Comparing the thermal performance of Living Lab monitoring and simulation with different level of input detail

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Comparing the thermal performance of Living Lab monitoring and simulation with different level of input detail

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Abstract. Dynamic envelope solutions are critical to achieve comfort conditions minimizing the need of active air conditioning systems, emphasizing the potential of thermal adaption of the building occupants. Dynamic systems are, however, difficult to be implemented in European building energy certification schemes, based on semi-stationary calculation method, standard uses and reference boundary conditions. In the attempt to develop a flexible and dynamic method able to reduce the performance gap between real and expected performance, this paper presents the comparison between measurements and simulations of a Living Lab office operated in thermal free floating, with different strategies for the solar protection and the night ventilative cooling. Simulations were performed using the dynamic platform PREDYCE, which allows for manipulating monitored and simulated data. The first phase was dedicated to the model calibration using the indoor air temperature as relevant indicator against monitored data. The coefficient of variation of the root mean squared error is in the 8-9% range. Building simulations of the calibrated model demonstrated a large variation of the results as a function of the input data, with increase of discomfort hour up to a factor 20 and a reduction of discomfort hours up to 95%.

1 Introduction

A recognised challenge in the building energy performance domain is the minimisation of the “performance-gap” between simulated (expected) and monitored (current) data [1, 2]. The adoption of simulation programs is spread worldwide to retrieve expected building behaviours, although actual buildings are underlined to behave differently from standardised ones. This difference is significant mainly when simulations support design retrofitting choices and energy diagnosis or even building labelling, considering their standardised performances, as well as for building energy certification purposes, based on standard conditions in Europe Member States.

As underlined by [3], part of the retrieved performance gaps can be justified by discrepancies between standard and actual building operations, but considering this, the sole cause opens to severe risks. The same study underlined the chance of not noticing procurement criticalities and that minimising the importance of the gap may considerably compromise building energy efficiency in Europe. Several potential causes have been identified in the literature, as the impact of simplified calculation and modeling approaches, i.e. steady-state methods [4, 5], as well as the quality and the availability of the input data that affect the result, independently from the calculation model accuracy [6].

Similarly, standardised data also have an impact considering building input values, e.g. the U-value, the airtightness [7], assumed climate data [8, 9], identified standardised profiles [10], set-points [11], or interactions between end-users and technologies [12]. Considering the literature review, aspects to be considered are connected to the usage of more reliable simulation tools, including free-running operations, the adoption of adapted input conditions, including inspections, and the definition of simulation real-boundary conditions supporting not only regulatory and static performance gaps but also dynamic operational ones [13].

This paper faces the performance gap topic supporting the verification of the E-DYCE project approach thanks to the adoption of dynamic calculations (EnergyPlus), the new dynamic simulation platform PREDYCE – a python library [14]. In particular, the objective is to demonstrate how different input modes, often simplified, affect the accuracy of the building thermal response. The task is carried out by implementing a detailed numerical model, calibrated against the measured data in a fully monitored building and, next, assessing the deviation of the building thermal performance for different input data in comparison with the reference calibrated case.

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2 Materials and method

To accurately assess the performance gap between measured and calculated data, it is necessary to make available detailed data acquired from the field. To achieve the objective of the study the following methodology is implemented:

a. Identification of the case use building, with associated input and output data;
b. Monitoring of the building and climatic relevant parameters;
c. Development of a detailed numerical model and validation against field data;
d. Seasonal (summer) simulation of the validated model to define the reference case;
e. Identification of a set of different input modes and details, and simulation of the building model incorporating the relevant variants.

The study is carried out for the building in thermal free-floating conditions. The relevant parameter should be the operative temperature according to the relevant standard [15], however preliminary monitoring demonstrated that the operative and the air temperatures differed by less than the instrument error, thus the latter is selected as the relevant performance indicator for ease of measurement. The model calibration is carried out according to the procedures and benchmark defined in [16].

The impact of the different input details is assessed by calculating the unmet comfort hours as key indicator, according to the procedures defined in [15], and comparing the results against that of the building reference case.

2.1 Building description

The building used as use case is an office building located in the ENEA Casaccia Research Centre in the northern outskirts of Rome. Part of the building is used as Living Lab to test smart building technologies and service.

More precisely, the case study refers to seven office rooms at the second floor; they have a single façade towards the outdoor, west oriented, except that at the building end, which has also an external south-oriented façade. With reference to the building lay-out, the latter is Room1, the other ones are numbered from 2 to 7. The rooms are 3.90m wide, 4.34m deep and 3.2m high; each has a hole-in-a-wall windows 200cm wide and 160cm high, with 30cm external intrados.

The building erected at the end of the 80' of the last century has the façade made of brick double layer with thermal insulation in between with 0.50 W/m^2 K thermal transmittance. With reference to Figure 1 and to the seven office rooms the Living Lab consists of, three window typologies are identified:

- W1 (Room 5-7) - original double glazing units with no-thermal break aluminium frame and external dark blind for solar control;
- W2 (Room 3 & 4) - low-emissivity selective double glazing unit with frame in aluminium with thermal breaks; one sash can be electrically opened/closed by a push place in place of the handle or by a remote management system;
- W3 (Room 1 & 2) - low-emissivity selective triple glazing unit with same frame than W2.

W2 and W3 are equipped with Venetian blinds inside the glazing gap, which can be remotely activated by an automated management system. The g-values of the glazing systems is respectively 0.79, 0.36 and 0.31 for W1, W2 and W3, respectively; the U-values of the window is 2.9, 1.4 and 1.1 W/m^{2}K, respectively. Additional details about the transparent systems can be found in [17].

The building energy supply consist of a district heating and a compression chiller for cooling. To ensure a detailed energy monitoring, each room of the Living Lab is instead equipped with a high efficiency dedicated compression chiller/heat pump, turned off during the monitoring phase of this study but activated during a dedicated measurement campaign. The 2.5 kW unit has declared efficiencies of 3.64 COP and 4.03 EER in heating and cooling modes, respectively.

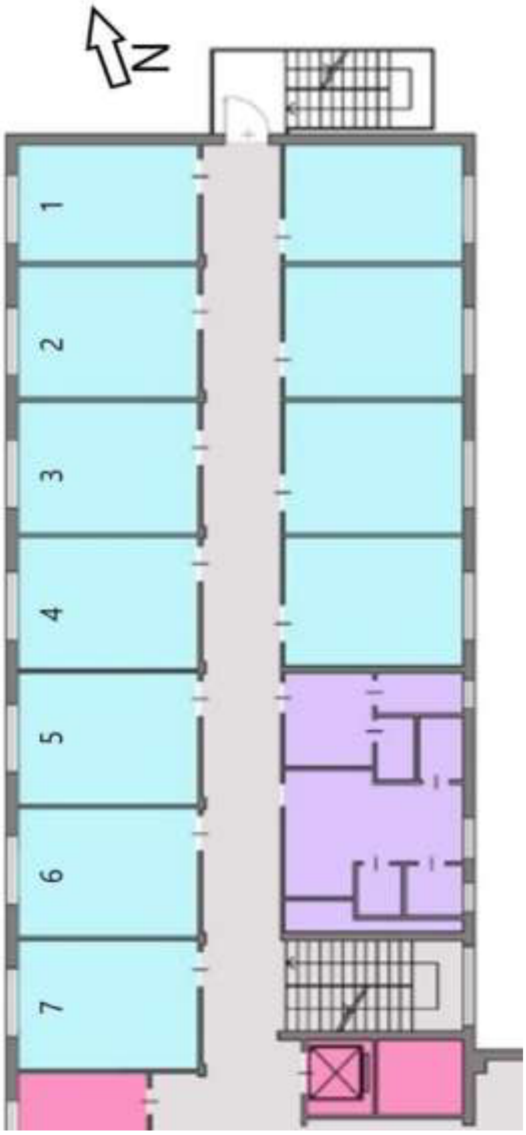

Fig. 1. Layout of the ENEA Living Lab.

2.2 The smart energy management system

The Living Lab has a smart management system to fully survey the security, safety, comfort and energy performance of the building. Dedicated applications are implemented to collect data of the relevant parameters and manage the control of different systems; in particular, the following quantities are continuously monitored:

- Climatic data (air temperature, relative humidity and velocity, and global horizontal solar irradiation), taken from a weather station placed on top of the building;
- Ambient air temperature acquired in each room in a sensor placed on the wall facing the external façade;
- Presence, CO2 concentration and global horizontal illuminance, even if data were not relevant for the present study;
- Ambient air temperature in rooms and corridors adjacent to the seven test rooms;
- Opening of the sash, activation of the venetian blinds, and the tilt of the lamellae of W2 and W3 windows.

The dedicated apps were used not only to monitor data, but also to write the rules for managing the dynamic elements of W2 and W3 windows.

Table 1. Rules for opening and closing of window sash and Venetian blinds as a function of indoor and outdoor air temperature (T), and horizontal global solar irradiation (H).

Room	Sash	Op/clos Rule	Blind	Op/clos rule
1	N	---	Y	H>150W/m^2 H<100W/m^2
2	Y	21:00 08:00 (next day)	Y	14:00 20:00
3	Y	$(T_{in}-T_{out})>3°C$ $(T_{in}-T_{out})<2°C$	Y	H>150W/m^2 H<100W/m^2
4	Y	$(T_{in}-T_{out})>3°C$ $(T_{in}-T_{out})<2°C$	N	---
6	N	---	Y	Static
7	N	---	Y	Static

2.3 Operational settings and field monitoring

The monitoring was carried out during the month of August 2021 during the summer closing of the ENEA Research Centre, thus the office rooms were unoccupied. This condition was preferred to test the impact of dynamic windows on the indoor built environment without the interference caused by the building users, and asses the accuracy of the calculation model in reproducing the physics of the problem under real conditions.

Table 1 reports the window settings and control rules for the monitored room, except office 5, who was constantly cooled so considered as adjacent zone in the exercise. In particular, two types of strategies are implemented for shading management and night ventilation: one according to a simple opening/closing schedule based and on physical parameters threshold values, namely: global solar horizontal irradiation and indoor/outdoor temperature difference for shading and night ventilation activation,

The monitoring lasted 11 days, form August 12th to 22nd; additional days were from August 25th until 30th with no rules applied, no blinds and sash always closed in rooms 1 to 4 to provide data for additional calibration tests. As results of the monitoring, a dataset of hourly values of the quantities indicated in section 2.2 was prepared and used as benchmark for the successive model validation.

2.4 Building reference case and variants

The reference case of the test building has the W2 window and the operational settings described for Room 3 in table 1. The building is in thermal free floating and since the building was unoccupied during the monitoring period, an occupation profile for each room was implemented upon the average schedules of the workers presence in the room, developed by dedicated one-to-one interviews. This approach was acceptable in the framework of the paper objectives, thus, once the model was calibrated, the effective occupation profile and the associated internal gains were inputted in the model and this configuration was considered as the reference case.

For each room are thus defined the following times: entrance, lunch break, and exit. Rooms 1, 3, 6 and 7 have one occupants, two workers in the other 3 rooms; each of them has a personal computer with two monitors, operating only during the working hours. Occupancy hours are reported in Table 2, additionaly the workers have one hour lunch break at 12:30 and one day of smart working from home per week, except for Room_2 in which the second worker is in smart working for two days. The building is closed during weekends.

Table 2. Average occupation profiles during working days (Monday to Friday)

Room	Worker	Entrance	Exit
1	1	08:30	17:30
2	1 2	08:30 09:30	16:30 15:30
3	1	09:30	17:30
4	1 2	08:30 08.30	17:00 17:30
5	1 2	09:30 08:00	18:30 16:30
6	1	08:30	17:00
7	1	09:30	18:30

A number of variants are next identified to check the impact of different input modes model on the thermal response of the building by thermal simulations. The variants are as follows:

1. Weather data
    1.1. Meteonorm database, world-wide used tools for energy performance assessment of buildings [18].
    1.2. Italian technical standard of weather data for building applications [19].
2. Internal gains
    2.1. Standard occupancy and other gains according to the Italian standard [20].
    2.2. Standard occupancy and other gains according to [21].
3. Night ventilation.
    3.1. Daily Schedule 21:00-08:00 next day with calculated ventilation rate at each time-step based on an empiric model for single side ventilation [22].
    3.2. Fixed 5 air exchange per hour (ACH) with the above schedule [23].
4. Shading system
    4.1. Static shading correction factor SC set to 0.1 for the selected glazing system, calculated for the current window with the procedure defined in [24].

3 Calculation

This section is dedicated to the description of the calculation platform implemented to develop a dynamic energy performance assessment for energy certification purposes

3.1 The calculation platform

In line with the E-DYCE project methodology [25], simulations, validation process and performance gap analyses were performed exploiting a newly developed Python library called PREDYCE (Python semi-Realtime Energy DYnamics and Climate Evaluation) [14] acting as a dynamic simulation platform. The platform architecture development is based on E-DYCE, while extra functionalities and use scenarios are developed under the EU H2020 project PRELUDE (958345). PREDYCE includes EnergyPlus [26] as a simulation engine and is based on three main modules and an EPW compiler. The library allows highly personalised and flexible handling of weather (EPW files) and building model inputs for EnergyPlus (IDF files) and it features an output KPIs computation module, allowing the monitored data integration. Figure 2 highlights how the library allows automating several steps of the analyses inside pre-defined usage scenarios, including sensitivity analyses, model verification supports, and performance gap detection between monitored and simulated post-elaborated results. A large set of personalised and standard-based KPIs can be calculated, including thermal comfort [21] and energy ones, in line with the above-mentioned E-DYCE methodology. The library returns two main outputs: a CSV reporting simulation-period-aggregated KPIs for all simulations and time-series results for every single simulation, aggregated with chosen time steps, e.g. hourly.

The platform allows the management of multiple parallel simulations by automatically applying a list of changes in EnergyPlus inputs and objects defined in a managing JSON file to IDF files. For example, it can be possible to add thermal insulation, change window properties, modify/add ventilative cooling and shading systems, change scheduling profiles, etc. Currently, the library is not able to perform geometrical changes, not including a CAD interface. It requires that users will generate a starting IDF, including building geometries, using one of the existing EnergyPlus interfaces. For this paper, DesignBuilder [27] is adopted. Nevertheless, all inputs and outputs are next modified using PREDYCE to perform the calculation for this paper. Finally, even if PREDYCE allows automatic graphical outputs for some KPIs, graphical elaborations for this paper are a result of post-analyses based on the library outputs.

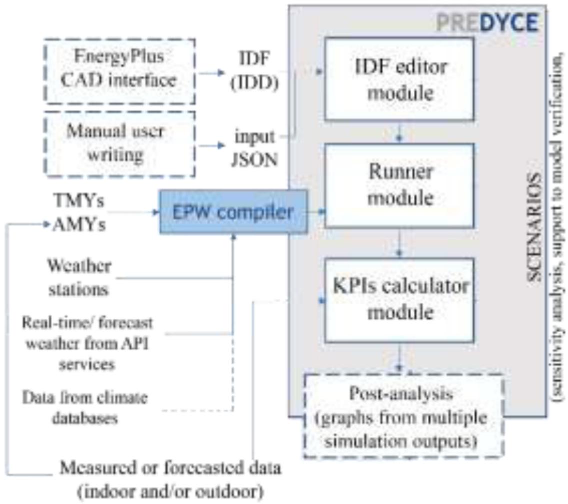

Fig. 2. Overview of PREDYCE modular structure.

3.2 Modelling of the ENEA Living Lab

The model used to perform the seasonal simulation was built to be as adherent as possible to the real configuration, even if some assumption was taken for construction and occupancy coherence. In particular, for the reference case:

- All the seven rooms are equipped with the W2 window, the night ventilation strategy is that based on the indoor/outdoor temperature difference, as applied in Room_3 and Room_4 during the monitoring, and the shading activation is that Room_2, taking place during the afternoon being the rooms west oriented.
- The ventilation rate with the opened window is calculated at each time-step with the model described in [27].
- The internal gains are those defined according to the occupancy profile of Table 2
- The weather data are those measured on site, and the surfaces surrounding the seven office rooms of the

Living Lab versus the other indoor zones were considered adiabatic. Since EnergyPlus requires some specific weather variables that were not directly monitored on the site, these were taken from the nearest station available on Weather Underground and merged with data from the local weather station.

Simulations were run for all the variants identified in section 2. As a successive step, the combination of variants was also simulated, in particular and with reference to Table 2, the combined variants are the following:

- Input data defined in 1.2 - 2.1- 3.2 - 4.1, linked to assumption applied in the Italian energy certification method;
- Input data defined in 1.1 - 2.2 - 3.2 - 4.1, to test the other options.

4 Results

This section reports the results obtained for the model validation and the impacts of the selected variants on the indoor ambient temperatures compared to the reference case.

4.1 Model validation

Figure 3, 4 and 5 report the comparison of the air temperature measured and simulated in the office rooms 2, 3 and 6 during the eleven days in August, as exemplary cases. The other 3 rooms are not presented for the sake of brevity. Table 2 reports the temperature difference of the calculated and measured values, as well as the relevant statistic indicators to assess the quality of the validation process.

The average temperature difference ranges between 0.29°C (Room_6) and 0.38°C (Room_3). Maximum differences are above in the 0.85-1.42°C range, but these peaks happen for few hours (maximum is 9 in Room_2) in a 11 days observation period. Differences are higher than 0.5°C in 20% of the period as maximum (again in Room_2), being that value the declared error. Of the temperature sensor-

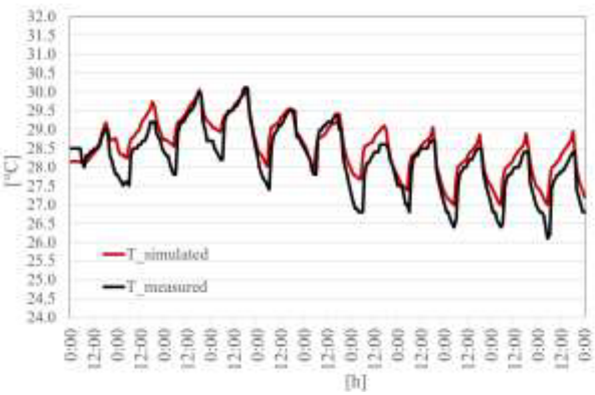

Fig. 3. Comparison of measured and simulated air temperature profiles in office room 2.

The accuracy of the validation process is confirmed by the values of the identified statistical indicators: the hourly mean absolute error (MAE) is in the 0.30-0.39°C range and the coefficient of variation of the root mean squared error (CV(RMSE)) is in the 8-9% range. The latter in full compliance with the requirements specified in [16], which set to 30% the limit for the hourly based thermal comparison.

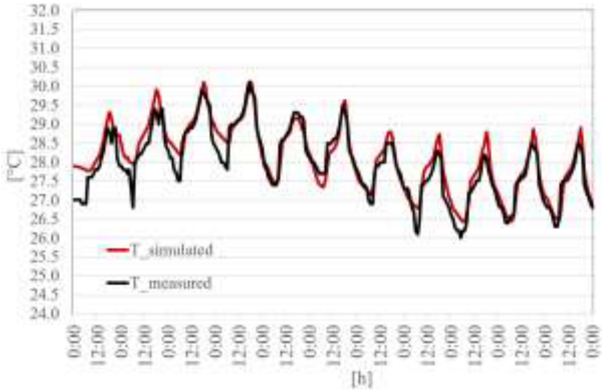

Fig. 4. Comparison of measured and simulated air temperature profiles in office room 3.

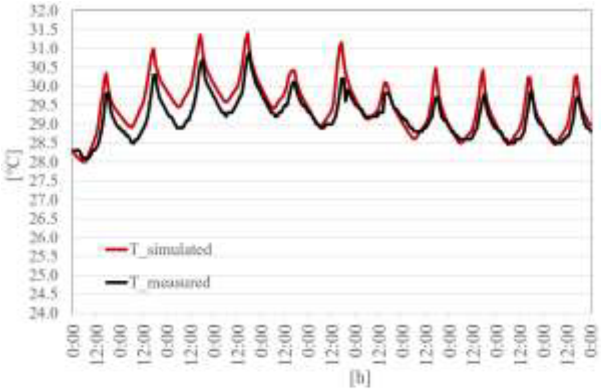

Fig. 5. Comparison of measured and simulated air temperature profiles in office room 6.

Table 2. Main temperature parameters and statistical indicators of the simulation/measurement comparison.

	Room_2	**Room_3**	**Room_6**
Av. temperature difference [°C]	0.30	0.38	0.29
Max. temperature difference [°C]	0.95	0.85	1.42
MAE [°C]	0.30	0.39	0.30
RMSE [°C]	0.72	0.77	0.70
CV (RMSE) [%]	2.5	2.7	2.4

4.2 Seasonal simulations

Table 3 reports the discomfort hours for the cooling season, defined as the period from June the 1st until August 31st in the rooms 1 to 6 the Living Lab, as well as the average value, as well as the average temperature in the period. Room 7 was treated as a boundary zone, thus not considered for the analysis. According to the relevant standard, the summer discomfort hours are calculated as those exceeding by 2 and 3°C the theoretical thermal comfort level for building categories 1 and 2, respectively (C_1 and C_2), the unmet hours were also calculated when exceeding 1°C (C_0), as additional information.

Figure 6 shows the profile of the operative temperature in Room_2 and Room_4. The plots are very close during the central days, as expected during weekends; the impact of different occupancy profiles, and thus internal gains, is easily inferred during the other four days.

Table 3. Average temperature and discomfort hours in Room_1 to 6, and the average values of the whole Rooms.

Room	T_av [°C]	Dis. hours C_0 [-]	Dis. hours C_1 [-]	Dis. hours C_2 [-]
1	27.5	302	25	0
2	27.5	254	7	0
3	27.5	315	24	0
4	27.8	396	69	0
5	27.7	358	2	0
6	27.5	273	4	0
Av.	27.5	324	4	0

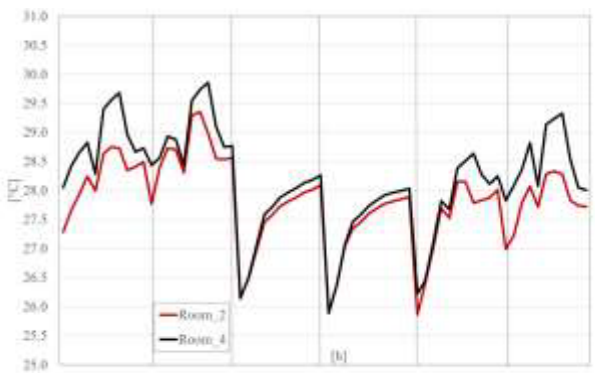

Fig. 6. Hourly operative temperature profiles in Room _2 and 4 in six exemplary days in July.

Figure 7 reports the discomfort hours for comfort categories C_1 and C_2, and the additional category C_0 for each variant as well as for the two identified combinations of variants. The reference case did not show any discomfort hour for C_2 and only 4 hours for C_1, the number of C_0 were 324. Extremely variable results were obtained with the other configurations.

Concerning the weather data, similar results were obtained using the Meteonorm (1.1 variant) database with 10 and zero hours in C_ and C_2 respectively (also C_0 is very close). This depends on the fact that the Research Centre, despite belonging to the Rome Municipality, in is the country side, with climatic conditions more similar to those of the weather station used by Meteonorm. Using the official Italian data (1.2 variant) lead to an impressive increase of discomfort hours, peaking 405 and 724 for C2 and C_1, respectively, thus not representative of the effective measured conditions.

Concerning the occupancy and internal loads, using national standard data caused relevant hours of thermal discomfort, reaching 227 and 549 for C2 and C_1, respectively, quite far compared to monitored data. Using the EU standard profiles, no C_2 discomfort hours were calculated, but the hours in C_1 (64) were significantly higher compared to the reference case.

Concerning the impact of the night ventilation, it was found that using a schedule instead of a physical control caused an increase of C_0 and C_1 discomfort hours: 629 and 64 against 324 and 4 of the reference case, respectively. The use of higher fixed ACH at night caused the strong drop of the temperature, with only 11 hours in C_0. The same applied for the shading performance, whit only 20 hours in C_0 category with fixed 0.1 SC.

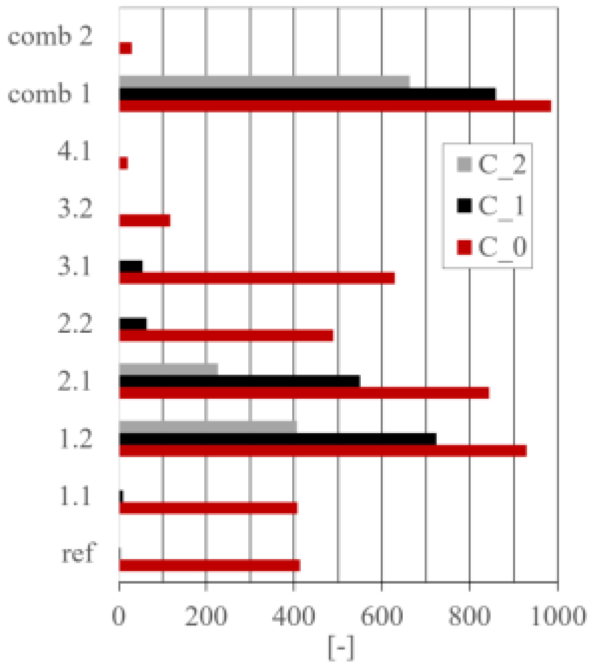

Fig. 7. Hourly operative temperature profiles in Room _2 and Room_4 in six exemplary days in July.

The effect of combining variants was largely dependent on the selected solutions/strategy. The combination 1 registered an impressive number of hours in C_2: 664; while the combination 2, based on the Meteonorm database combined to solar shading recorded only 20 hours in C_0.

5 Conclusions

This paper analysed the impact of different simplifications on the thermal response of an office building by calibrated simulations, with the objective to provide insights to better understand and minimise energy performance gap.

To this purpose, a validated and detailed model was built starting from the field monitoring of a Living Lab, consisting of seven office fully monitored rooms. The model was validate according to relevant bibliography, with 8-9% variation of the root mean squared error of an eleven days hourly dataset. In the next step the impact of different simplifications was assessed respect to the detailed and validate reference case. In this case, assumptions, simplification and utilisation of standard data can deeply affect the results. Increase above 400 and 600 discomfort hours were calculated for single or combined variants compared to the base case; relevant decrease in the 75-95% range were calculated with other configurations.

These results raise the attention on the objective and the reliability of the tools used for the building energy certification, with the need of more accurate method able to provide reliable results to end users and address them to a more energy-conscious behaviour.

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