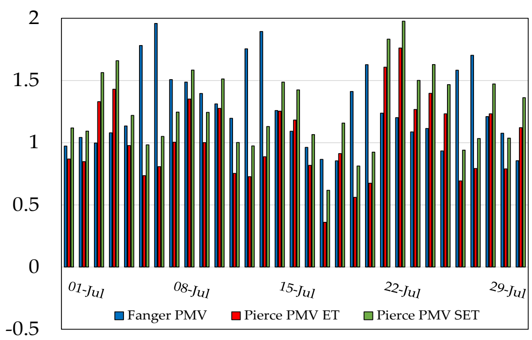

Fig. 11 – Some comfort indices for July 2012, Case 1-VAR2

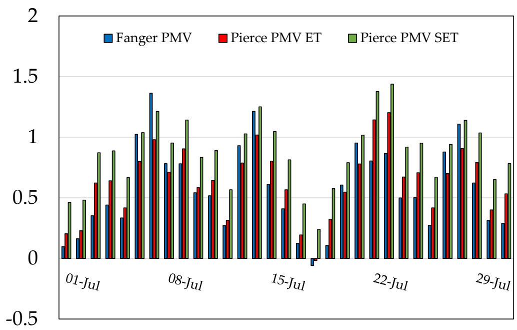

Fig. 12 – Some comfort indices for July 2012, Case 1-VAR3

Case 2 produces similar results to those obtained for case 1. The addition of internal loads and clothing resistance growth determined a Fanger PMV less than 1 with VAR 1 and VAR 3. VAR 2 produced a slightly warm thermal zone with PMV up to 1.5. This result shows that a continuous operation of the radiant ceiling system can guarantee proper thermal comfort conditions when people's activity level is high, so control systems must intervene to limit cooling loads by acting, for instance, on the shading device of the transparent surfaces. Furthermore, even in this case, in the situation of VAR 3, the w_f value fails to return the discomfort increase. On the other hand, all the indices confirm VAR 2 as the situation that causes the greatest discomfort. Nevertheless, the functioning of the radiant ceilings 24 hours per workday allows for more easily meeting the comfort range than an intermittent functioning, but with obvious energy repercussions.

Table 8 – w_f index determined with Case 2 in different situations

Base Case	VAR 1	VAR 2	VAR 3
w_f = -5.03	w_f = 45.87	w_f = 61.94	w_f = -5.03

Passing to fan-coils (case 4), again operative temperatures remain almost the same with VAR 3. Unlike the other two previous cases, VAR 2 produced a slight increase. Conversely, VAR 1 determined a significant increase (Figure 13 and Table 9). Indeed, PCs were set mainly as a radiative load (which in the previous cases is instantaneously removed from radiant ceilings), whereas metabolism is prevalently a convective load. This means that fan-coils interact in a worse manner to contrast the endogenous loads. Similarly, regarding the w_f index, the operative temperature increases more with the presence of PCs and not with people's metabolism, and, again, the increase in clothing resistance does not affect its value.

Table 9 – Operative temperatures with variations in Case 4

Base Case	VAR 1	VAR 2	VAR 3
Mean = 27.2 °C	Mean = 28.8 °C	Mean =27.5 °C	Mean = 27.2 °C
Max = 31.3 °C	Max = 31.8 °C	Max =31.5 °C	Max =31.3 °C
Min = 24.3 °C	Min = 24.7 °C	Min = 24.4 °C	Min =24.3 °C
w_f = 324.08 °C/month	w_f = 418.45 °C/month	w_f = 331.05 °C/month	w_f = 324.08 °C/month

As for Case 1, in Figure 14 and Figure 15, the average daily values concerning the comfort indices are displayed for the base case and VAR 1. It can be noticed that the variant records significant discomfort compared with the base case. In accordance with the w_f index, the PMV indices record the greatest discomfort in VAR 2, even if the PMV is more sensitive to the increase in met than the other indices. These results are in line with radiant ceilings. However, it is highlighted that thermal comfort conditions are more difficult to control in presence of fan coils.

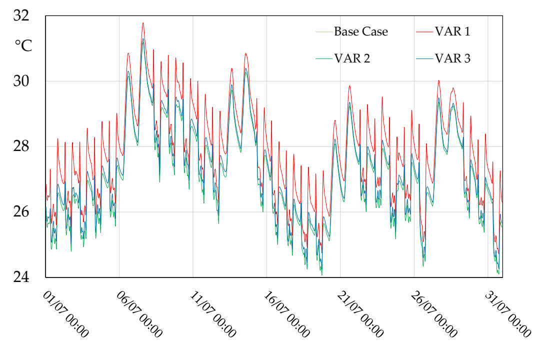

Fig. 13 – Operative temperatures in Case 4 with variants

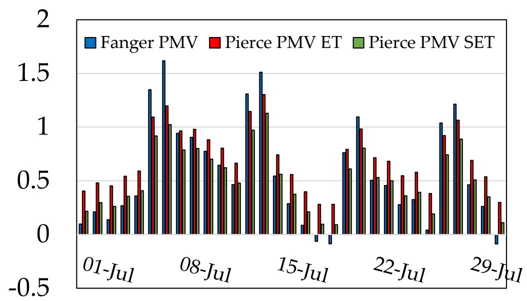

Fig. 14 – Some comfort indices for July 2012, Case 4-base case

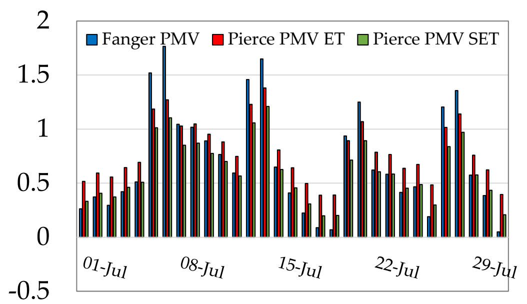

Fig. 15 – Some comfort indices for July 2012, Case 4- VAR 1

4. Conclusions

Thermal comfort conditions were analyzed by a digital twin for a conference room located in South Italy. This allows, in successive steps, for the implementation of predictive control strategies to apply by IoT for preserving thermal comfort conditions, without exceeding energy consumption, by acting on envelope and cooling plant.

A DesignBuilder model was validated by statistical indices calculated starting from experimental data of the indoor microclimatic parameters. Analyses referred to the degree hours criterion (EN 15251) and the Fanger and Pierce comfort indices.

The latter agree with the results of the degree hours criterion. However, when clothing resistance has to be considered is not indicated. Radiant ceilings in a continuous regime offer more days in which the average comfort remains within the range of -0.5 and +0.5. Nevertheless, the risk of zone undercooling occurs. Intermittent functioning produces appreciable comfort conditions only when plant activation is planned in advance. In a parametric study, the Fanger PMV denoted negligible variations, while, conversely, wider deviances were observed for Pierce PMV ET and PMV SET, which are more sensitive. In particular, with the modification of clothing resistance, the degree hours criterion fails and only Fanger and Pierce comfort indices provide accuracy. In these situations, the Fanger PMV varies from -0.5 to -0.05 with intermittent functioning, and from -0.79 to -0.29 in continuous operation. The same index varies from -0.09 to 0.31, assuming fan coils supplied at 15 °C. The variation of the inlet temperature in fan coils does not modify the comfort indices noticeably. The variation of internal loads and people's metabolism shows a considerable increase both in the w_f coefficient and in the other comfort indices. The slight undercooling detected by the Fanger PMV in the continuous operation of radiant ceilings can be easily overcome by increasing internal gains. The increase in people's metabolism produces overheating both with the Fanger PMV and the Pierce PMV. Therefore, the activation of solar shadings is recommended. Fan coils are more difficult to manage because they are ineffective against removing radiative loads instantaneously, so a predictive control is highly recommended for these emitters.

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