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Implementing User Behaviour on Dynamic Building Simulations for Energy Consumption

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***Abstract* – User behaviour influences the energy consumption of domestic properties with different range of variations and this has an effect on the results of building simulations based on default or general values, as opposed to implementing user behaviour. The aim of this paper is to evaluate and quantify the effect of implementing user behaviour in building dynamic simulation to calculate heating and domestic how water energy consumption to reduce the performance gap. The results for space heating and domestic hot water from dynamic building simulations will be compare to actual energy bills for a general building simulation technique and a calibrated building simulation, incorporating user behaviour details. By using user behaviour details to create calibrated building simulations, a correlation to actual energy bills of over 90 % can be achieved for a dataset of 22 properties. This study has shown that by incorporating user behaviour into building simulations, a more accurate estimation of energy consumption can be achieved. More importantly, the methodology approach allows the user behaviour parameters to be collected by means of a questionnaire, providing an easy and low budget approach to incorporate user behaviour into dynamic building simulations to reduce the performance.**

***Keywords* – Building simulation; dynamic simulation; energy consumption; user behaviour**

1. INTRODUCTION

Retrofitting buildings to improve energy efficiency of the stock is a priority in Europe, if we take into account that buildings energy consumption in Europe account for 40 % of the EU energy consumption and globally, the energy consumption of buildings takes almost 30 % of the world final energy consumption [1]. The importance and relevance of the task increases in the light of the carbon reduction agreements for Europe with a target of 20 % reduction by 2020 [2] and the size of the building stock in Europe, with only 1 % of new buildings being constructed [3]. The European answer to this situation with the building is address with Directives and policies such as, the Energy Efficiency Directive [4], the European Strategic Energy Technology Plan [5] or the Research and Innovation Roadmap [6]. Achieving a low carbon society requires a joint approach to tackle the issues of refurbishing in Europe, if a sustainable reduction of the energy consumption of the building stock is to be reached [7]. With a wide range of buildings across Europe and indeed, in each country, the retrofitting process presents some challenges to achieve reduction of the energy consumption, as a range

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of different retrofitting approaches must be deployed to match the different conditions of each building [7]. In the case for retrofitting, one solution does not fit all [8].

The most important step to start a good approach to building retrofitting is to be able to evaluate the current energy consumption of the building in the current stage, prior to any retrofitting. This process could be based on several methods [9], [10]: by a monitoring process, applying support vector machines [11], applying vector regression method [12], using generative adversarial nets [13], based on a hybrid nature-inspired optimization algorithm [14] or using machine learning models [15]. Additionally, the evaluation of the current energy consumption of a building could be done by building simulations, which could be using a steady stage approach or a dynamic approach, where the building will be simulated on an hourly basis [16]–[18].

Although building simulation has come around a long way since their beginnings, the reality is that building simulation is based on a series of default values and assumptions to be able to create a computer model of the building to assess the energy consumption and other factors in the building. Taking into account these assumptions, it is understood that there will be certain variation between the building simulation result and the real performance of the building, as known in the construction industry as the performance gap [19]–[21]. The reasons for the performance gap in a particular building can be several but in general, the performance gap happens due to quality of the construction, accuracy of the default values in the building simulation, variation of the weather data or the influence of user, understood as user behaviour.

There are several studies that reflect the need to calibrate the building energy simulation models [22]–[24], where some authors propose to improve the simulation using interpolated weather data to determine on-site meteorological parameters at the building location [25].

The first two reasons for the performance gap happen during the design and construction phase, while the influence of user behaviour relates to the operational phase of the building. The operational phase of the building is far longer that the design and construction phase, meaning that it will have a greater impact in the reduction or increase of the building stock as a whole.

According to Crowther [26], the energy consumption calculated by building simulations could not be more accurate than ±15–20 %, as the simulation will be based on default values to model the user behaviour. Furthermore, the research showed that the influence of user behaviour has more influence in the performance gap than the weather. The performance gap can be as high as 2 or 3, as presented by Lutzenhiser [27] during his evaluation of energy consumption in similar domestic properties, considering user behaviour and using defaults values, which is ratified by other authors as well [28]. User behaviour can be assessed and integrated in building simulations and steady state calculations in different ways but some approaches will require more input for data collection than other. Jansson-Boyd et al. [29] presented how the user behaviour can be improved to achieve energy reduction and unless this is translated into the building simulations; there will be a wider performance gap. Further links between energy consumption and user behaviour are explore by Shippee [30].

The aim of this paper is to evaluate and quantify the effect of implementing user behaviour in building dynamic simulation to calculate heating and Domestic Hot Water (DHW) energy consumption to reduce the performance gap.

2. METHODOLOGY

Although other authors have used other approaches using building simulation software to implement linkages between energy use and user behaviour [31], in this research, 22 properties were simulated using *DesingBuilder* [32] and International Weather Files for Energy Calculations [33] for the city of Bilbao, Donostia-San Sebastian and Vitoria-Gasteiz, the final energy demand for space heating and domestic hot water for the properties was calculated. *DesignBuilder* is a dynamic energy simulation tool, a graphical user interface for the widely worldwide used *EnergyPlus* [34]. *DesignBuilder* generates detailed data regarding the energy performance of a building, on an hourly basis, by using weather data as well as temporal aspects such as solar radiation, thermal mass or user occupancy.

During this study three different scenarios will be analysed. The first scenario (1) considers the current Spanish regulation simulation inputs to obtain the energy consumption of each case study (see Table 3). The second scenario (2) adapts the simulations developed during the scenario 1 with some specific inputs provided by each inhabitant of the case studies: heating thermostats temperature, hours of space heating use in hours per day and number of showers per week. Finally, the third scenario (3) is based on the actual energy bills. Table 1 indicates the three different methodological approaches taking in this study and if the user behaviour has been taking into consideration.

TABLE 1. METHODOLOGICAL APPROACH FOR ENERGY CONSUMPTION

Scenario	Methodology	Parameters	User behaviour consideration
1	Dynamic Building Simulation	Current legislation	No
2		Specific for each inhabitant	Yes
3	Actual Energy Bill		Yes

3. CASE STUDY

3.1. Case Study Data and Hypothesis. Scenario 1

During the first step of this research, several data were collected by means of a questionnaire, which was filled up by all participant properties in the study (22 apartments). The questionnaire contained a series of questions related to general information and building specific information as follows:

General Information:

- Location (city);
- Housing Tenure (own user or rented);
- Number of people living in the property.

Building specific information:

1. Select the apartment typology (single family house or multifamily building block);
2. In case of multifamily building block, is the flat located in the last floor (Yes/No);
3. Building construction date (prior 1981, between 1981–2007, after 2007);
4. Treated floor area (less than 70 m^2; between 70 and 120 m^2; more than 120 m^2);
5. Facade area (more than 20 m^2 or less than 20 m^2);
6. Window area (more than 10 m^2 or less than 10 m^2);
7. Glazing (simple, double or double low emissivity);

8. Frame (wood, aluminium or PVC);
9. Main facade orientation (North, East, West or South).

The 22 properties assessed by this study have the following characteristics:

- 64 % of the properties were located in Bilbao, 14 % in Donostia-San Sebastian and 22 % in Vitoria-Gasteiz;
- Properties running on natural gas as space heating and domestic hot water fuel;
- 86 % of properties are owned by the users, with the remaining 14 % being rented;
- The number of people living in the properties varies between 1 to 7 occupants;
- 82 % of properties are multifamily buildings and 18 % single family houses;
- 82 % of properties were built during the period 1981 and 2007, 14 % prior to 1981 and 4 % after 2007;
- The floor area of properties varies from 74 m^2 to 160 m^2.

These results of the questionnaire provided the base of the building simulations. However, it must be noted that the participants in the study usually do not understand technical concepts such as the thermal transmittance (*U*-value) of the envelope elements (facade, roof, glazing or frame), which is a relevant parameter within a building thermal simulation process. In order to solve this lack of information, in accordance to regulations by the current Spanish Technical Building Code [35], default *U*-values and airtightness are defined for each relevant property of the simulation building (see Table 2).

TABLE 2. DEFAULT *U*-VALUES AND AIRTIGHTNESS [35]

Parameters	Variable selected by the inhabitant	Default value
Building Construction date	Prior 1981	U facade = 2.9 W/m^2k U roof = 2.5 W/m^2k Airtightness = 1.2 ach
	Between 1981–2007	U facade = 1.4 W/m^2k U roof = 0.7 W/m^2k Airtightness = 0.9 ach
	After 2007	U facade = 0.6 W/m^2k U roof = 0.4 W/m^2k Airtightness = 0.7 ach
Glazing	Simple	U = 5.7 W/m^2k
	Double	U = 2.7 W/m^2k
	Double low emissivity	U = 2.0 W/m^2k
Frame	Wood	U = 3.6 W/m^2k
	Aluminium	U = 4.7 W/m^2k
	PVC	U = 3.4 W/m^2k

Furthermore, in this study, parameters such as the occupancy rate, schedules, or DHW demand have been taken from Spanish building regulations [35] and are shown in Table 3.

TABLE 3. GENERAL DEFAULT SIMULATION PARAMETER

Parameter	Unit	Value
Occupancy	Living area, people/m²	0.03
	Schedule	Until 07:00 (100 %), Until 15:00 (25 %), until 23:00 (50 %), until 24:00 (100 %)
Heating system	Setpoint, ºC	20
	Period	From 30 September to 31 May
	Schedule	Until 07:00 (Off), until 11:00 (On), until 18:00 (Off), until 23:00 (On), until 24:00 (Off),
Domestic Hot Water	Quantity, litres/(person·day)	28

Finally, in order to standardize the dimensions of the simulation buildings, the authors of this study defined a determinate surface value (see Table 4) to the questions related to the floor, facade and window area.

TABLE 4. GENERAL DEFAULT SIMULATION PARAMETER

Parameters	Variable selected by the inhabitant	Default value
Treated Floor Area	Less than 70 m^2	60 m^2
	Between 70 and 120 m^2	95 m^2
	More than 120 m^2	150 m^2
Facade Area	More than 20 m^2	25 m^2
	Less than 20 m^2	15 m^2
Window Area	More than 10 m^2	13 m^2
	Less than 10 m^2	7 m^2

A combination of the answers for the nine questions related to the building specific information and considering the values defined by the Tables 2–4, allowed the researchers to generate 1728 different building simulation scenarios. Based on the results of these simulations, this study obtained the gas consumption for space heating and DWH for any combination of questionnaires answers provided by the participants, which will be the results for the Scenario 1.

3.2. Calibrating the Building Simulation. Scenario 2

In order to calibrate the simulation buildings developed during the scenario 1, this study proposed three new simple questions to each inhabitant:

1. Usual value of the heating thermostats temperature, ºC;
2. Average of number of hours of space heating use in hours per day (in winter);
3. Amount of number of showers per week.

The answer of these three questions allows adapting the default values defined by the Table 3, which were based on the current Spanish regulation. As an example, a study of heating patterns of residential buildings in the United Kingdom demonstrates the importance of correctly implementing the indoor temperature. It showed a deviation between monitored indoor temperatures in living rooms and the assumptions for simulation models [36].

Fig. 1 shows the results from the questionnaire for three parameters considered during the calibration of the building simulation process.

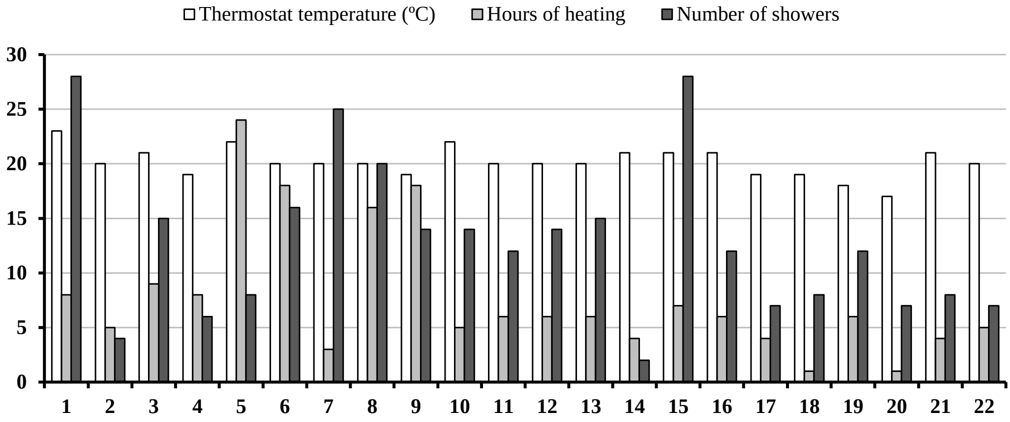

Fig. 1. Questionnaire responses for the three main user behaviour parameters influencing energy consumption.

Regarding the heating thermostats temperature, the values vary between 17 ºC and 23 ºC. However, highlight that the average value 20.13 ºC is really similar to the value defined the current regulation 20 ºC. The values about the number of hours of space heating use in hours per day vary notably, obtaining values between 1 and 24 hours. The average number of heating hours is 7.4 hours, which is lower than the value defined by the regulation (9 hours). Finally, the results about the number of showers per week show that due to different reasons such as the possibility to have a shower in the sport centre or at the school, the amount could vary between 2 and 28. This variation may influence directly into the energy consumption assessment.

3.3. Energy Bills. Scenario 3

The final part of the questionnaire asks the participant to provide gas energy bills to collect the actual energy use for space heating and DHW. As a quality measure, the participants were requested to provide at least a one-year consumption data and for bills to be monthly or bimonthly to allow auditing for errors. All properties had an individual boiler providing space heating and DHW.

4. RESULTS

During this section the space heating and DHW energy consumption from building simulations Scenario 1 and Scenario 2 were plotted and analysed against the actual energy consumption from energy bills in Scenario 3. Furthermore, the data for each comparison was fitted with a linear regression and the coefficient of determination, R^2, calculated to understand how close the building simulation energy consumption was representing the actual energy consumption from energy bills. Table 5 presents the energy consumption results for the three scenarios consider in this study (see Table 1).

TABLE 5. ENERGY CONSUMPTION (KWH/M^2·A) FOR GENERAL SIMULATION (SCENARIO 1), CALIBRATED SIMULATION (SCENARIO 2) AND ACTUAL ENERGY BILLS (SCENARIO 3)

Case study	General Simulation (Scenario 1)	Calibrated simulation (Scenario 2)	Actual Bills (Scenario 3)
1	79.0	90.1	94.1
2	78.9	38.8	35.9
3	52.6	73.6	75.3
4	59.2	41.2	38.8
5	41.9	29.7	26.6
6	60.4	46.1	40.0
7	60.3	18.5	15.8
8	92.4	88.5	114.6
9	59.2	70.2	69.4
10	64.6	74.2	86.6
11	60.5	59.2	62.2
12	41.0	79.1	89.8
13	63.2	48.8	48.7
14	57.6	39.9	43.2
15	63.0	63.4	59.4
16	72.5	74.5	76.2
17	113.0	36.2	28.7
18	63.3	12.9	10.6
19	95.3	77.3	106.6
20	87.9	7.0	4.8
21	60.5	47.8	72.0
22	114.3	80.4	80.0

The results of plotting the energy consumption from the general simulation (scenario 1) versus the energy consumption from energy bills are presented in Fig. 2. Furthermore, a linear regression is plotted. The linear regression formula and coefficient of determination for the regression general simulation versus actual energy bills are indicated in Eq. (1):

$$y = 0.0977x + 64.344 \ , \text{ with } R^2 = 0.02342 . \tag{1}$$

In a similar way and for easiness of comparison, the results of energy consumption from the calibrated simulation (Scenario 2), considering the three parameters for user behaviour, versus the energy consumption from energy bills are as well shown in Fig. 2. The linear regression formula and coefficient of determination for the regression calibrated simulation versus actual energy bills are indicated in Eq. (2):

$$y = 0.7568x + 10.407 \ , \text{ with } R^2 = 0.91525 . \tag{2}$$

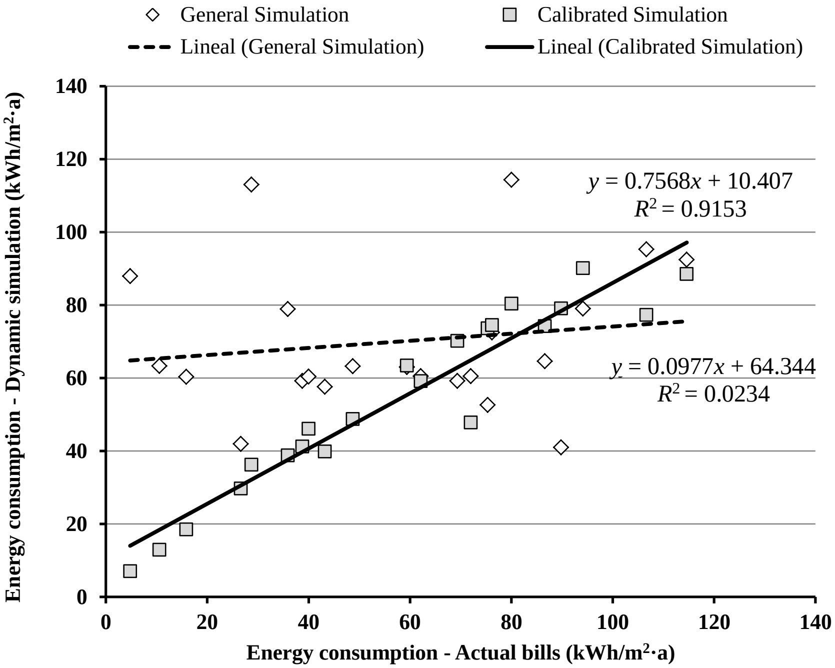

Fig. 2. Energy consumption for general simulation versus actual energy bills and calibrated simulation versus actual energy with linear regressions.

5. DISCUSSION

The aim of this paper was to understand the effect of implementing user behaviour in building dynamic simulation to calculate energy consumption and quantify their influence. As presented through the paper in the methodology and results section, the approach to understand how accurate was the dynamic building simulation calculating the energy consumption for space heating and DHW was assess by correlating the energy consumption results to the energy consumption from actual bills. The next two subsections focused on each alternative for dynamic building simulation, general and calibrated, to evaluate their results separate in connexion to the actual energy bills.

5.1. General Simulation versus Actual Bill Energy Consumption

As presented in Table 5 and Fig. 2, the results for energy consumption for space heating and DHW obtained by the general dynamic building simulation are very much far out form the actual energy consumption obtained by the energy bills. This is very much in accordance to the literature [26]–[29] and expected from treating the building simulations as general parameters taking from Table 3, without considering the user behaviour for the building simulation. More specifically, parameters in relation to the heating set points and use of space heating, as well as the estimation of DHW requirements. Eq. (1) and Fig. 2 provides an inside regarding how scatter the correlation between general simulation and actual bills is, with a coefficient of determination R^2 = 0.02342, meaning that less than 3 % of the actual energy consumption of the properties can be explained by the general building simulation.

Furthermore, analysing the percentage different between energy consumption from general simulation and the actual energy consumption from energy bills, the average disparity of results is around 135 % overestimation of the energy consumption according to the general simulation. Even more important is that the standard deviation, which provides an understanding on the spread of the results, is about 380, confirming the issues presented in the literature regarding the performance gap between actual energy use and building simulations based on general parameters.

5.2. Calibrated Simulation versus Actual Bill Energy Consumption

Following the results from the questionnaire, the three parameters shown in Fig. 1 were used to set the heating set point, hours of space heating and provide a better estimation of DHW use for each property to generate the energy consumption for the calibrated building simulation, considering the user behaviour.

As shown in Table 5 and Fig. 2, the correlation between the energy consumption from the calibrated building simulation and the actual energy bills has improved massively, providing an argument that by considering only three parameters to adapt the building simulations, a much better estimation can be assure from the dynamic building simulation. The coefficient of determination as improve to an R^2 value of 0.91525, meaning that over 90 % of the time the calibrated building simulation can estimate the actual energy consumption for the property.

Looking into the disparities between calibrated simulation and actual energy bills, the average disparity of results is just over 1 % and the standard deviation is around 18, this provides a good foundation to reduce the performance gap by incorporating user behaviour details into building simulations for the calculation of the energy consumption of space heating and DHW.

It can be argued that a more accurate estimation of the user behaviour can be achieve by physical monitoring of heating set points, heating use, and so on, but this is always accompanied by intrusions into the normal life of the participants and a cost attached to it. This study has demonstrated that by using just three parameters captured by a questionnaire approach, a more robust energy consumption estimation can be achieved with the use of calibrated building simulations

6. CONCLUSION

This study has shown that by incorporating user behaviour into building simulations, a more accurate estimation of energy consumption can be achieved. More importantly, the methodology approach allows the user behaviour parameters to be collected by means of a questionnaire, providing an easy and low budget approach to incorporate user behaviour into dynamic building simulations to reduce the performance gap.

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