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Insights into the effects of occupant behaviour lifestyles and building automation on building energy use

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Abstract

In order to optimize building energy consumption, Member States will have to establish minimum efficiency requirements for systems, and promote the introduction of active control system in new constructions or major renovations. Energy saving, plant efficiency and environmental sustainability are also factors delineating smart buildings. Interestingly, occupant behaviour is known to be one of the key sources of uncertainty in the prediction of building energy use. The success of automation strategies is recognized to be dependent on how the occupants interact with the building. The present research describes the effect of different building occupants' lifestyles and building automation on a high performing building.

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Keywords: Occupant behaviour; smart buildings; subjective questionnaire; dynamic energy simulation; high performing building

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1. Introduction

"Home automation", "Building automation" and "Intelligent building" are terms that are getting more and more common in everyday use representing an innovative sector, which continues to grow thanks to the fact that an increasing number of people begin to become familiar with automated devices. This interest is also driven by the potential (energy and cost) savings that these devices are able to achieve thanks to an optimization of the building operation, always oriented at obtaining at the same time optimal comfort conditions. Automation, control and supervision systems can have a significant impact on the energy performance of buildings and on the comfort of their occupants, in particular, they can reduce the consumption of buildings from 10% up to 50% [1]. Therefore, the

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European Committee for Standardization issued the EN 15232 Standard: Energy Performance of Buildings - Impact of Building Automation, Controls and Building Management for use in conjunction with their Energy Performance of Buildings Directive (EPBD) in order to encourage the implementation of these systems. These documents define conventions and methods for estimating the impact of building automation and control system (BACS) on the building energy performance. In the context of nearly-zero energy buildings (nZEBs), the nearly zero or very low amount of energy required should be covered significantly by energy from renewable sources, including renewable energy produced on-site or nearby. In this framework, the building automation could help to reach the nZE level, or rather decrease the building energy demand by balancing energy losses, internal gains and energy needs, with particular regard to the optimization of the balance between heating and cooling needs. Effective control of the heating, ventilation and air conditioning systems in a building is essential to provide a productive, healthy and safe working and living environment for the occupants. Along with high performing building design and efficient HVAC systems, the building control systems play a vital role in the prevention of energy waste and the reduction of the environmental impact of the building. Controls and building automation used in buildings range from simple thermostatic radiator valves, automatic balancing valves, automatic air damper, thermostats and schedulers to building automation and control systems (BACS), building management systems (BMS), also known as building automation system (BAS), energy management systems (EMS) and building energy management systems (BEMS). In the more complex forms, BMS and their related subsystems may have many thousands of data points controlling non-residential buildings and dispersed estates. Residential controls traditionally have a single room thermostat controlling the boiler and pump on/off, a scheduler to set the stop and start times for heating and domestic hot water systems plus thermostatic radiator valves for room temperature control. More sophisticated controls are available for residential and small non-residential buildings, including weather compensation, wireless zone-control systems, and home automation systems that can include curtain activation and audio-video systems, fire alarm and security system. The aim of this research is to demonstrate how the balance between the use of automated systems in a residential environment and an aware occupant interaction with the building and installed systems can lead to significant energy savings. The energy behaviour of a real residential nZEB located in the Northern part of Italy was simulated studying the variations on the obtained energy performances by changing the assumptions related to the users' behaviour. Two user profiles were used: a "standard consumer" (SC) as defined in the EU standards and identified for the standard lifestyle pattern and a "low consumer" (LC) identified as a "sustainable" lifestyle, corresponding respectively to a major interaction and a minor interaction with the building system. Preferences in terms of window opening were defined by analysing an international questionnaires database.

1.1. Technical building management and BACS efficiency classes

EN 15232 standard [2] was created to assess the impact of the building automation on the energy performance of buildings, both in the operational stage and design or retrofit stage. This standard allows estimating the energy savings achieved by automating control functions such as: heating and cooling, ventilation and air conditioning, and blind control. Building automation and controls can have Technical Building Management (TBM) functions, as described in EN 15232, as part of Building Management (BM) that provide information about operation, maintenance, services and management of buildings, especially for energy management – measurement, recording trends, alarming capabilities and diagnosis of energy use. The energy management provides requirements for documentation, controlling, monitoring, and optimisation and supports continuous corrective actions to improve the energy performance of buildings. EN 15232 defines four different building automation and controls classes (A, B, C, D) of functions both for non-residential and residential buildings:

- Class D corresponds to non-energy efficient BACS.– BACS is in class D if the minimum functions of class C are not implemented;
- Class C corresponds to standard BACS – minimum functions shall be implemented (e.g. emission control, control of distribution network, interlock between heating and cooling control of emission and/or distribution);
- Class B corresponds to advanced BACS with some specific functions and TBM;
- Class A corresponds to high-energy performance BACS and TBM – Technical building management function shall be implemented in addition to class B. Room controllers shall be able to demand control building services (e.g. adaptive set point based on sensing of occupancy, air quality, etc.) including additional integrated functions

for multi-discipline interrelationships among the various building services (e.g. HVAC, lighting, solar shading, appliances).

1.2. Interaction between building's occupants and a smart building

During the design phase of the building, it is crucial to be aware of the way in which the occupant interacts with his/her own home since this has major implications on the indoor environmental quality (IEQ) and the building energy performance itself. This means that the energy performance of the same building may change significantly when the user itself changes inside. Accordingly, occupant behaviour is a key factor for the huge gaps between real and predicted energy performance of buildings.

Occupant behaviour can be divided into three different categories: one related to only the presence of the occupant, another related to the manual interaction with the appliances, and the final one related to the interaction between the occupant and buildings with automated systems. About the first category, the user manually interacts with the building to establish its comfort conditions and adapting itself to the environment ("self-adaptation") or adapting the surrounding environment to its preferences ("adaptation to the environment"). Regarding the second category, the user interacts with automated buildings, which means that the occupant's knowledge of the smart technologies becomes crucial in order to fully obtain the benefits of automation, in terms of both comfort and energy efficiency. The optimal situation is created when users and smart technology of a building come together to guarantee some factors that contribute to both energy saving and comfort: user satisfaction, avoiding discomfort conditions, rapid response of the building to the human needs, assisting management, and energy efficiency of a building. If the operation of the building automation system is based only on energy saving targets, probably the occupant does not feel a comfortable condition inside the building. For this reason, it is important to balance energy efficiency and occupant's needs in perceived comfort. There are many aspects that have an impact on the occupants perceived comfort: environmental factors e.g. climate, physiological factors e.g. sex and age, or social factors e.g. work place.

However, sociologists and psychologists affirm that, another important factor that influences occupants' satisfaction is the perception of control. Veitch [3], in her studies about occupants' satisfaction and control, identified the "perceived control" as an aspect that has a very important impact on satisfaction, mostly in the working environment. This means that these complex automation systems could decrease the satisfaction of the users for an inadequate perceived sense of control; this aspect was confirmed by most studies in this field. The Kroon Hall (Fig. 1), LEED-Platinum building of the Yale School of Forestry and Environmental Studies, could be an example showing an optimal interaction between occupants and a smart building.

This building embodies the characteristics of a green building and has an innovative system of red and green lights to indicate to the occupants when it is necessary to open and close windows. This interactives system allows users to raise their awareness and consequently improves both the building operations and the final energy performance [4].

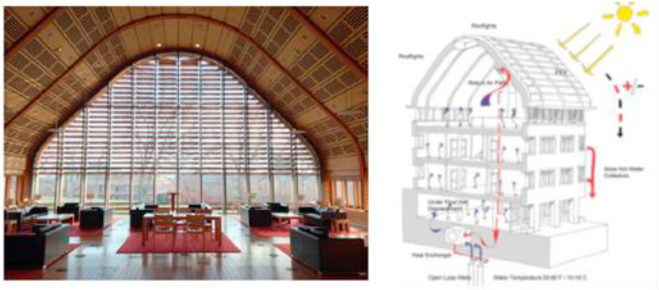

Fig. 1. Kroon Hall, on the left: internal view, on the right: energy scheme.

2. Methodology

The main goal of this study is to assess the impact of manual occupants' interaction together with building automation system on the energy performance of a high performing building. Literature showed how the performance of a building and indoor environmental quality change by varying the occupant behaviour. It is important, therefore, to assess the interaction between occupant and automated system to predict and design a building, which takes into account both energy efficiency (and related costs) and occupants comfort perception. Two important approaches were applied in this study: building dynamic energy simulations (using the dynamic simulation software IDA ICE v. 4.7) to evaluate the effect of occupant behaviour on energy use and analyses of questionnaire data to understand users' needs and behaviour within a residential environment (using the statistical software R). In detail:

- Two occupant behaviour lifestyles (standard lifestyle consumer "SC" and sustainable lifestyle consumer "LC") were simulated and evaluated. Six types of users' interactions and the building envelope/systems (1. regulation of heating and cooling set-points 2. energy use for equipment, 3. Energy use for lighting, 4. energy use for DHW (Domestic Hot Water) production, 5. ventilation rates, 6. regulation of window blinds) were considered in the assessment and BAC efficiency factors were calculated (BACS efficiency factors are calculated as defined in the standard EN 15232);
- BAC factors were calculated on the "SC" and "LC" consumer typologies, associating "SC" scenario to the reference class (C) and a "LC" scenario to the class B;
- A logistic regression on probability of window opening related to indoor temperature was performed, resulting on occupant-driven window opening schedule proportional to indoor temperature in the building energy simulation software.

2.1. Case study

The case study (Figure 2) represents an Italian significant design experience of a residential 147m^2 nZEB [5], in which the architectural quality in the refurbishment of a traditional rural building is combined with high-performing energy solutions [6]. The design is based on bioclimatic principles and the strategies adopted consist of a strongly insulated building envelope ($U_{wall,ceiling}$=0.15 W/m^{2}K; U_{slab}=0.19 W/m^{2}K) characterized by an exterior layer made of high-density rock-wool panels (λ=0.037 W/mK; ρ=150 kg/m^3). Windows are composed by aluminium frame with thermal break with low-e triple-pane glass with argon (U_{window}=0.96 W/m^{2}K). With regard to the building primary system, a controlled mechanical ventilation (CMV) system with heat recovery and dehumidifier is combined with radiant floors for space heating and cooling in all rooms. Space heating and cooling is provided by a water-to-water heat pump (coefficient of performance=4.4; energy efficiency ratio=4.2), which supplies also DHW production. The case study represents a model of an all-electric building; according to nZEB definitions, a distinctive element of the building is thus, the possibility to increase the energy independence from fossil energy sources. Electricity needs of the building for space heating and cooling, ventilation, lighting, equipment, and DHW production are covered by a 7 kW peak grid-connected photovoltaic (PV) system installed on the roof.

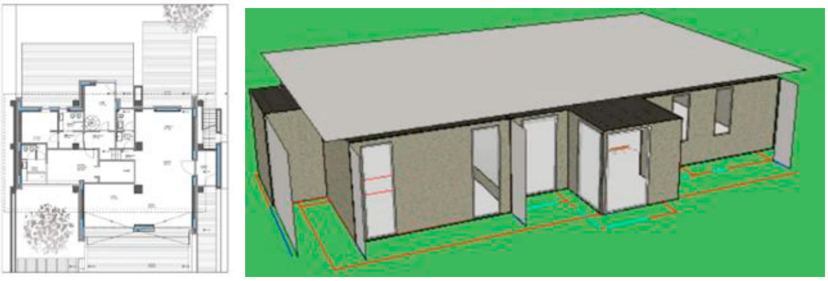

Fig. 2. Case study floor plan and the simulation model.

2.2. Standard and sustainable lifestyle

In this study, two categories of energy-related occupant behaviour lifestyles were defined and analysed to assess a primary impact on energy performances in high performing residential buildings. These two types of occupant behaviour lifestyles were assumed to influence the building energy performance through several key variables as defined by Barthelmes et al. [7]. The heating/cooling set-points and the ventilation rates refer to comfort categories described in EN 15251 [8]; standard lifestyle ("SC" consumer) refers to category II and the sustainable lifestyle ("LC" consumer) variables refers to categories III. In both configurations, the heating system was assumed to be active from October 15 to April 15, according to Italian regulations for Climatic Zone E (Turin). The cooling system was set to operate from April 30th to September 30th. For the occupancy level, the number of people per zone floor area were fixed to 0.04 person/m^2, as defined by Italian Standard UNI 10339 [9], which leads to 5.88 occupants in the building. Lighting and electric equipment power densities were respectively defined equal to 3.88 and 5.89 W/m^2, according to ASHRAE Standard 90 [10]. The standard lifestyle schedules for lighting and equipment refer to those of residential reference buildings available on the Department of Energy (DOE) dataset [11]. In order to assess the sustainable lifestyle scenarios (Figure 2), the operational levels of these standard schedules were reduced by 10% [12]. Additionally, the sustainable lifestyle related to lighting use was optimized through daylight control (continuous/off dimming) means to the definition of illuminance set-points throughout the building; in this method daylighting illuminance levels are calculated by the software and then used to determine how much the electric lighting can be reduced. In particular, an illuminance level of 500 lux was guaranteed for the reference point in the studio and 300 lux for the other reference points in all the other rooms of the building. The standard lifestyle was assumed to close the blinds in summer only if the incident solar radiation was major than 300 W/m^2 [13], while the sustainable lifestyle blinds control was optimized through daylight control and activated if the glare index resulted higher than 22. The use of DHW was set to 60 l/pers day for the standard consumer and to 40 l/pers day respectively for the low consumption profiles.

2.3. Questionnaire database

An international database of subjective questionnaires [14] was analysed to depict patterns of occupant behaviour related to user and building characteristics. Answers were analysed by logistic regression models, using the statistical software "R".

Window opening and closing reasons, heating switching on/off and different human interaction preferences and attitudes towards or against home and related to a state of cold/ hot temperatures were deduced by means of logistic regression with interaction between variables accordingly to the following equation (1):

$$\mathrm{Log}\frac{p}{1-p} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + c_{12} x_1 x_2 + c_{13} x_1 x_3 + \cdots \quad (1)$$

where: p is the probability of a switching on/off event; β_0 is the intercept; β_n are coefficients; x_n are explanatory variables such as illuminance, room temperature; c_{nm} are interactions coefficients.

In statistics, logistic regression is a regression model characterized by dependent variables (DV). These could be "binary dependent variables" where there are only two variables or "multinomial logistic regression" if there are more than two categories [15]. The logistic function for first-order polynomial models with a single independent variables is a common "S" shape (sigmoid curve) defined in equation 1.

Dependent variables were:

- State of the window
- Window opening reasons
- State of the heating
- Occupant's preferences to react to cold and hot temperatures

Independent variables were:

- Dwelling ownership information

- Floor area of the dwelling
- Perceived illuminance level (PIL) by the respondent at the time of the response
- Perceived air quality (PAQ) at the time of the response
- Sex of the respondent
- Age of the respondent
- Average age of inhabitants
- Location of the respondent
- Survey place

It was decided to take into account the analysis of window opening reasons for simulation purposes. Then, a semi-probabilistic approach to simulation was adopted. A probabilistic approach is presented in literature [16] in simulations to investigate how user patterns probabilistically defined, influence energy consumptions of a high performing building, improving accuracy of calculated energy performance in buildings simulation tools. The goal is to determine how occupant behavioural patterns describing user interaction with the windows opening affect the building energy performance prediction. In this study, a combined effect of building automation and user preferences of control were investigated. For this reason, it was decided to study the "T50" parameter, calculated as the inversion of the logistic regression formula (Equation 1) and expressed in the formula below (Equation 2).

$$\mathrm{T}_{50} = \frac{a + b_1x_1 + b_2x_2 + \; b_nx_n + log\left(\frac{1}{F_{(x)}} - 1\right)}{b_1} \tag{2}$$

The "T_{50}" represents the temperature at which the probability of opening a windows is 0.5. The same analysis could have been carried out also with other data obtained from the questionnaires, e.g. the state of the heating (on/off) based on the temperature above which people prefer to turn on or off the heating.

3. Results

The energy simulation was divided into three steps. The first step was the definition of the energy performance for the standard and the low consumer scenarios. The second step was to implement these performances adding a level of automation according to EN 15232. Finally, the third and final step was the implementation of user preferences depicted by the regression analysis with regard to the opening and closing the windows adopting a semi-probabilistic approach. The aim of this study was to understand how, through the application of BAC and a semi-probabilistic behaviour pattern, it was possible to have different energy performance levels compared to the estimated standard. In the following, the results obtained from the three steps of the energy simulation are presented.

3.1. Energy needs and the delivered energy for the Standard lifestyle and the Sustainable lifestyle

The results of this first analysis are shown in Table 1 and Figure 3. From this first analysis, it is possible to observe that with a sustainable lifestyle ("LC" consumer) the building energy needs and consumptions are reduced by 43% for the heating and by 14,7% for the equipment (see Fig.3). The results reveal a significant difference in terms of energy performance of the building with respect to the reference paper [7]. These differences may be due to several factors, such as (i) use of different software for energy simulation (IDA ICE and Energy Plus) and (ii) different thermal zone models.

Table 1. Delivered energy for SC and LC lifestyles.

Delivered energy (kWh/m^2)	Standard Lifestyle ("SC")	Sustainable lifestyle ("LC")
Heating	14	8
Cooling	10	6
Lighting	14	10

Ventilation	28	21.4
Equipment	34	29

Fig. 3. Energy performances of SC and LC.

3.2. Energy evaluation of SC and LC profiles considering BAC

The second step of this simulation analysis was to calculate the impact of BAC/TBM on the total building energy performance. The standard lifestyle (“SC” consumer) was referred to class C of BAC (Standard); while the sustainable lifestyle (“LC” consumer) was assumed to match the class B (Advanced). Based on this class, the annual energy use of the building energy system was calculated using the BAC efficiency factors. The energy calculations were then performed only for the “LC” scenario, considering an efficiency factor of 0.88 for heating and cooling needs and 0.93 for ventilation and lighting. Table 2 shows the results of the calculations implementing the two scenarios with building automation and control system (BAC). From this second analysis, it is clear that, implementing the case study with a Class B of BAC, it is possible to obtain a reduction of the building energy needs and consumption with respect to the previous analysis. For the “SC” scenario, there was no reduction of energy needs because it was implemented with a Class C of BAC, (BAC efficiency factors equal to 1).

Table 2. Implementation of SC and LC to BAC.

Delivered energy (kWh/m^2)	Standard Lifestyle (“SC”)	Sustainable lifestyle (“LC”)
Heating	14	7.15
Cooling	10	5.6
Lighting	14	9.3
Ventilation	28	20

3.3. Energy evaluation of LC profile implementing user preferences model

The third and last step of this work is the implementation of the IDA ICE model considering the “T50” parameter. It is a semi-probabilistic model that allows to know at which temperature building occupants prefer to open/close the windows. The aim of this work is to combine the real building, in this case a real nZEB, with real data of occupant behaviour taken from the questionnaire analysis: the state of the window at the time of the compilation of the questionnaire. This temperature was assessed in R software and corresponds to 21°C, and considered as a user preference for opening/closing the windows. According to this results, if outdoor temperature was higher than 21°C windows were opened. Respectively, if the outdoor temperature decreased below than 21 °C, the open windows were closed. Table 3 shows the values of the in terms of energy performances of the LC (low consumer) scenario associated with class B of BAC and implemented with a semi-probabilistic model.

Table 3. Implementation of LC – Class B with user preference model.

Delivered energy (kWh/m^2)	Sustainable lifestyle (“LC”), Class B with user preference
Heating	7.15
Cooling	5
Lighting	9.3
Ventilation	12

Fig. 4. Energy performances of SC and LC with BAC and window opening preferences.

The implementation of the “T50” parameter in IDA ICE allowed comparing the “LC” scenario associated with the user preferences and the “SC” scenarios (Figure 4). It emerges that the energy performance changed significantly when considering the semi-probabilistic model. Figure 4 shows the comparison between the standard lifestyle (“SC” Class C), the sustainable lifestyle consumer associated to BAC (“LC” Class B) and a sustainable lifestyle consumer implemented with a user preference related to window openings (“LC” Class B+OB). In this last case, the total energy needs decreased by 49% for heating and by 50% for cooling; the energy for lighting decreased by 33.6% and the ventilation by 57%. This is because the semi-probabilistic model took into account the automation of the windows (considering user preferences) that affect the cooling and ventilation consumptions. The two cases analysed in the paper are actually combining two aspects: different behaviour and different level of automation so that it is difficult to distinguish which of these aspects influences the results more. Further analysis are then required on elaborating the different impacts on energy savings.

4. Conclusions

Energy and indoor environmental performance of buildings are influenced by numerous factors, such as: outdoor/indoor climate, building characteristics, and occupants’ behaviour. For this reason, the main purpose of this research was to assess how and to what extent the implementation of automated building systems may affect the energy performance within the home. Besides the use of the BAC, also another factor is decisive for the energy performance of a building: the occupants’ interaction with the building itself. For this reason, this study took into account the analysis of two different user lifestyle on a real case study building, an nZEB. From the energy simulations, it emerged that a conscious user, less interacting with the building, allowed reaching better energy performance. If this type of user is matched with an automated system, the energy savings are considerable. Only by switching from a standard lifestyle ("SC") to a sustainable lifestyle ("LC") scenario, it is possible to achieve energy savings for heating, cooling, lighting, ventilation and equipment. By implementing the same building with different levels of automation, even higher energy performance may be achieved. The sustainable lifestyle consumer ("LC") defined for Class B of automation systems permits to obtain significant energy savings with respect to Class C. Implementing the user preferences related to window opening reasons (as resulted from the questionnaires analysis) lower level of energy use could be revealed. To conclude, energy savings in homes can be obtained either by considering both a conscious behaviour of the user that lives and controls those spaces, and the building automation systems. Combining these two aspects, automation/control and a user acting in a conscious way, permits to achieve important energy savings, to reduce energy demand and consequently to guarantee high building performance.

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References

[1] Staddon S, Cycil C, Goulden M, Leygue C, Spence A. Intervening to change behaviour and save energy in the workplace: A systematic review of available evidence. ERSS 2016;17:30-51.

[2] European Committee for Standardization (CEN). 2007. EN 15232 Standard. Energy performance of buildings - Impact of Building Automation, Controls and Building Management. Bruxelles, Belgium: European Committee for Standardization.

[3] Veitch JA, Gifford R. Assessing beliefs about lighting effects on health, performance, mood and social behaviour. Environ Behav 1996:446-70.

[4] Center for the Built Environment. "Behavior and Buildings". Centreline newsletter. Berkeley, 2010.

[5] Corgnati SP, Guala C, Luciano M. The challenge of designing and building nZEBs: a single-family house in Italy. REHVA J 2014;51(6):38–42.

[6] Barthelmes VM, Becchio C, Bottero MC, Corgnati SP. The Influence of energy targets and economic concerns in design strategies for a residential nearly-zero energy building. Buildings 2014;4(4):937–62.

[7] Barthelmes VM, Becchio C, Corgnati SP. Occupant behavior lifestyles in a residential nearly zero energy building: Effect on energy use and thermal comfort. STBE 2016;22:960-75.

[8] European Committee for Standardization (CEN). EN 15251 Standard. Criteria for the Indoor Environment Including Thermal, Indoor Air Quality, Light and Noise. Brussels: European Committee for Standardization; 2008.

[9] Italian National Unification Association (UNI). UNI 10339, Impianti aeraulici a fini di benessere. Generalità, Classificazione e Requisiti. Regole per la Richiesta d'Offerta, l'Offerta, l'Ordine e la Fornitura [Aeraulic systems for the purpose of wellbeing. Overview, classification and requirements. Rules for the inquiry, the offer, the order and delivery]. Milan, Italy: Italian National Unification Association; 1995.

[10] ASHRAE. ASHRAE Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings I-P Edition. Atlanta: ASHRAE; 2013.

[11] U.S. Department of Energy (DOE). http://energy.gov/eere/buildings/residential-buildings-integration

[12] Brandemuehl MJ and Field KM. Effects of variations of occupant behavior on residential building net zero energy performance. Proceedings of the 12th Conference of IBPSA, Sydney, Australia, November 14–16; 2011.

[13] Italian National Unification Association (UNI). UNI TS 11300-1, Determinazione del Fabbisogno di EnergiaTermica dell'Edificio per la Climatizzazione Estiva ed Invernale [Determination of the building thermal energy demand for space cooling and heating] (In Italian), Milan, Italy; 2014.

[14] Andersen RV, Toftum J, Andersen KK, Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings. Energ Buildings 2009;41:11–16.

[15] Schweiker M, Shukuya M. Comparison of theoretical and statistical models of air-conditioning-usage behavior in a residential setting under Japanese climatic conditions. Build Environ 2009;44:2137-49.

[16] V. Fabi, Andersen RV, Corgnati SP, Olesen BW. A methodology for modelling energy-related human behaviour: Application to window opening behaviour in residential buildings. Build Simul, 2013;6:415-427.