TRANSITION FROM INDOORS TO OUTDOORS – APPROACHES TO MODELLING THE EFFECT ON THE HUMAN THERMAL STATE

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ABSTRACT

Building occupants move between zones in a building and between outdoors and indoors several times during the day, exposing the body to multiple step-changes in its thermal environment. This phenomenon has never been studied in building simulation tools before. The thermo-physiology, sensation and comfort tool PhySCo coupled with ESP-r was used to simulate two typical warm and cold days. Two different methods to represent the outdoor environment were used and the effect of the dynamic movement of occupants on their thermal comfort has been studied. The results showed that moving from a hot environment to a cooler one requires more time to reach thermal steady-state compared to moving from cold to neutral.

INTRODUCTION

Our thermal environment is usually transient and non-uniform even in a well-conditioned building, since the building occupants move between different areas of the building and between indoors and outdoors. For example, from an unconditioned zone into a conditioned one or from a hot or cold outdoor environment to indoors.

Under a sudden change in the ambient conditions, the human body reacts to cope with the changes in the heat balance to preserve the neutral core temperature of around 37 °C. A detailed and dynamic physiology model is needed to account for the transient environmental changes and the accompanied thermo-physiological response.

Solar radiation plays a major role in the energy balance of the human body. Consequently, the solar heat gain on the body has been studied for many years, and several models have been proposed from very simple to advanced methods (Blazejczyk et al. 1993).

Höppe (2002) addressed the different aspects of assessing indoor and outdoor thermal comfort. When moving from a comfortable indoor environment to a cold environment the human body may require several hours to reach a steady-state. Whereas when moving to a hot environment, a steady-state may be reached within 30 minutes only. Since a steady-state thermal comfort model cannot provide realistic assessments under cold and hot conditions, a transient model is required.

Several indices have been proposed in the literature to evaluate the thermal conditions of humans in the outdoor environment. The two most used nowadays are the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI).

The PET, introduced by Höppe (1999), is defined as "the air temperature at which in a typical indoor environment the heat balance of the human body is maintained with core and skin temperatures equal to those under the conditions being assessed". It allows a person to compare the integrative effects of complex outdoor thermal conditions with an indoor experience.

The UTCI which is based on an advanced thermo-physiological model of human temperature regulation (Fiala et al. 2010) was set to achieve a climatic index applicable for an extremely hot and cold environment. The method used the Dynamic Thermal Sensation DTS model, which can predict the human overall thermal sensation. It is a function of the rate of change in the skin temperature and the core temperature based on a regression analysis.

The main purpose of using a building simulation tool is to study the energy performance of a building and the occupant thermal comfort. The outdoor thermal environment is complex and using the hourly weather data from the weather file is not an accurate way to study the outdoor human thermal comfort. It is, however, acceptable as a simplified way to project the thermal state of the building occupants.

The detailed human physiology and thermal comfort model PhySCo, which has been presented in several research papers (Boudier et al. 2016, Ganji et al. 2018, Boudier et al. 2019), shows a robust prediction of the thermal perception. PhySCo has been fully implemented in ESP-r for detailed indoor thermal analysis.

This paper is the first approach that uses building simulation combined with an integrated physiological model to study the effect of the occupant outdoor-indoor transition on thermal comfort. The paper also describes the method of assessing the outdoor thermal environmental parameters and compares two different methods of calculating the mean radiant temperature (MRT) on projecting the outdoor thermal comfort.

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METHODOLOGY

PhySCo

PhySCo is a human thermo-physiology model based on the Tanabe's 65 nodes model (2002) and the Berkeley model (Huizenga 2001). The model is constituted of 16 body parts (head, back, chest, pelvis, shoulders, arms, hands, thighs, legs, and feet) where each body part has four concentric layers (bone, muscle, tissue, and skin) in addition to a central blood node (Stolwijk 1971, Tanabe et al. 2002, Huizenga et al. 2001). Hoffmann et al. (2012) added the effect of direct and diffuse solar radiation through complex fenestration. The model handles asymmetric environments and transient conditions and considers personal parameters such as clothing value (clo) and activity level. The physiology model is combined with the thermal sensation and comfort model of Zhang (2003). The model predicts local sensation and local comfort based on local skin temperatures and core temperature. The overall sensation and comfort reflect the overall thermal state of an occupant. (Boudier et al. 2016, Hoffmann and Boudier 2016)

PhySCo has been integrated with the building simulation tool ESP-r (ESRU). ESP-r was selected for this study because it is research-oriented, accurate, dynamic, and open-source (Clarke 2001). Figure 1 sketches the coupling process and the parameters exchanged. The coupling of ESP-r with PhySCo comprises the implementation of a control logic of centralized HVAC and decentralized personal comfort systems depending on thermal comfort and local thermal sensation values (Boudier and Hoffmann 2019).

The occupant clothing ensemble adaptation is a function of the environmental changes, the current perception, and the perception history. This was applied using PhySCo in Rida and Hoffmann (2019) which is based on the model of Schiavon et al. (2013). Ganji et al (2018) developed the (Wo)Man in Cube approach for local MRT calculation.

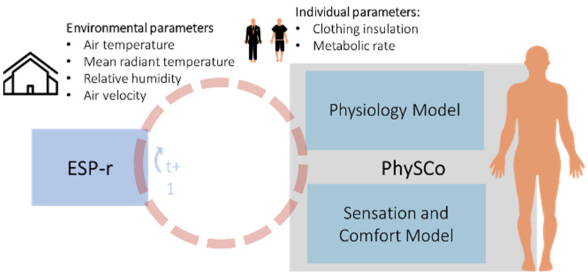

Figure 1: Schematic of PhySCo and ESP-r coupling.

Dynamic clothing model

The dynamic clothing model developed in Rida and Hoffmann (2019) has been updated to account for the outdoor winter clothing ensemble. The outdoor winter clothes are defined with a high insulation value resulting in a total clo value of 1.8 clo. The clothes distributed over the whole body define a person wearing a winter outdoor jacket on top of the indoor winter clothing based on the International Standard Organization (ISO-7730).

The outdoor winter outfit is considered only in the cases when the occupant is set to be outdoors and the dry-bulb temperature is less than 14 °C. When the dry-bulb temperature is higher than 14 °C, clothing was selected from one of the four indoor clothing ensembles (summer, spring, autumn and, winter) (Rida and Hoffmann 2019).

In the sensation model of PhySCo, the neutral setpoint temperatures for the winter outdoor clothing have been updated. The neutral set points can be defined as the local skin temperature distribution at steady-state of a corresponding neutral environmental condition. Each combination of clothing and metabolic rates has different neutral environmental conditions based on Zhao et al. (2010).

Indoor environmental parameters

Indoor air temperature

The air temperature distribution is considered uniform over the human body parts and equal to the dry-bulb temperature of the air node of the corresponding zone.

Indoor Mean radiant temperature

Using the (Wo)Man in Cube approach, local MRT can be calculated for each body part. In ESP-r a pre-defined sensor of three boxes with 14 surfaces defines the human body location inside a zone. The ray-tracing method used to calculate the view factor and consequently, the radiant temperature of the surfaces of the imaginary boxes. By using a pre-defined set of view factors (considering the human posture), the local body MRT is calculated. The pre-defined view factors between the surfaces of the imaginary box and the human body surfaces (243 surfaces) were calculated using the software view3D. Figure 2 shows a representation of the (Wo)Man in cube approach used for view factor calculation in addition to the heat exchange between the human and its environment.

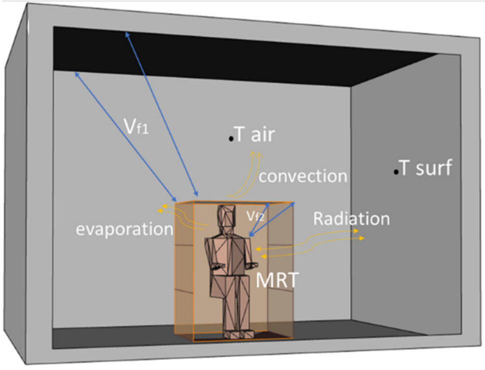

Figure 2: Representation of the (Wo)Man in cube approach for view factor and heat exchange with surroundings.

Indoor air velocity

The indoor air velocity is considered constant and uniform with a value of 0.1 [m/s].

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Relative humidity

The relative humidity is considered uniform over the human body parts and is equal to the relative humidity of the air node of the corresponding zone.

Outdoor environmental parameters

Outdoor air velocity

The outdoor air velocity is calculated based on the equation provided by Kuttler (2000) equation (1).

$$V_h = V_{ref} (\frac{h}{h_{ref}})^a \qquad (13)$$

$$a = 0.12 * Z0 + 0.18 \qquad (2)$$

Where V_h [m/s] is the air velocity at a certain height h [m] and V_{ref} [m/s] is the air velocity measured at the height h_{ref} [m]. In our case, we estimated that h_{ref} =10 [m], which represent the hight of the weather station, estimating that the data was measured at a height of 10 [m], and the V_{ref} is the air velocity given from the weather file. The air velocity required for our calculation is to be taken at a height of 1.1 [m] above the ground, representing the centre of the human body.

The roughness exponent a is calculated from equation (2). Where Z0 is the roughness length in [m]. Table 1 presents some typical values for this coefficient taken from Kuttler (2000).

Table 1: Roughness exponent for different locations.

LOCATION	ROUGHNESS EXPONENT (a)
Outer city and open area	0.16
Low-dens suburb	0.28
Densely built-up urban area	0.4

Outdoor MRT modelling approaches

Two different methods were used in the modelling process:

Method 1 uses a separate outdoor zone in which MRT from the (Wo)Man in cube approach could be considered.

Method 2 uses the weather data to calculate the outdoor MRT without defining a zone.

Method 1: Outdoor MRT using the (Wo)Man in Cube approach (with an outdoor zone)

Modelling the outdoor space as a thermal zone by representing the surrounding outside surfaces of a building, allows us to use the (Wo)Man in Cube approach to calculate the outdoor MRT. The bottom surface of the zone representing the ground with a corresponding ground temperature profile. The inner surface of the ground represents a pavement where its thermal characteristics are presented in Table 2.

Table 2: Thermal characteristics of the outdoor ground layer (pavement).

MATERIAL CHARACTERISTIC	VALUE
Conductivity [W/m.K]	1.4
Density [kg/m³]	2100
Specific heat [J/kg.K]	653
Ir emissivity [-]	0.9
Solar absorptivity [-]	0.65

The top and the open sides are considered as fictitious layers with a transmissivity of 0.99 and solar absorptivity of 0.01.

A very high infiltration rate of 30 air changes per hour is considered to reach outdoor conditions.

Method 2: Outdoor MRT from weather data (without outdoor zone)

In this approach, we tend to adopt a simplified method to calculate the outdoor MRT using the weather data as dry-bulb temperature and solar radiation based on the equation taken from Jendritzky (1990). No outdoor geometry is needed for this approach.

The outdoor mean radiant temperature index is given by Jendritzky (1990) in equation (3) can be described as follows:

$$MRT = \left[\left(\varepsilon T_i^4 + \frac{(1-a)\left(I_{dif} + I_{ref}\right)}{s\sigma} + 273.15\right) + \frac{(1-a) f_p I_{dir}}{\varepsilon\sigma}\right]^{0.25} - 273.15 \qquad (3)$$

where T_i is the temperature of the surfaces around the human (in this study we assume it to be equal to the air temperature in [°C].), Ɛ is the emissivity of the radiating surface and is equal to 0.95, σ is the Stefan-Boltzman constant equal to 5.7x10^{-8} [W/(m^{2}K^4)], a is the mean albedo of skin and clothing and is equal to 0.33, I_{dir}, I_{dif}, I_{ref} are the intensity of direct, diffuse and reflected solar radiation on a horizontal surface r [W/m^2], fp is the projected area and it can be calculated from equation (4) according to Jendritzky (1990).

$$f_p = 0.308 \cos[h(0.998 - \frac{h^2}{50000})] \qquad (4)$$

where h is the sun altitude.

SIMULATION

The two methods of outdoor MRT calculation have been considered and compared. Figure 3 shows the model setup using Method 1 where the outdoor is modelled as a defined zone, the top corner of figure 3 shows an elevation sketch of the setup. Figure 4 shows the model setup using Method 2 for calculating the outdoor MRT and air temperature is taken directly from the weather file.

In both Figures 3 and 4, the location of the (Wo)Man in Cube sensors is shown.

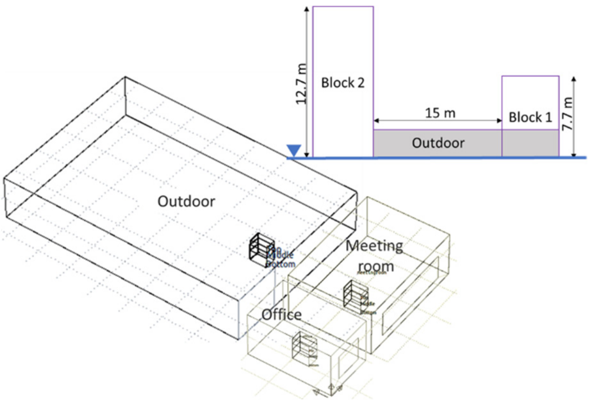

Figure 3: The (Wo)Man in Cube location based on Method 1.

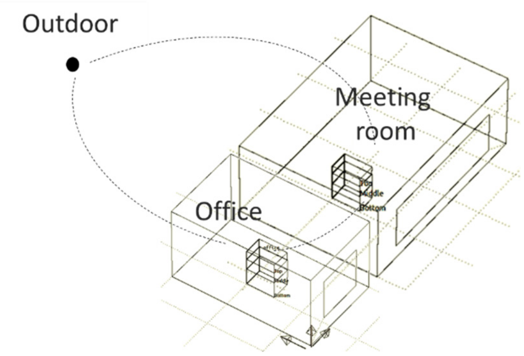

Figure 4: Simulation setup based on Method 2.

Figure 5 is a flow chart showing the model algorithm inside the building simulation ESP-r based on the predefined occupant location. If an outdoor zone is constructed the location of the human body needs to be defined as in Method1, otherwise the Method2 is applied. Environmental parameters are calculated like MRT and sent to PhySCo.

We simulated a case where the occupant moves between three different thermal environments including outdoors (Figure 6).

Room geometry

The model setup can be described as:

- An office room with a floor area of 15 m² and a south facing window of 2.4 m².
- A meeting room with a floor area of 35 m² and a window area of 7.5 m².
- An outdoor zone of 15 m distance between Block 1 and Block 2.
- Block 1 is 7.7 m high and Block 2 is 12.7 m high.

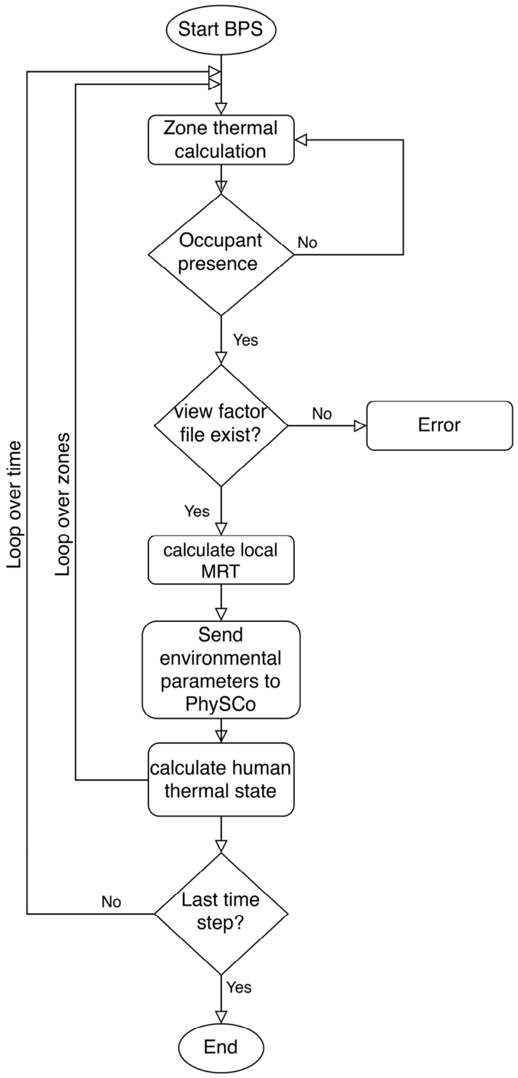

Figure 5: Application flow chart

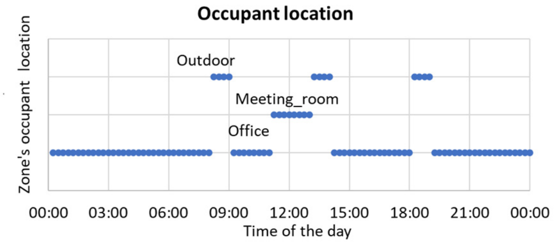

Figure 6: Occupant locations during the simulations

The U values of the different construction types in the two zones, office and meeting room are presented in Table 3.

Table 3: thermal characteristics of the construction surfaces in the office and meeting rooms.

Construction	U-value [W/m²K]
Floor	0.15
Ceiling	0.33
External wall	0.38
Internal walls	1.46
Windows	1.08

Setup

The weather data of the city of Mannheim (Germany) were selected for this study. The office zone was conditioned to 24 °C and the meeting room to 20 °C in terms of operative temperature, by using a basic controller.

The occupant spends three hours in the outdoor zone distributed over the day at 8, 13, and 18. Another two hours of the day, between 11:00 and 13:00, the occupant is located in the meeting room, and the rest of the time the occupant is in the office room.

Simulations were conducted over a random day of June and January to represent a hot and cold day respectively. The climate in Mannheim is classified as warm temperate (Cfb) according to Köppen-Geiger classification. The summer season occurs from May to August and the winter season occurs from November to February.

Results

Figure 7 shows the results for a summer day in June using Method 1 and Figure 8 shows the same day for Method 2. (a) shows the air temperature, (b) shows the MRT for a selected body part, (c) represents the air velocity, (d) shows the total clothing insulation value for the different time of the day, (e) shows the local skin temperature, (f) presents the overall thermal sensation and thermal comfort of the occupant.

Similarly, Figure 9 presents the results for a cold winter day in January using Method 1, and Figure 10 shows the results data from a simulation of the same day but using Method 2 for outdoor thermal environmental conditions.

Discussion

From the results presented in Figures 7 and 8 (a), we can see the differences in the dry-bulb temperature between the two different methods. Method 1 showed a higher air temperature, since it is the outdoor air zone node temperature, compared to Method 2 where the dry-bulb temperature is taken directly from the weather file. The differences are due to the enclosed outdoor zone, even though a high air change rate was considered.

The major differences can be seen in the MRT calculation. Method 1 uses the (Wo)Man in Cube approach in an outdoor zone without considering direct solar radiation. However, solar radiation still hits the person and its surrounding surfaces through the fictitious walls. MRT in Method 2 shows higher values due to the consideration of the direct solar radiation affecting the MRT (see Equation 3). Moreover, the MRT is uniformly distributed over the whole body in Method 2 as Figure 8 (b) shows during the outdoor phase.

The differences in the environmental parameters cause the dynamic clothing insulation model to predict different values (Figures 7 to 10 (d)). For example, Figure 8 (d) shows higher clothing insulation during the first hour outdoor and that is due to the lower dry-bulb temperature using Method 2. The outdoor velocity in both methods uses the same equation. Because of that, similar results of air velocity can be seen in both methods (Figures 7 and 8 (c)).

When comparing the results from the two methods on a cold winter day (Figures 9 and 10), only small differences can be found on the environmental parameters due to the very low outdoor air temperature. The main difference can be seen in MRT prediction. Even with very low solar radiation, MRT showed higher values between 13:00 and 14:00. This elevated MRT yield a slight increase in the overall sensation in Figure 10 (f) and skin temperature in Figure 10 (g). In this example, the importance of considering the direct solar radiation in simulation can be seen.

The overall sensation and comfort results in (f) show how human thermal perception varies when moving between different thermal environments. Also, comparing Figures 7 and 8 (f) and 9 and 10 (f), it can be seen how MRT and consequently the solar radiation can enormously influence the comfort prediction.

The results also show that moving from the outdoor to indoor zone in a hot summer day requires around one hour for the body to reach thermal steady-state. Which can be expressed by either the skin temperature or the sensation values. On the other hand, for the case of moving from cold winter day to indoor, it requires around 45 minutes for the body to reach thermal steady-state, even though the temperature and air velocity difference was greater compared to the hot case.

CONCLUSION

In this paper, we modelled the thermal comfort of the occupant moving between different environments during a day using a combination of the detailed human thermo-physiology, sensation and comfort model PhySCo and the building simulation tool ESP-r. This co-simulation approach allows us to understand and project the outdoor thermal perception of the building occupant. Moreover, the paper presented and evaluated two methods for considering the outdoor thermal environment surrounding the human. The outdoor environmental parameters can be simplified if no outdoor zone is applicable by using the weather data provided. In this method, the simplified uniform MRT considers the direct solar radiation on the human. On the other hand, when an outdoor zone is defined, the outdoor environmental parameters were defined using a specific zone. This method allows using the (Wo)Man in Cube approach to calculate local MRT by considering a ray-tracing method for long-wave radiation.

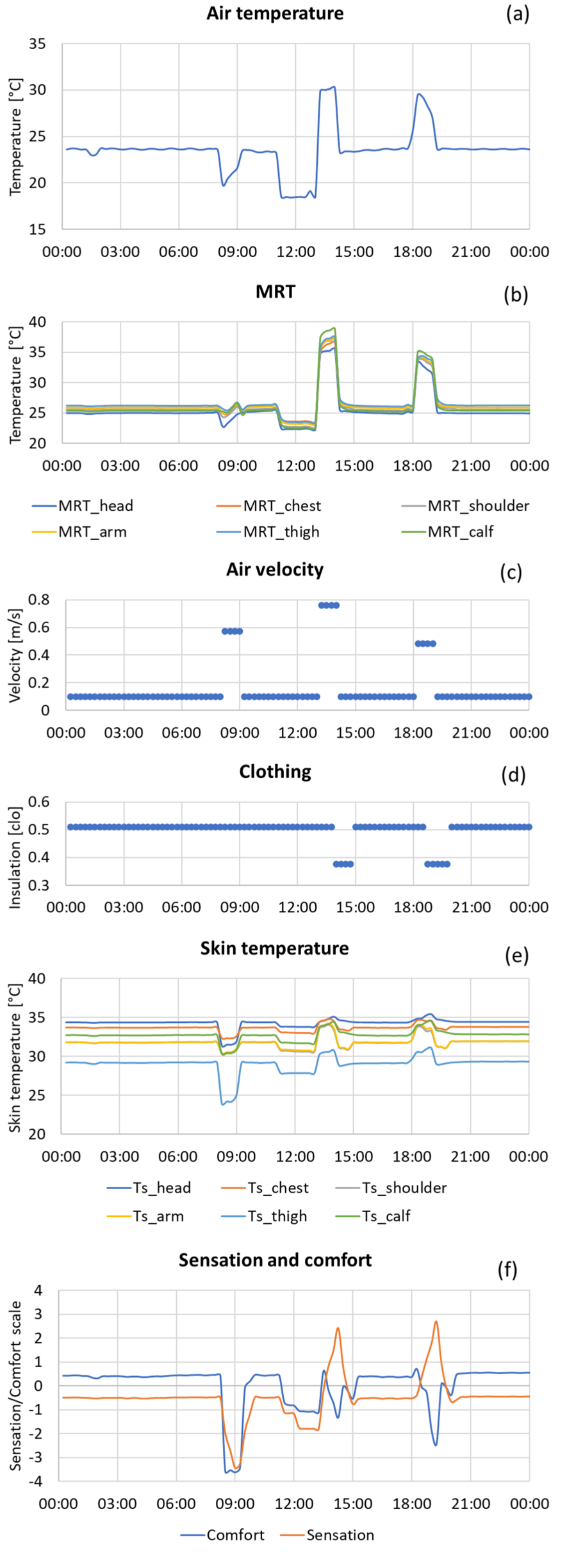

Figure 7: Results for a summer day in June with outdoor zone, (a) air temperature, (b) MRT, (c) air velocity, (d) clothing insulation, (e) skin temperature and (f) sensation and comfort.

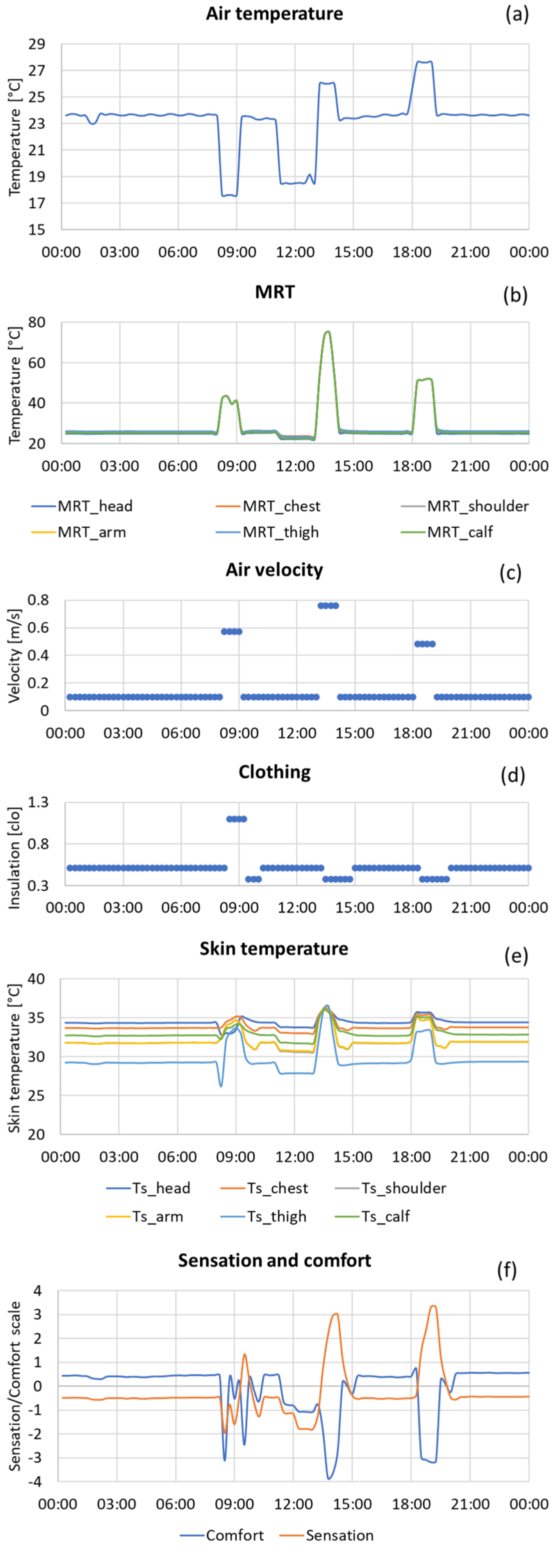

Figure 8: Results for a summer day in June without the outdoor zone, (a) air temperature, (b) MRT, (c) air velocity, (d) clothing insulation, (e) skin temperature and (f) sensation and comfort.

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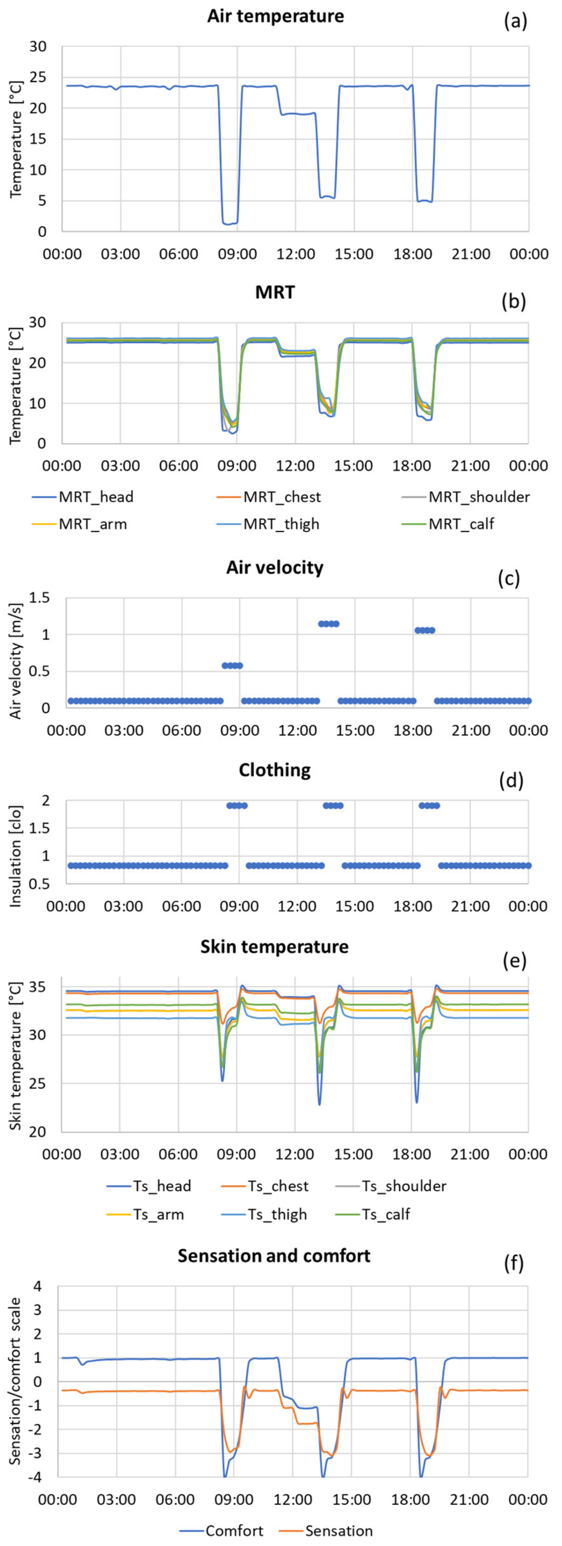

Figure 9: Results for a winter day in January with outdoor zone, (a) air temperature, (b) MRT, (c) air velocity, (d) clothing insulation, (e) skin temperature and (f) sensation and comfort.

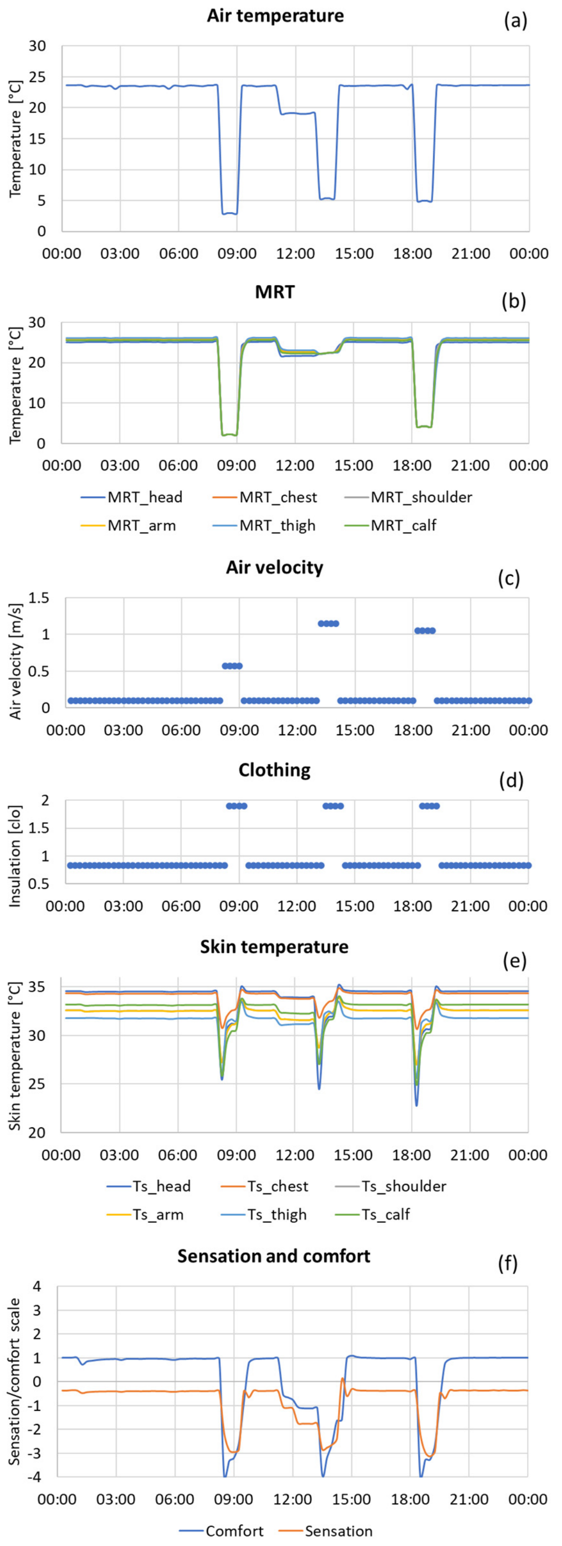

Figure 10: Results for a winter day in January without the outdoor zone, (a) air temperature, (b) MRT, (c) air velocity, (d) clothing insulation, (e) skin temperature and (f) sensation and comfort

These two methods allow us to evaluate the effect of detailed outdoor geometry consideration and direct solar radiation on the human body. The results also showed that the thermal state of the building occupant is transient and the human body requires some time to reach thermal steady-state when step-changes in the environmental conditions occurs.

However, more research on this topic needs to be undertaken, the authors intend to improve the way outdoor environmental parameters are assessed in building simulation for outdoor thermal comfort, especially for the MRT calculation and the consideration of solar radiation. Moreover, a comparison with existing experimental results is planned to validate the approach.

In future investigations, it might be possible to use an occupant behaviour model for movement and presence by generating a realistic occupancy schedule.

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