EVALUATION AND COMPARISON OF BUILDING PERFORMANCE IN USE THROUGH ON-SITE MONITORING AND SIMULATION MODELLING

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ABSTRACT

In recent years in Europe, the improvement of the energy efficiency in buildings has been constantly addressed as a priority. In order to achieve this goal, the first step is to have a calculation method that determines the energy performance of buildings. For this purpose, dynamic thermal simulation programs are used. However, numerous studies (Branco, Lachal, Gallinelli, & Weber, 2004; Burman, Mumovic, & Kimpian, 2014; Johnston, Wingfield, & Miles-Shenton, 2010; Majcen, Itard, & Visscher, 2013) have shown that the measured energy performance of buildings does not correspond to the simulated performance. This is referred to as the "performance gap" and thus, the predictive potential of these tools is reduced.

This paper is part of a research that aims to study the differences between measured and simulated thermal performance through two case studies. Monitoring equipment was installed in two flats located in two originally identical residential buildings, but one of them has been recently refurbished. Both buildings are located in the city of Madrid, Spain. In this paper, we showed only the results the refurbished building. This investigation shows how in-situ measurements and energy monitoring procedures in buildings in use can be used to adjust energy simulation models in order to bring the results closer to the actual thermal performance of buildings.

INTRODUCTION

Nowadays, the study of the actual energy performance of buildings has become a priority. This interest has been mainly driven by the evidence of the high variability in the energy consumption of buildings with very similar characteristics. To that end, it is necessary to define the most influencing factors regarding energy performance of buildings (Cipriano, Vellido, Cirpriano, Martí-Herrero, & Danov, 2015) . Recent research has shown that building energy use is mainly influenced by six factors: 1) climate and site, 2) building envelope and form, 3) building services and energy systems, 4) building operation and maintenance, 5) occupant´s activities and behaviour, and 6) indoor environmental quality provided (Annex53; Annex58). However, there is a lack of approaches considering the interaction and combination between these factors, and consequently, their influence on the energy and thermal performance of buildings. Moreover, in Spain there are few studies regarding this issue (León, Muñoz, León, & Bustamante, 2010; Menezes, Cripps, Bouchlaghem, & Buswell, 2012; Sendra, Domínguez-Amarillo, Bustamante, & León, 2013; Terés-Zubiaga, Campos-Celador, González-Pino, & Escudero-Revilla, 2015). These types of studies usually carried out in North European Countries, with the purpose of analysing the "performance gap" in terms of heating consumption. (Bell, Wingfield, Miles-Shenton, & Seavers, 2010; Branco et al., 2004; Burman et al., 2014; P. de Wilde & Fuertes, 2015; Majcen et al., 2013).

In this study, we aim at studying building performance independently of occupants' behaviour. Therefore, climate and building envelope (U-value) are the factors studied, as relevant variables in the thermal performance of the building (Aste, Angelotti, & Buzzetti, 2009; Goldstein & Eley, 2014).

The selected monitoring period was during the summer holidays, trying to ensure that the residents were not at home, and so, eliminating their possible influence in the thermal performance of the building. Since energy systems are not considered, the temperature evolution has been analysed instead of energy consumption.

In this research, the Technical University of Madrid conducted a monitoring campaign in two case studies in collaboration with TU Delft, partners of the Building Technology Accelerator project (BTA), a Climate-KIC's flagship, by using the BTA-BOCS Platform. Furthermore, the SusLab Integrated Toolkit and its proposed methodology based on mixed methods have been use. Both of them are outcomes of the SusLabNWE project, an Interreg European research project, that aimed at developing a research platform to support the collection of objective and subjective data, on thermal comfort and occupancy practices, in real homes and for long periods of time. In particular, this collaboration allows us to collect building data, during a year, to apply and test the mixed-methods methodology to assess thermal comfort and occupancy practices, and to investigate the "performance gap" in the case studies, and therefore, to discuss the shortcomings and opportunities associated with them.

This paper focuses on the "performance gap" for the domestic part of the building sector. Residential buildings are commonly overlooked in the discussion of the "performance gap" which is commonly focuses on non-domestic buildings (Pieter De Wilde, 2014; Menezes et al., 2012). That is in part because of the difficulty in obtaining actual data of residential buildings due to the availability and involvement of the occupants. However, it represents a key sector of buildings that should not be forgotten.

METHODOLOGY

This paper investigates the "performance gap" between measurements undertaken on actual buildings, and energy models. The actual thermal performance (indoor temperature evolution), in one room in the flat studied during one week in the summer, is compared with three transient DesignBuilder simulation models which have been created with input data, based on the Spanish current regulation and officially recognised Spanish databases. In this case study, a post-occupancy monitoring study has been performed. The building monitoring process consists on five types of data collection. These types are the following: 1) the measurement of building envelope parameters, 2) the energy metering for gas and electricity, 3) the monitoring of the indoor parameters in the dwellings, 4) the collection of subjective data on comfort and related practices from the occupants, and 5) the collection of local weather data.

After completed the monitoring campaign, a bottom-up approach was used for developing a residential energy model including input data from the field study (Guerra-Santin & Tweed Aidan, 2015). Because the aim of the study is to compare the indoor temperature evolution in different scenarios, in a free-running mode (that is without any heating or cooling system running), the period studied is only one week. It allows us to check the differences between the scenarios, which would be difficult if the study period was longer. To study energy consumption, a longer period would be more appropriate.

Simulation results were carried out with DesignBuilder software, (Energy Plus interface). Firstly, a building energy model was created; including input theoretical data from Spanish current regulation and officially recognised Spanish databases (Model 0). Secondly, three different transient energy Design Builder models were created including monitored factors as input data, one by one. All transient models are based on the model 0 and have one variant: transient model 1 includes weather information data from a weather station, transient model 2 includes the U-value from the façades, and transient model 3 includes weather station data and the measured U-value. Finally, we compared each transient model with the actual indoor temperature evolution during one week in a bedroom of the monitored flat in order to evaluate how much influence each of the studied factors has on the building thermal performance.

Case study

The building selected is situated in the south of Madrid, specifically in a neighbourhood called "Ciudad de los Angeles" (Fig.1). This building was built in 1972 and represents one the most representative building typologies in the period of 1950-1980 in Spain (Cuerda, Pérez, & Neila, 2014).

This dwelling has a surface of 63 m2 (Fig.2), with a North-South orientation. The installations consist on individual gas boiler and hot water heating. Household's and dwelling's characteristics are defined in table 1.

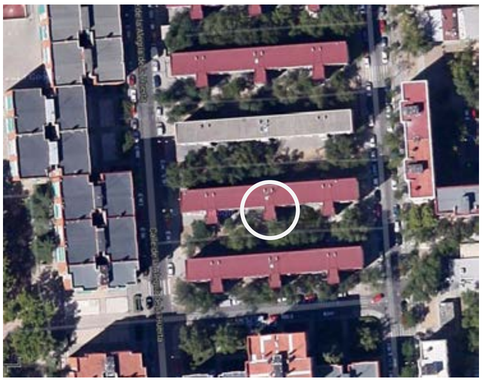

Fig. 1 Case study apartment building

Table 1
Household and dwelling characteristics

	DWELLING CP
Household size	1
Age/ gender	Elderly woman
Occupation	Employed- part time
Type tenure	Owner
Type dwelling	Apartment
Last renovation	2009/03/24-2011/03/03
Features	Renovated
Construction year	1972*
Features	Double glazing, floor insulation, façade insulation

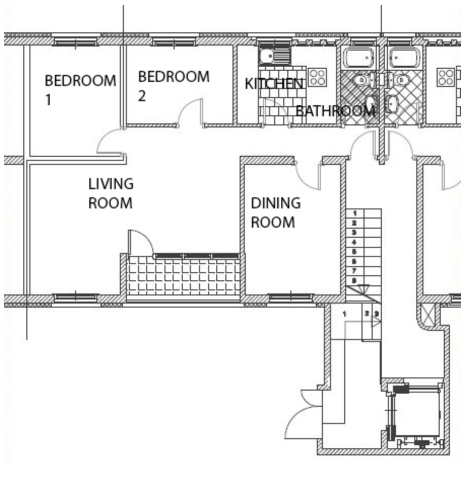

Fig. 2 Case study floor plan

Data generation and collection

The type of the data collected was as follows:

- Simulated energy performance use data: from Spanish current regulation and officially recognised Spanish databases.
- Measured thermal performance data

Simulation Model 0: thermal performance data

For the Model 0, architectural project information (drawing and documents) was obtained from the original architectural design team. The characteristics of the dwelling (indoor environment, envelope and windows) were obtained from the Spanish current regulation and officially recognised databases (Table 2).
The target of the study was to investigate the influence of weather and building quality (U-value). Therefore, the study period selected was a week during the summer, when the household was on holiday. Thus, energy systems can be considered turned off.

Table 2
Household and dwelling characteristics

ELEMENT	EXPECTED PERFORMANCE
External walls	0.61 W/m2K
Floors	0.3 W/m2K
Windows	2,08 W/m2K (g-value 0.63)
Roof	0.57 W/m2K
Airtightness	0.24
Main heating and heating control	Off
Ventilation	Off

Measured thermal performance data: building envelope parameters, indoors parameters and weather station.

One of the most influencing factors in the efficiency of buildings is the impact of faults in the building envelope (Guerra-Santin et al, 2013), the influence of occupants (Guerra-Santin & Tweed Aidan, 2015) and weather data sources. Consequently, this investigation has been developed when the flat was without occupants and it has been decided to look into the building envelope and the weather data resources.

It should be noticed that there are few uncertainties regarding the dwelling. There is no information about the status of windows, shading elements and internal doors when the resident leaves the house. Therefore, the windows have been considered close and, internal doors and shading elements completely open. In a future study, a sensitivity analysis is recommended.

The blower door test was performed in order to obtain the building airtightness. The value obtained was 0.24, a figure similar to recommendations from officially recognised Spanish databases. The façade U-value was measured with the multifunction TESTO 435-2 (Fig.3), instrument with surface temperature probe to determine U-value, and radio probe for temperature and humidity. This equipment measures the thermal transmittance (and calculates the heat flux) of a building element by measuring the following temperatures: the inner surface of the construction element considered, the indoor air temperature and the outdoor temperature. To measure the temperature of the inner surface (T_{pi}) of the element of construction, the apparatus is equipped with three probes that are fixed on its surface at a distance of 30 cm between them (Fig. 4). This probe has an integrated connection socket TESTO 435-2 and a sensor for measuring indoor air temperature (T_i). Outdoor temperature (T_e) is measured with a especial wireless probe located outside (Fig.5). The outer temperature can be measured quickly and easily, with the window closed, using the wireless probes. The probe is located outside and transmits the values wirelessly to the measuring instrument inside.

Fig. 3 TESTO 435-2 instrument, instrument with three probes fixed on the inner surface of the façade and the wireless probe located in the external window sill respectively.

Fig. 4, 5 and 6. TESTO 435-2 instrument, instrument with three probes fixed on the inner surface of the façade and the wireless probe located in the external window sill respectively.

The TESTO 435-2 instrument is a complex system consisting of the measurement sensors for physical parameters, data acquisition and processing system.
The U-value of the element, in this case the façade, is automatically calculated by:

$$U=\frac{(T_i-T_{pi})\ hci}{(T_iT_e)}$$

Where T_i and T_e are the indoor and outdoor air temperature respectively, T_{pi} is the interior surface temperature of the building element, and hci is the convection transfer coefficient [W/(m^2.K)]

The measurement sensor for physical parameters is composed of:

- Sensor for measuring outside air temperature, type ATF01_pt1000 according to DIN EN 60751, class B, measurement range (-50, +90) ºC.

- Sensors for measuring the temperature of the outer and inner surfaces of construction elements of the building envelope OFTF_PT1000_PVC1 type 5 according to DIN EN 60751, class B, measurement range (-30,+105) ºC.

The U-value was measured in the north façade in order to avoid the direct incident radiation. The protocol followed was performed for 24 hours in the flat, and the data was collected on 10 minutes interval. The measures value obtained was 0.8 W/m^2K and it was used to calibrate transient model 2.

To collect the indoor temperature evolution, the SusLab Toolkit was used. It provides a local network based on zigbee technology to collect sensor-based data automatically as well as personal data by means of self-reports. Sensor boxes were deployed to collect indoor climate data (temperature, humidity and CO2 level) as well as relevant contextual data such as sound, light and movement (Figure 6). The accuracy of the temperature sensor is $\pm 0.5^oC$, ±2%RH, 200ppm CO_2.

The sensor boxes were located in each room of the flat, excluding the bathroom and kitchen for safety reasons.. The parameters were measured and sent to a central database on 16 seconds intervals. The data can be downloaded at any interval desired by the researcher. For this preliminary analysis, a 30 minutes interval was chosen and the temperature was the data used for this analysis.

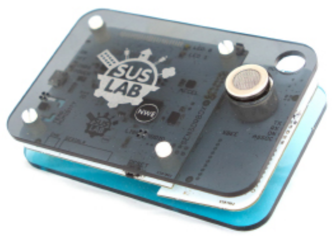

Figure 7 Suslab Sensor Box

In addition, weather data were collected on 10 minutes interval from a meteorological station situated in the neighbourhood during two years. The temperature sensor is ST-0031, accuracy ±0.1ºC. The data collected were: dry bulb temperature (ºC), relative humidity (%), global horizontal radiation (Wh/m2), wind direction (deg), and wind speed (m/s). The data collected was used to generate a new weather file in Design Builder in order to evaluate the influence of this factor.

Transient DesignBuilder simulations:

First, three transient simulation models, of the case study, were all produced (Fig.7) in Design Builder. Second, indoor evolution temperatures were obtained from each of the three models. The results are specifically taken from one of the rooms (bedroom 2).

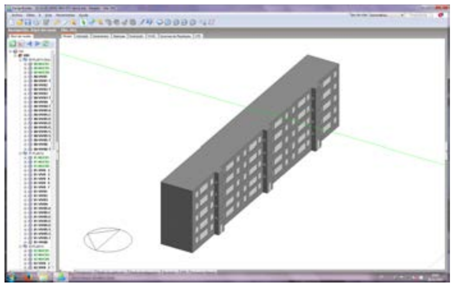

Fig. 8 Transient Design Builder model example

RESULTS AND DISCUSSION

The following are the description of the various models generated:

- Model 0: Spanish current regulation and officially recognised Spanish databases are used as input data.
- Transient model 1: It is based on Model 0 and includes weather information data from a weather station.
- Transient model 2: It is based on Model 0 and includes the measured façade U-value.
- Transient model 3: It is based on Model 0 and includes weather data information and the measured façade U-value.

Comparison of exterior dry bulb temperature evolution. Weather station monitored data vs. Spanish Meteorological National Institute data.

Fig. 8 shows a comparison between the monitored dry bulb temperature evolution from the weather station situated in the neighbourhood (monitored data) and dry bulb temperature evolution from weather data file from the Energy Plus database (Spanish Meteorological National Institute data (SMNI)). It is evident that there is a gap between both curves. The curve from the SMNI temperature is wider than the curve from the monitored temperature. The differences between maximum and minimum peak values, considering the average of the week are: 14.02ºC in the case of SMNI database and 10.12ºC in the case of the monitored data. However, the maximum and minimum temperature values are aligned in both curves.

Fig.9 and followings show the data of three days, instead of a week, in order to show accuracy results.

Model 0. Weather data and indoor temperature evolution

Figure 9 shows the same information from the Fig. 8, and additionally, the indoor temperature evolution in bedroom 2. The black continue curve shows the measured indoor temperature evolution (MITE) and the grey one shows the simulated indoor temperature evolution (SITE) using Spanish Meteorological National Institute weather data. The maximum difference between both indoor temperature curves reaches an average per week of 1.25 ºC. However, it is important to emphasize that the maximum values in the simulated results (grey curves) are essentially aligned (marked with the line 1), everyday between 14:00 or 15:00 hours, while the maximum values in the measured curves are displaced vertically between 5 or 6 hours (marked with the line 2), everyday at 20:00 hours approximately. This could mean that the thermal transmittance data of the Spanish current regulation do not correspond to the actual U-value, and therefore the thermal inertia is not being calculated properly. Consequently, the next step consists on including the monitored weather data in the model and, the measured façade U value as input in the simulation model.

Transient model 1. Actual weather data and indoor temperature evolution

Transient model 2 is used to evaluate the influence of the measured weather data. Fig. 10 shows monitored exterior dry bulb temperature (dashed black curve), monitored indoor temperature evolution (MITE) in solid black curve and simulated indoor temperature evolution (SITE) in black circles curve.

The average difference between simulated and monitored indoor evolution temperature is 1ºC, however both curves tend to become indistinguishable from each other, apart from the displacement mentioned before.

The line 1, 2 and 3, show the vertical displacement of the peak values that are repeated approximately at the same time each day of the week. Monitored outdoor and indoor temperatures reveal that there is a displacement between the time in which the maximum values are reached (line 1 and 2). This time lag gives the corresponding delay explaining the thermal wave from outside to inside. However, there is no this delay between exterior temperature and simulated indoor temperature, meaning that thermal inertia is different in both cases.

Transient model 2. Building envelope parameter and indoor temperature evolution

In order to study the influence of the façade thermal transmittance in the "performance gap", the façade U-value was measured (0.80 W/m^2K) and this value was used in transient model 2, in contrast to the standardised U-value (0.61 W/m^2K) used in the Model 0.

Fig. 11 shows monitored exterior dry bulb temperature (dashed black curve), MITE (solid curve) and SITE (square dot curve). The average difference between the simulated and the monitored indoor evolution temperature is 1.8ºC. The lines 1, 2 and 3 show the vertical displacement of the maximum values. Adding the measured U-value to the simulation model, it provides a result where the simulated indoor maximum temperature is displaced two hours (line 3) respect to the maximum peak exterior temperature. However, it is still far (4 hours) from the maximum peak value of the MITE (line 2).

Transient model 3. Building envelope parameter, monitored weather data and indoor temperature evolution

Transient model 3 is used to evaluate the influence of the measured weather data and the measured U-value at the same time. Fig. 12 shows the monitored exterior dry bulb temperature (dashed black curve), MITE in continuous black curve and SITE in black dashed-dot curve. The maximum difference between the measured and the simulated indoor temperature is 1 ºC. The lines 1, 2 and 3 show the vertical displacement of the maximum values that are repeated approximately at the same each day of the week. The displacements of the peak temperatures in the three curves are the same than in transient model 2.

Comparison between models

Fig. 13 shows a comparison of the the indoor temperature evolution in bedroom 2 simulated with the different models (Model 0, transient model 1, transient model 2 and transient model 3).

The comparison shows that the transient model 1 gave fairly the same results than the measured indoor temperature, despite of the fact that it is vertically displaced 4 hours horizontally and 1ºC vertically. It demonstrates that the most influencing factor in this case study is the weather data.

Regarding the influence of façade U-value, it is demonstrated that it has an influence in the displacement of the curves. However, considering the measured data and the configuration of the façade (solid brick one foot thick and 4 cm insolation thickness), the difference in the number of hours between the maximum peak temperature in the transient model 2 and 3 (with the measured U-value) and the measured temperature should be smaller.

Regarding the indoor temperature values, it is important to evaluate the simulated indoor temperature range due to the influence that it has on energy consumption and comfort level. Temperature simulated ranges are the followings: model 0 (0.78ºC), transient model 1 (0.93ºC), transient model 2 (1.54ºC) and transient model 3 (1ºC). These ranges would change widely when occupants were at home, due to the internal gains and the ventilation rates, consequently, it would be crucial to evaluate them. Additionally, the temperatures are over 29ºC during the day, representing an evident thermal discomfort. The presence of occupants will be affect indoor temperatures and should be evaluated as well.

CONCLUSIONS

In order to meet the energy efficiency goals of the retrofit measures in buildings, it is crucial to bridge the gap between measured and actual energy performance of buildings. To that end, it is necessary to measure and evaluate the thermal and energy performance of the building previous and after the retrofitting. However, the influencing parameters should be evaluate independently, before measuring energy consumption, in order to calibrate the models.

This paper presents a procedure to evaluate and analyse the interaction and combination between the influencing factors on the energy performance of buildings. In addition, the existence of a gap between predicted and actual thermal behaviour through a case study has been discussed.

The data collected from the monitoring campaign were: exterior temperature from a weather station, building envelope parameters (infiltration and U-value), and indoor evolution temperature. Four building energy model were created including the monitored input data one by one for the purpose of evaluate the influence of each of the parameters.

The results show that there is a gap between predicted and actual thermal performance and the influence of each of the parameters.

1. Current regulation and officially recognised database.

It is important to have as few uncertainties as possible, in order to create an accurate model. First, sources of uncertainties have to be identified, and if it the data is unavailable, standardised parameters should be obtained from a recognised database.

2. Monitored weather data

It has been demonstrates that monitored weather data has a crucial influence in the calibration model. In Fig.13 can be seen that transient model 2 (including monitored weather data) has the same tendency of the actual thermal performance (monitored indoor evolution temperature). It demonstrates the importance of requesting weather data from weather station closer to the case study to get relevant results. It should be noticed that the study was conducted in the city of Madrid; therefore, these conclusions are subject to this city.

3. Building envelope parameters

The results have demonstrated that the U-value has an influence in the displacement of the curves. However, considering the measured data and the configuration of the façade (solid brick one foot thick and 4 cm insolation thickness), the difference in the number of hours between the maximum peak temperature in the transient model 2 and 3 (with the measure U-value) and the measured temperature should be smaller. As a conclusion, thermal inertia and therefore U-value is sensible and relevant data that should be study in depth.

4. Procedure

The procedure is based on full-scale in situ measurements and simulations. The protocol of measurement and configuration of experiment were well documented and introduced. The results of the research, studying the influencing factors independently and together, show the importance of the followed procedure.

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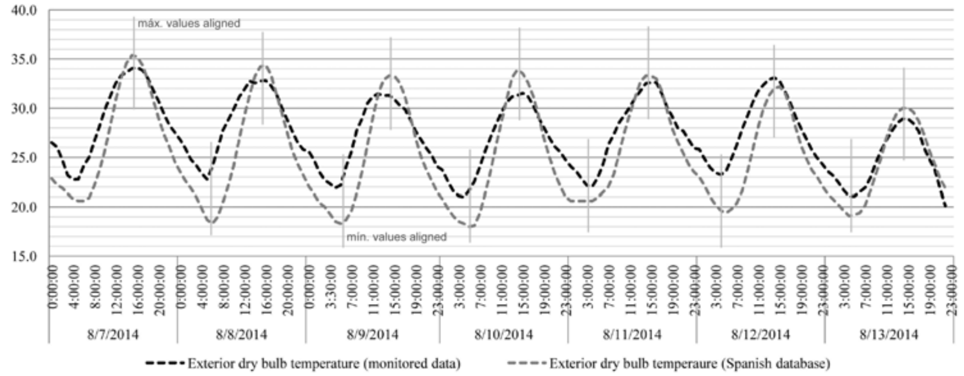


Figure 8 Weather data comparison. Spanish Meteorological National Institute (SMNI) data and monitored exterior dry bulb temperature evolution (ºC)

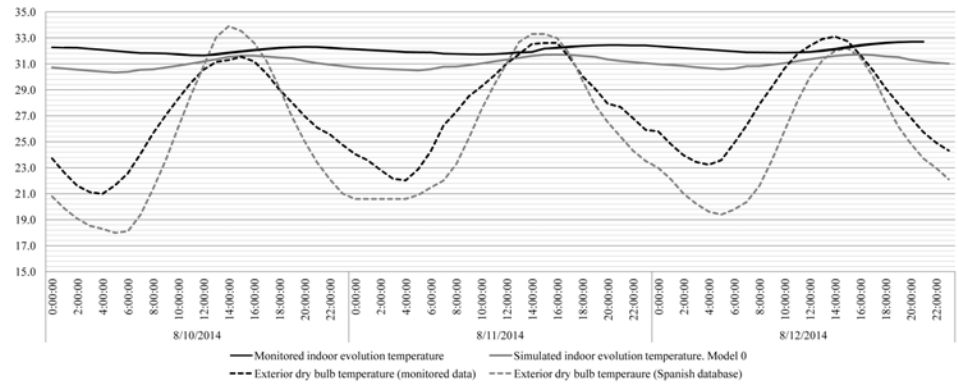


Figure 9 Simulated (Model 1) and measured indoor temperature evolution (ºC). SMNI and monitored exterior dry bulb temperature (ºC).

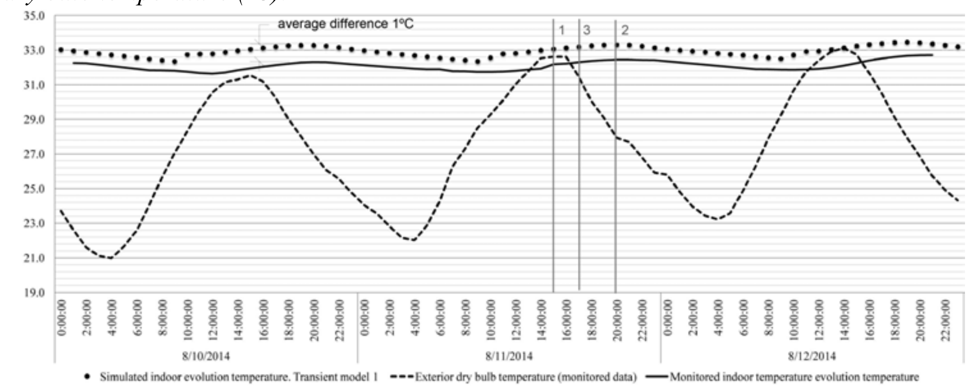


Figure 10 Measured indoor temperature evolution, simulated indoor temperature evolution (transient 2) with measured U and standardised weather data (ºC). SMNI exterior dry bulb temperature (ºC).

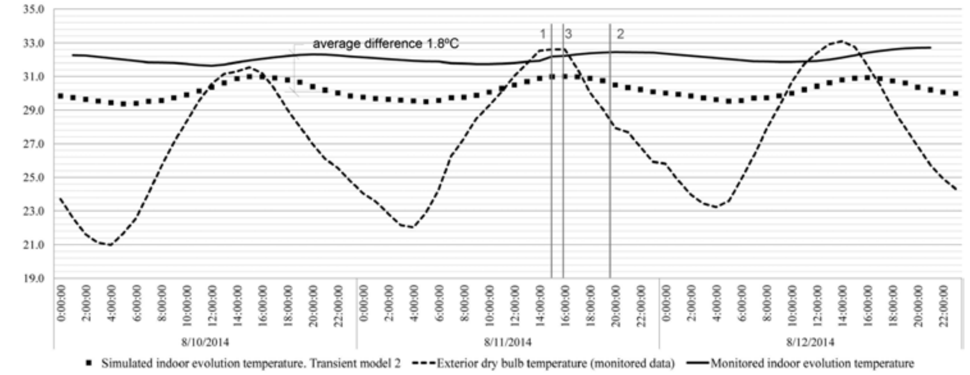


Figure 11 Measured indoor temperature evolution, simulated indoor temperature evolution (transient 3) *with measured U-value and measured weather data (ºC). SMNI exterior dry bulb temperature (ºC)*

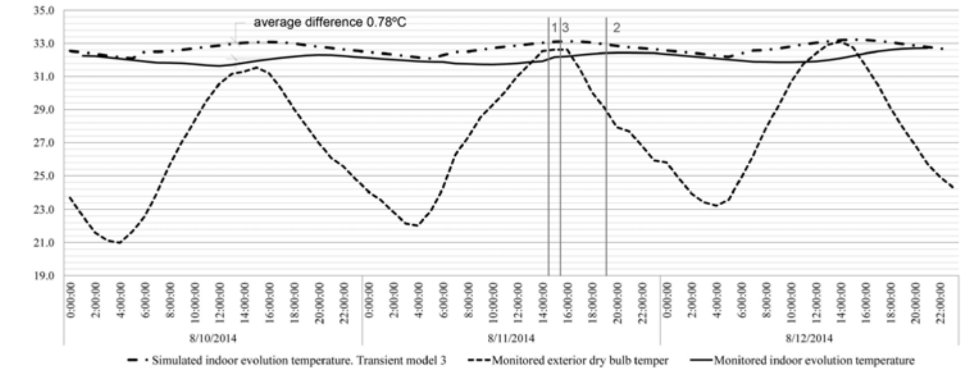
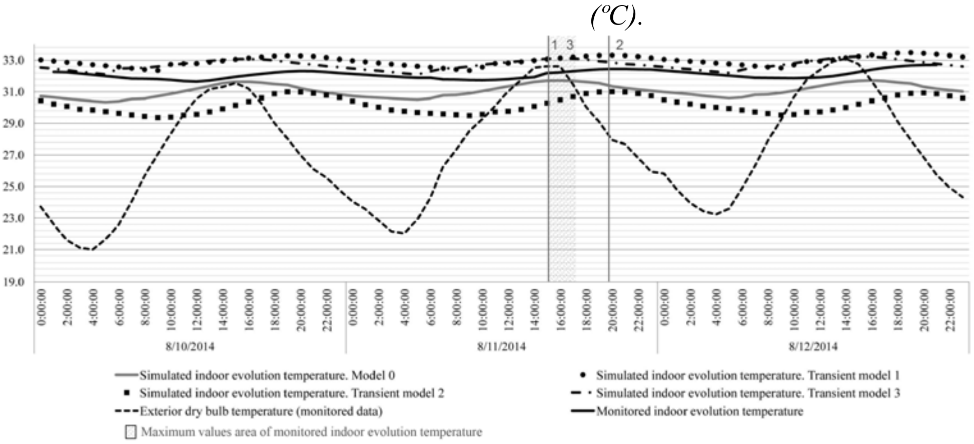


Figure 12. Measured (M- Bedroom 2.T) and simulated bedroom 2 temperature evolution in model 0 (S-Bedroom 2.T) transient model 1(S-Bedroom 2.T-clima), transient model 2(S-Bedroom 2.T-U) and transient model 3(S-Bedroom 2.T_climaU)(ºC). SMNI and monitored exterior dry bulb temperature (ºC).



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