Multi-zone Dynamic Simulations for Investigation of Occupant Behaviour and Building Performance

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Abstract. The study aims to investigate the correlation between occupant preferences, occupant thermal comfort and building energy performances by means of dynamic building simulations. Moreover, the design power of a central heating system is studied in correlation with an increasing number of occupants with non-standard behaviour. A building consisting of 24 office rooms and a common traffic zone, distributed on 3 floors is simulated in MATLAB Simulink environment. The heating demand evaluated considering the climate of Stuttgart accounts for 49 kWh/(m^{2}a), which decreases to 17 kWh/(m^{2}a) when the mechanical ventilation heat recovery is implemented, i.e. thermal building quality according to the Passive House standard. Furthermore, the climates of Rome and Stockholm are considered to take into account the effects of different boundary conditions. A floor heating system is implemented in every office room and the hot water is supplied by a central heat pump. Non-standard behaviour (i.e. setpoint temperature, window shading, window opening and a combination of them) in an increasing number of offices is implemented to study the impact on the heating demand, on the thermal comfort (room temperature and floor temperature) and on the design power of a central heating system. Peculiar behaviours of some of the occupants can have a relative influence on the building performance. For example, extensive ventilation in only one office can have the same impact on the building space heating demand as higher setpoint or shading in several offices at the same time. Results of the dynamic simulations address the robustness of a central heat pump compared to an electric system. Moreover, a general correlation between the number of office rooms with non-standard behaviour and increase of space heating demand cannot be found as the correlation depends on climate and quality of the building envelope. Finally, the position of the office with non-standard ventilation has an impact on the required heating power.

Keywords. Multi-zone simulation, occupant behaviour, building performance, floor heating system, heat pump, space heating demand, design power, robust system
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1. Introduction

Occupant behaviour can heavily influence the building performances and it is one of the most common reasons for differences between design energy demand and monitored energy demand (1). Moreover, considering a different input of occupant behaviours has an impact on the building and system performances (2), (3). However, it is not clear if it is possible to foresee the increase of space heating demand due to the increase of occupants with non-standard behaviour (i.e. more energy-consuming behaviours). In addition, an open question is how the design power of the heating system would change if an increasing number of occupants with non-standard behaviour is considered, along with the robustness of the heating system (4). This study investigates these topics, performing multizone simulations in MATLAB Simulink environment. The building model used in the current study is CarnotUIBK (5), which implements elements of the CARNOT toolbox (6). One advantage of the CarnotUIBK building model is the easily rezoning, thanks to the first import of the rooms and the following grouping into thermal zones. The accuracy of CarnotUIBK has been tested in several projects. Among them, a recent study (7) proves the agreements in the results between the CarnotUIBK and the ALMABuild building model, both working in MATLAB environment. Moreover, the study demonstrates the accordance of the evaluated space heating demand when a building is simulated with a single-zone and a multi-zone approach (under the same inputs), proving the robustness of the model and the possibility to investigate more in detail on zone-level.

2. Methods

In the current study, multizone simulations are performed considering different envelope levels and climates (as described in 2.1), different offices with non-standard behaviour (described 2.2) and different space heating systems (described in 2.3).

2.1 Building description

A simplified building consisting of 24 office rooms (from A1 to H3) and a common traffic zone, distributed on 3 floors (see **Fig. 1**) is dynamically simulated in MATLAB Simulink environment, using the building model CarnotUIBK and the CARNOT toolbox. Simulations are performed in the climates of Stuttgart, Rome and Stockholm.

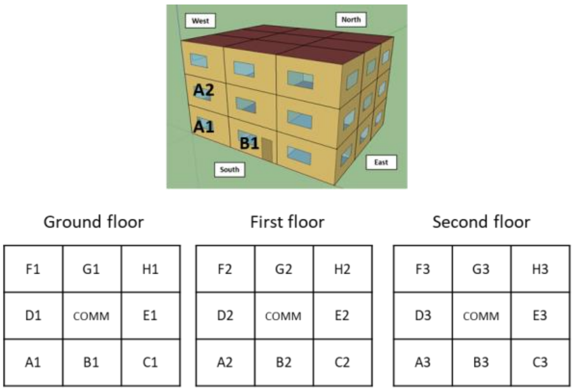


***Fig. 1** - Sketch of the building and location of the offices.*

Two envelope levels are considered: Low Energy Building (LEB) and Passive House (PH). The properties of the envelopes are presented in **Tab. 1**.

***Tab. 1** - Properties of the LEB envelope and of the PH envelope.*

	LEB	PH
U-value External wall [W/(m² K)]	0.182	0.125
U-value Floor [W/(m² K)]	0.135	0.135
U-value Roof [W/(m² K)]	0.162	0.085
n_{50}	0.6	0.6
MVHR efficiency	0	75%

2.2 Thermal zoning and offices with non-standard behaviour

Multi-thermal zones simulations are performed, considering the offices in the corners (A1, C1, F1, H1, A3, C3, F3, and H3) as different thermal zones, while the remaining offices and common room are considered as a unique thermal zone (called "central thermal zone"). The influence of people on the building performance is investigated, considering standard and non-standard behaviours in the offices, as they are defined in **Tab. 2**.

***Tab. 2** - Properties of offices with standard and non-standard behaviour.*

	Standard behaviour	Non-standard behaviour
Setpoint room temperature	20°C	22.5°C
Shadings	None	Windows shaded (70%) from 08:00 to 18:00 on weekdays
Window ventilation	None	Windows always tilted of 10°

Firstly, the building with all the offices with standard behaviour is simulated. Secondly, a combination of the offices with non-standard behaviour is considered. This approach allows studying the correlation between the number of non-standard offices with the performances of the building and of the system. The building is simulated with 1, 2, 6, or 8 (or none) offices with non-standard behaviour (as shown in **Tab. 3**), which correspond to 4%, 8%, 25%, or 36% (or 0%) of the offices in the building. The 8 offices are those located in the corners of the building. This choice has been made to investigate the non-standard behaviours in the most exposed offices to the external ambient. Afterwards, the non-standard behaviour is implemented at one office at a time, in order to study the influence of orientation and position of the "non-standard office" on the building performances.

***Tab. 3** - Offices with non-standard behaviour.*

Number of offices with non-standard behaviour (and % respect to the total number of offices)	Offices with non-standard behaviour
0 (0%)	None
1 (4%)	A1
2 (8%)	A1, H3
6 (25%)	A1, C1, F1, C3, F3, H3
8 (36%)	A1, C1, F1, H1, A3, C3, F3, H3

2.3 Space heating system

In the central thermal zone, ideal heating and ideal cooling are implemented, to maintain a temperature of 20°C in winter and 25°C in summer. The offices in the corners are heated with a floor heating (FH) system, while in summer the temperature is not controlled (no cooling system). Eight FH systems are implemented, one for each thermal zone (excepted the central thermal zone).

Each FH system has been implemented in MATLAB Simulink as an ideal floor heating (active power in the floor) and later post-processed to evaluate the required flow temperature of the hydraulic floor heating system and the required power from a central heat pump (HP). The FH power is set to 875 W in each office and the system is controlled in order to meet the setpoint room temperature and to keep the active layer at a maximum temperature of 29°C. For every floor heating system, the mass flow and the flow temperature are calculated as follow (equations (1) and (2)).

The mass flow of the floor heating is evaluated according to equation (1)

$$\dot{m} = \frac{P_{FH}}{c_p \cdot (\vartheta_{flow} - \vartheta_{return})} \quad (1)$$

The design difference between flow and return temperature of the floor heating is set to 5 K.

The flow temperature is evaluated from equation (2)

$$P_{FH} = U \cdot A \cdot \Delta\vartheta_{log} \quad (2)$$

where U is evaluated considering both convection and conduction (using the temperature of the active layer, the room temperature and the superficial temperature of the floor).

The performances of a central heat pump, which provides hot water for all the FH systems, are evaluated considering the Carnot COP, knowing the ambient temperature, the flow temperature of the floor heating and a reference COP value of 4 for an air-water HP A7/W35. The flow temperature is evaluated as the maximum of the flow temperature of all the FH systems. The mass flow is evaluated as the sum of the mass flows of all the FH systems.

Moreover, simulations are performed with two different approaches for the heating system:

- Sys1: ideal system (unlimited power). This system is not representative of the reality (especially for floor heating, where the floor temperature cannot exceed 29-30°C for health reasons). However, this approach allows to directly compare the space heating demand among simulations with different number of offices with non-standard behaviour.
- Sys2: real system (limited power), system as described before. This approach represents a real system. The heating power guarantees the comfort in all the thermal zones in standard conditions, but the comfort is not guaranteed when offices have non-standard behaviour. The space heating demand is not directly comparable among simulations with different number of non-standard behaviours.

3. Results

In this section, the space heating demand on building level is compared for different climates, building envelope and number of offices with non-standard behaviour. Moreover, the thermal comfort is discussed considering zones with different behaviour and simulation with the two approaches to the heating system (Sys1 and Sys2). Finally, the power required from a HP system is investigated, considering different numbers, orientations and positions of the offices with non-standard behaviour.

3.1 Space heating demand

The space heating demand in case of all offices with standard behaviour is shown in **Tab. 4.** For sake of simplicity, they will be referred to as "references cases".

Tab. 4 *- Space system demand evaluated with different climates and building envelopes. All offices with standard behaviour (reference cases).*

	Space heating demand [kWh/(m² a)]	
	LEB	PH
Rome	14.6	1.8
Stuttgart	49.5	17.2
Stockholm	67.5	27.6

The increase of space heating demand due to either the change of setpoint temperature or the implementation of shadings or window openings with respect to the reference case of Stuttgart with LEB envelope is presented in **Fig. 2**. Results are shown for an increasing number of offices with non-standard behaviour and for the two approaches of heating system. Due to the ventilation conditions chosen for the current study, the increase of space heating demand is dominated by the ventilation losses, while shadings and setpoint have a similar influence on the space heating demand. The increase of offices with non-standard behaviour leads to a linear increase in space heating demand. **Fig. 2** shows that the extensive window ventilation in only one office has a higher effect on the heating demand than the change of setpoint and window shading applied in 8 offices. A great difference is highlighted between the two approaches of heating system. In case of 8 offices with non-standard behaviour and windows ventilation, the increase of space heating of 50 kWh/(m²a) in case of Sys2 rises to 113 kWh/(m²a) in case of Sys1. With the combination of the calculated space heating demand, it is possible to evaluate the required energy for a combination of behaviours in the offices, i.e. some standard offices, some offices with only ventilation, others with only shadings, etc.

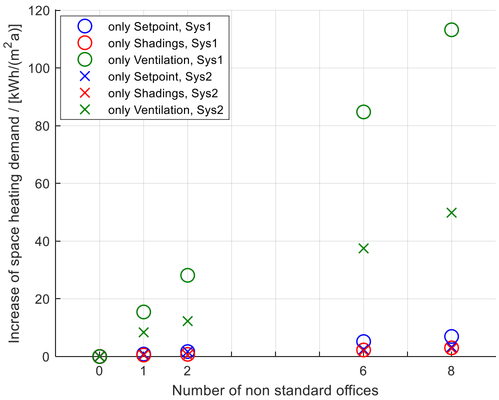
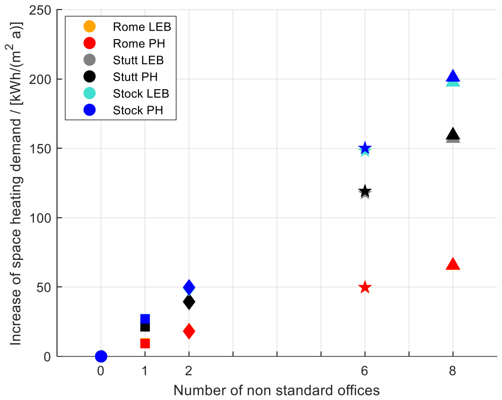
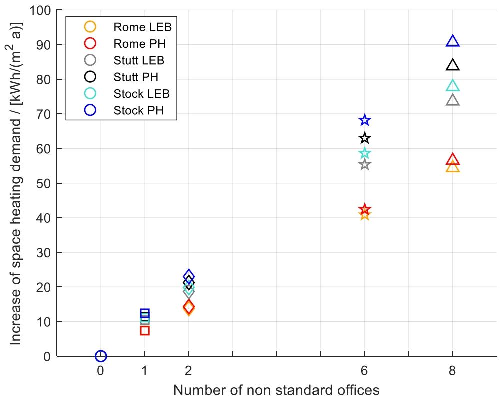


***Fig. 2** - Increase of space heating demand due to increasing number of offices with non-standard behaviour. Comparison of approaches Sys1 and Sys2. Case of Stuttgart LEB.*

In order to consider the maximum possible increase of space heating demand under the conditions of the current study, the investigation proceeds considering the combination of the three user behaviours simultaneously. **Fig. 3** shows the increase of space heating demand for an increasing number of offices with non-standard behaviour considering different climates and different envelope qualities. In case of ideal power (Sys1) – see **Fig. 3(a)** – the climate plays the main role in the space heating demand increase. Nevertheless, when the real system is implemented (Sys2) – see **Fig. 3(b)** – the increase is influenced both by climate and envelope quality. Moreover, in case of Sys2 the required energy is underestimated, as the thermal comfort is not reached in several offices (see next section 3.2).



(a)



(b)

***Fig. 3** - Increase of the space heating demand with the increasing number of offices with non-standard behaviour. Results with Sys1 (a) and Sys2 (b).*

Monthly values of the space heating demand with different climates and different numbers of non-standard offices are presented in **Fig. 4.** Moreover, the wider and brighter columns represent the approach Sys1, while thinner and darker columns represent results from approach Sys2. In all the climates, the biggest difference in space heating demand between standard behaviour and some offices with non-standard behaviour (Sys1) is highlighted in winter. When the Sys2 is implemented, there is a quite constant increase in space heating demand throughout the months because the comfort is not fulfilled. No difference between Sys1 and Sys2 is presented for reference cases (i.e. all standard behaviour) because the comfort is always guaranteed. The non-standard behaviour of some offices leads to space heating demand also in summer for the climates of Stuttgart and Stockholm.

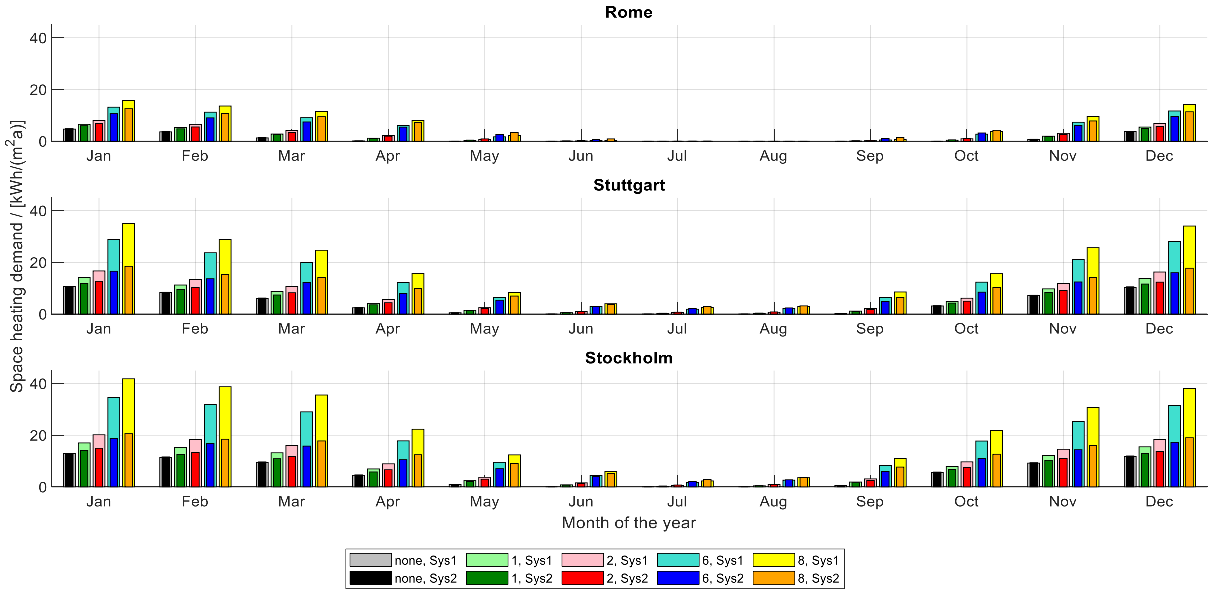


***Fig. 4** - Monthly values of the space heating demand evaluated in three cities with the LEB envelope. Different colours represent different cases for the number of offices with non-standard behaviour and approach to the heating system.*

3.2 Thermal comfort

When the "real system" (Sys2) is implemented, the comfort is not guaranteed for offices with non-standard behaviour. The system working at the maximum power is not able to keep the room temperature at the setpoint. An example is given with **Fig. 5**, results referred to Stuttgart, LEB envelope, non-standard behaviour of the office A1. The room temperature of all the offices meets the thermal comfort, except for office A1 (green line). The temperature of the floor of all the offices is always below 29°C, as required for the comfort of the occupants.

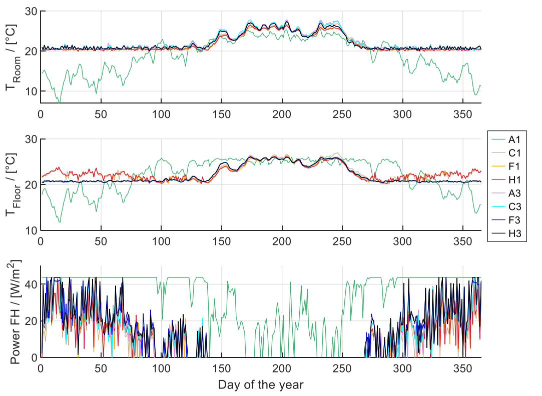


***Fig. 5** - Case of non-standard behaviour of A1, climate of Stuttgart, LEB envelope, "real system" (Sys2). Dynamic temperatures and heating power to study the comfort in the offices.*

When the Sys1 approach for the heating system (infinite power) is applied, the room temperature of the office room A1 always meets the setpoint temperature (22.5°C). The floor temperature is higher than the limit, proving the non-feasibility of this system in the reality (**Fig. 6**).

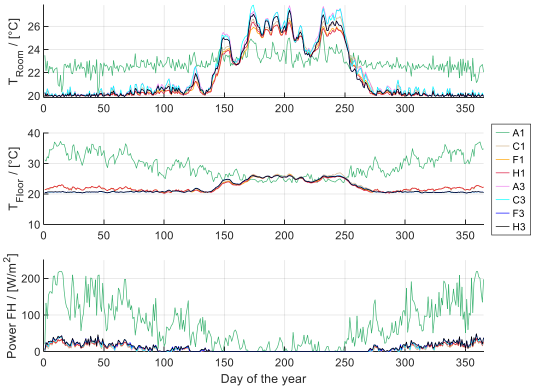
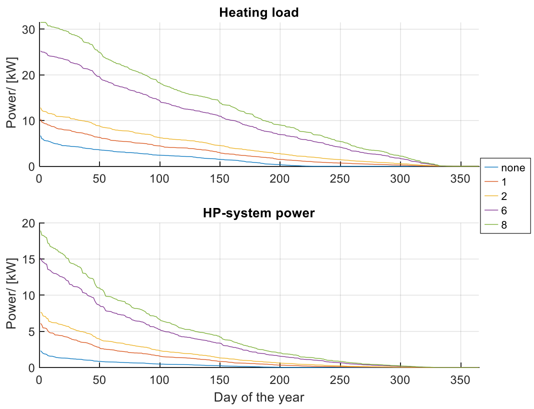


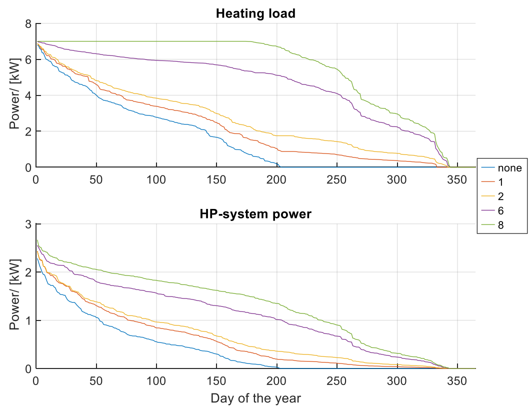
***Fig. 6** - Case of non-standard behaviour of A1, climate of Stuttgart, LEB envelope, "infinite power system" (Sys1). Dynamic temperatures and heating power to study the comfort in the offices.*

3.3 Power of the space heating system

The sorted heating load and the sorted electric power required by a heat pump system in one year are presented in **Fig. 7**. Results are presented for the LEB building in the climate of Stuttgart. The difference between the heating load and the power to be supplied to the HP represents the beneficial effect of the heat pump (COP>1). If a completely electric system is installed, the required power would correspond to the heating load. In case of ideal system (Sys1, **Fig. 7a**), the maximum power (both of heating load and HP power) increases with the increasing number of offices with non-standard behaviour. While with a real system (Sys2, **Fig. 7b**), the maximum heating load of 7kW is common for every case. Moreover, the maximum heating load in case of 8 offices with non-standard behaviour is constant for 180 days. With both approaches (Sys1 and Sys2) the implementation of a fully electric system would lead to a bigger increase of heating power with the increasing number of offices with non-standard behaviour. Therefore, the HP system is preferable to mitigate the effects of the occupant behaviour.



(a)



(b)

Fig. 7 *- Sorted heating load and electric power for a HP with approach Sys1 (a) and with Sys 2 (b) considering LEB building in Stuttgart. Comparison among different number of offices with non-standard behaviour.*

In order to investigate the effect of orientation and position of the office with non-standard behaviour, the three behaviours are considered separately. 8 cases are simulated: for each case a different office is considered with non-standard behaviour. Changes in setpoint and shading do not show appreciable differences among the heating power of the 8 cases. On the contrary, the sorted electric power required by the HP in case of only non-standard ventilation in one office presents a clear difference among the considered offices (see **Fig. 8**). The plot presents results for the case of LEB envelope in Stuttgart. A difference is presented between offices with non-standard behaviour on the ground floor and on the second floor. The ones on the ground floor require higher heating power. The orientation of the office doesn't influence the heating power appreciably.

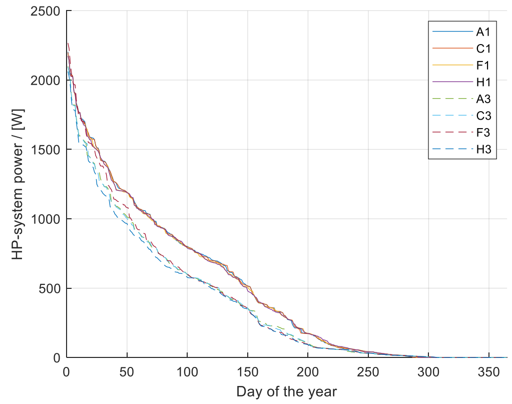


Fig. 8 *- Sorted heating power for a HP system (Sys 2) for cases with one office with only ventilation as non-standard behaviour. Comparison among cases with only one office with non-standard behaviour and different position (solid line for offices on the ground floor, dashed line for offices on the second floor) and orientation in the building. Case of Stuttgart, LEB envelope.*

4. Conclusions

Multizone dynamic simulations have been carried out for an office building considering different envelope qualities, climates, number and position of offices with non-standard behaviour and space heating systems. The increasing number of offices with non-standard behaviour leads to a higher electric power to be provided to the HP (case of infinite power). When a real system is implemented, the maximum power is independent of the number of non-standard offices because comfort cannot be guaranteed. With both approaches (ideal and real system) the increase of power is lower than what would be required from an electric system, proving the robustness of a HP system with the increasing number of offices with non-standard behaviour. A non-standard ventilation in only one office can have the same (or higher) effect on the building space heating demand as the non-standard setpoint or shading in 8 offices at the same time. When the office with non-standard ventilation is located on the ground floor, the heating power is higher than the power required in case the office with non-standard ventilation is located on the second floor. Due to the limited power of the FH system, the thermal comfort of the room temperature cannot be fulfilled when an office has non-standard behaviour. Finally, there is a linear increase of space heating demand with the increasing number of offices with non-standard behaviour (for either non-standard setpoint, non-standard shading, non-standard ventilation and the combination of them). It is not possible to foresee the space heating demand based on the number of offices with non-standard behaviour because climate and envelope lead to different trends.

5. References

1. Liu P, Lin B, Wu X, Zhou H. Bridging energy performance gaps of green office buildings via more targeted operations management: A system dynamics approach. J Environ Manage [Internet]. 2019;238(September 2018):64–71. Available from: https://doi.org/10.1016/j.jenvman.2019.02.111

2. Barthelmes VM, Becchio C, Fabi V, Corgnati SP. Occupant behaviour lifestyles and effects on building energy use: Investigation on high and low performing building features. Energy Procedia [Internet]. 2017;140:93–101. Available from: https://doi.org/10.1016/j.egypro.2017.11.126

3. Calì D, Andersen RK, Müller D, Olesen BW. Analysis of occupants' behavior related to the use of windows in German households. Build Environ. 2016;103:54–69.

4. Calì D, Osterhage T, Streblow R, Müller D. Energy performance gap in refurbished German dwellings: Lesson learned from a field test. Energy Build [Internet]. 2016;127:1146–58. Available from: http://dx.doi.org/10.1016/j.enbuild.2016.05.020

5. Siegele D, Leonardi E, Ochs F. A new MATLAB Simulink Toolbox for Dynamic Building Simulation with B.I.M. and Hardware in the Loop compatibility. Proc Build Simul 2019 16th Conf IBPSA. 2020;16:2651–8.

6. Solar-Institut Juelich. CARNOT Toolbox Ver. 6.3, 10/2018 for Matlab/Simulink R2018b. 2018.

7. Pacillo V, Naldi C, Venturi E, Ochs F, Morini GL, Magni M, et al. Effect of the building zoning on the energy consumption with different dynamic energy simulation tools:ALMABEST versus carnotUIBK. 2021;

Data Statement

The datasets generated during and/or analysed during the current study are not publicly available because of ongoing works, but will be available by contacting and agreeing with the authors.