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REAL TIME MONITORING OF INDOOR ENVIRONMENT QUALITY AND ENERGY CONSUMPTION IN A RESIDENTIAL BUILDING

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Abstract

Several theoretical studies were oriented towards the relationship between the main two building design estimators (building energy consumption and indoor environmental quality) but very little experimental research has been carried out in order to underline the correlation between this two parameters. This paper is focused towards the experimental study of the correlation between these two design estimators. Several indoor comfort parameters (air temperature, radiant mean temperature, sound pressure level, outdoor ventilation rate and lighting level) as well as energy consumption were monitored in different rooms inside a laboratory experimental house at real scale located in Bucharest, Romania. Time variations of these parameters and space distribution maps inside the house were analysed in order to understand the indoor comfort variations. Four comfort indexes (thermal comfort index, acoustic comfort index, indoor air quality index and visual comfort index) were determined and their time variations were used to emphasize the correlation between the indoor environment quality and the energy consumption. The overall indoor environment quality was found to be inversely correlated with the energy consumption and that this general trend can be easily influenced by the weight of the four comfort types.

Key words: building operating, energy efficiency, IEQ

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1. Introduction

Buildings, beside their main functionality (protection to rain, snow and wind), must also provide an indoor comfort level: warm thermal condition in cold climates; cooler conditions in hot climates; indoor air quality through controlled ventilation in order to reduce odours and other discomfort associated with human bio-effluents (Godish, 2016). Due to technological progress, nowadays individual's expectancy related to comfort is more demanding and one can assume this trend might continue in the future (Calvaresi et al., 2018; Ortiz, et al., 2017; Sarbu and Sebarchievici, 2013). The present expectations of the occupant regarding comfort include higher airflow rates, smaller temperature variations and smaller sound pressure levels.

Currently, there are two general methods to evaluate indoor comfort level:

- depending on just one environmental parameter, such as: (1) Fanger's PMV (Danielle, et al., 2012; Pei, et al., 2015; Quang, et al., 2014; Sarbu and Sebarchievici, 2013; Yang, et al., 2014), (2) lighting level and (3) the indoor air quality (Ncube and Riffat, 2012; Quang, 2014; Sarbu and Sebarchievici, 2013; Toftum, 2010).
- depending on four types of indoor comfort: thermal comfort, indoor air quality, acoustic comfort and visual comfort (Huang, et al., 2012; Ncube and Riffat, 2012; Pei, 2015; Sarbu and Sebarchievici, 2013; Toftum, 2010) in order to obtain a global

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comfort index named Indoor Environment Quality Index (I_{IEQ}).

The main energy consumption of a building is closely associated with the necessity of maintaining the indoor environment quality (IEQ) in a certain range (Catalina and Iordache, 2012; Lee et al., 2017; Petcu, 2010; Sarbu and Sebarchievici, 2013; Wong et al., 2008). However, the legislation in several countries aims to reduce the energy consumption and the carbon footprint without any decline of the indoor comfort and productivity (Buhl et al., 2018; Campeanu et al., 2007; Pérez et al., 2011), which represents the main challenge of the researchers in the field of energy and environment sustainability.

Knowing that the energy efficiency of a building is considerably affected by the thermo-physical proprieties of the construction elements, the present legislations require that during the design stage, engineers use construction elements that meet certain performance criteria (C107, 2005). Besides building thermal properties, its operation has also a major impact on the energy consumption (Toftum, 2010). Different building management strategies (for example the setup values of comfort parameters or the building services systems operation) significantly influence the energy consumption of a building (Toderaşc et al., 2015). Other studies show that the optimized control algorithms for the heating, ventilation and air conditioning systems (HVAC) can generate an increase of the indoor comfort with an important decrease of energy consumption (Revel, et al., 2015). Building management strategies can be applied in order to comply with the design setup limit values (EN15251, 2007), and improve indoor environment quality and energy performance (Pereira, et al., 2014). However, building management strategies and HVAC operation are affected by human behaviour. Human behaviour influence IEQ through subjectivism (Heinzerling, et al., 2013; Huang, et al., 2013), gender (Karjalainen, 2012; Nobuko, et al., 2010), level of educations, the relationship, psychosocial atmosphere, occupants' age, type of job, country of origin (Frontczak and Wargocki, 2011). Beside its influence upon the IEQ, the human behaviour was found to be an important factor influencing the building energy consumption (Toftum, 2010; Andersen, et al., 2007).

The relationship between the Indoor Environment Quality (IEQ) and the Energy Consumption (EC) was studied using mathematical models (Catalina and Iordache, 2012; Sarbu and Sebarchievici, 2013) or simulations (Kim et al., 2017). While some researchers found a direct relation between the variation of the two parameters (Wong and Mui, 2009), others found an inverse correlation (Kim et al., 2017; Catalina and Iordache, 2012).

Compared to these theoretical studies, our study represents a novel approach (experimental monitoring during the operation of a real building) in order to understand the relationship between these two indexes. The objective of our study is to understand if the two parameters are independent to one another or if they vary simultaneously. In this last case, we aim to understand if the two parameters are directly or inverse correlated. We aim to understand if good IEQ is achieved only with higher energy consumption. The correlation between the IEQ and EC may vary (influenced by the building operation or by its architecture) and consequently a baseline correlation study is necessary to understand the effect of the different parameters (setup changes, architectural changes, HVAC management changes) upon the IEQ and EC. In this research, we respond to this necessity by studying the correlation between the two indexes for a real building in a free operation mode. We believe this study, along with previous research works (Catalina and Iordache, 2012), could help us to better understand the correlation between IEQ and EC, and how HVAC solutions might change this correlation and influence the optimum operation strategy.

The paper presents firstly the methodology for IEQ and EC identification, followed by the experiments, the variation of the measured physical parameters, the IEQ calculation and the correlation between two indexes

2. Material and methods

We carried out an experimental monitoring campaign for a real scale house. In our monitoring stage, we measured all the necessary physical quantities that underlie the comfort indexes: the operative temperature for thermal comfort index, sound pressure level for acoustic comfort index, the outdoor ventilation rate for indoor air quality and the lighting level for lighting comfort index. These four physical parameters were further used to estimate the four specific comfort indexes. These four indexes were combined in order to determine the global IEQ index (Catalina and Iordache, 2012). Further we shall succinctly present this method for the calculation of the four comfort indexed and the global IEQ index.

Thermal comfort is an important parameter of IEQ, which also engenders the energy consumption in buildings (Corgnati et al., 2009). The thermal comfort index, I_{CT} (-), will be calculated with (Eq. 1). The two conditions in (Eq. 1) correspond to the two extreme seasons: winter and summer. Fluctuations in the outside temperature and the solar radiation will produce a variation of interior wall/glass surface temperature and transmitted solar gain, respectively (Dascalaki et al., 2009). Consequently, the thermal comfort index is calculated based on the operative temperature (Eq. 2) that takes into account the solar gains (Catalina and Iordache, 2012).

$$I_{CT} = \begin{cases} 28.57 \cdot \theta_{op} - 514; when\ \theta_{op} \leq 21.5 \\ -28.57 \cdot \theta_{op} + 800; when\ \theta_{op} \geq 21.5 \end{cases} \tag{1}$$

$$\theta_{OP} = \frac{\theta_i + \theta_{MR}}{2} \tag{2}$$

where θ_{0P} [ºC] represents the operative temperature, θ_i [ºC] represents the indoor air temperature and θ_{MR} [ºC] represents the mean radiant temperature.

The second of the four types of indoor comfort is the acoustic comfort. The acoustic comfort index, I_{CA} *(-),* is calculated as a linear variation to the sound pressure level, L_{pi} *(dBA)*, (Eq. 3) which represents the physical parameter that is most often used to evaluate indoor acoustic ambiances (Chiang and Lai, 2008; Lowry and Thomas, 2010).

$$I_{CA} = -3.33 \cdot L_{pi} + 200 \tag{3}$$

The third of the four types of indoor comfort is the indoor air quality. The indoor air quality can be modified by changing outdoor ventilation rate (Quang, 2014). Previous studies have demonstrated that the higher the outdoor ventilation rate the better the occupant health and performance (Park and Yoon, 2011; Sekhar, et al., 2003; Seppänen, et al., 2006; Tham, 2004; Wargocki, et al., 2004). In other studies, it was found the outdoor ventilation rate is correlated to the sick building syndrome (Wargocki, et al., 2000). In our study, we will evaluate the indoor air quality index, I_{IAQ} *(-),* using the specific air flow, q_{ap_s} [m^3/(h·pers)], as input parameter (Eq. 4).

$$I_{IAQ} = 3.125 \cdot q_{ap\_s} - 12.5 \tag{4}$$

Last but not least, the indoor comfort depends on the visual comfort. The quantity of light that is hitting the retina controls the body's circadian rhythm by influencing the hypothalamus gland and controlling melatonin secretion (as sleep hormone) (Ahadi, et al., 2016). Especially, natural lighting results in improved worker performance, lower stress and greater motivation (Kellert, et al., 2011). In order to calculate the indoor visual comfort index, I_{CV} *(-)*, is calculated as a function of the illuminance level, *E (lx)*, (Eq. 5).

$$I_{CV} = 0.33 \times E \tag{5}$$

Further, the indoor environment quality index I_{IEQ} *(-)* is calculated as a weighted average of the four comfort indexes (Catalina and Iordache, 2012) (Eq. 6).

$$I_{IEQ} = \frac{I_{CT} \cdot \mu_{CT} + I_{CA} \cdot \mu_{CA} + I_{CAI} \cdot \mu_{CAI} + I_{CV} \cdot \mu_{CV}}{\mu_{CT} + \mu_{CA} + \mu_{CAI} + \mu_{CV}} \tag{6}$$

The weights: μ_{CT}, μ_{CA}, and μ_{CV} were determined by a survey study carried out at the Faculty of Building Services Engineering (Toderaşc and Iordache, 2016). The purpose of these coefficients is to take into account the subjectivity of the people towards the four types of comfort (Frontczak and Wargocki, 2011). Besides the IEQ index (calculated based on experimentally identified values of indoor environment parameters), we further measured the energy consumption, EC. In the next paragraph, we will present the experimental campaign and the measurement protocol for the physical parameters as well as the energy consumption.

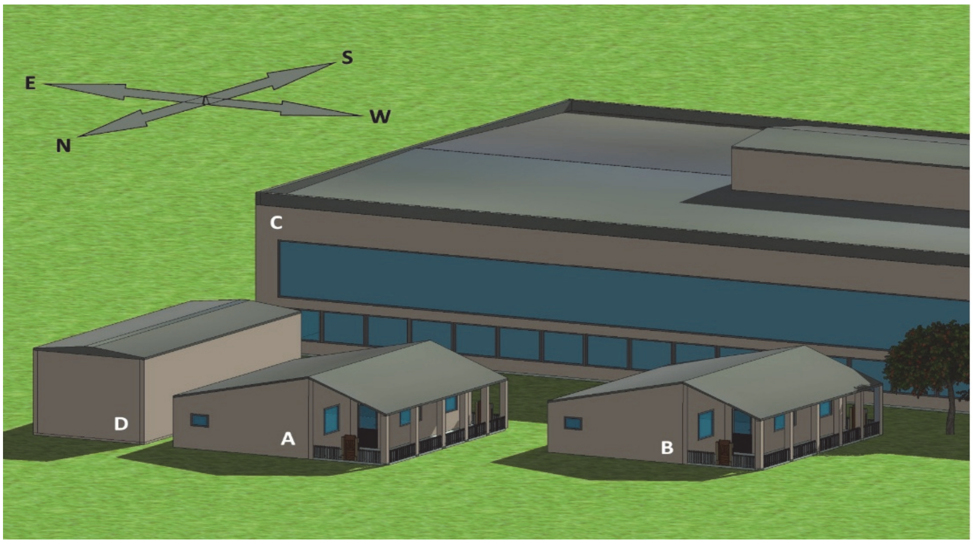
3. Experiments

The experiments were carried out in a small family house (ground level), located in the courtyard of the Romanian building research institute (INCD URBAN INCERC), Bucharest, Romania. The house (building A in Fig. 1a) is composed of: one living room, two bedrooms, one bathroom, corridor and a porch (Fig. 1b).

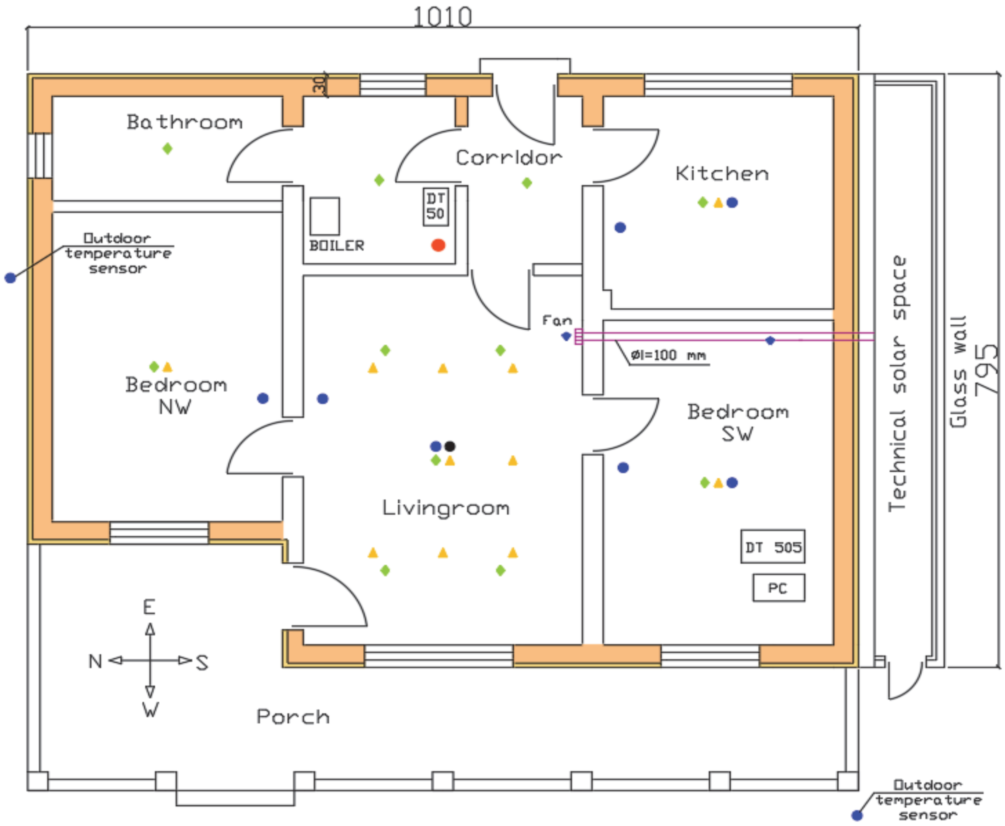
The closest construction to the experimental building is placed at about one meter on the east side of it (building D in Fig. 1a). Having the same height as the experimental building, the neighbouring building D overshadows the east wall for most of the time. The other neighbouring buildings are placed at two meters on the west side (building B in Fig 1a), respectively at 8 m on the south side (building C in Fig. 1a). The buildings B and C overshadow the experimental building only for short periods during the day. The walls structure is compounded of 25 cm autoclaved aerated concrete with six cm expanded polystyrene covered with a decorative plaster on outdoor wall surface and drywall on indoor wall surface. The inclined ceiling is adjacent to outdoor environment. The ceiling is made by 20 cm width reinforced BCA slabs interlocked by 8 cm reinforced concrete and insulated with a layer of glass wool in the interior and a final layer of drywall. The building is equipped with PVC doors and windows with double glazing system on the exterior walls.

The Heating, Ventilation and Air Conditioning (HVAC) system of the experimental house is composed of two different systems for the space heating and for the ventilation. The heating system is composed by the electric supplied wall mounted boiler, distribution pipes, radiators and thermostatic valves. The indoor air temperature is automatically set using a room thermostat. The ventilation system is composed by the variable speed fan, air tube, inlet grille and outlet grille. The fresh air is brought in through the living room, and polluted air is evacuated through kitchen window grille. The fan can supply 37 m^3/h of fresh air, which is enough to ensure good conditions for two occupants (I5, 2010).

The quantity of fresh air introduced can be adjusted by the transformer that supplies the fan. Using it we varied the supply voltage of the fan from 110 V to 220 V. As a consequence, the flow varied from 22 to 37 m^3/h and, as a result we obtained 13 operating scenarios of the building.



(a)



(b)

Fig. 1. The experimental building: (a) Experimental building and neighbours, (b) architectural plan and measurements points. Sensors locations: • - air temperature; • - mean radiant temperature; ♦ - quantity of fresh air introduced; ♦ - sound pressure level; ▲ - lighting level; • - energy transducer

In this phase, we measured all the physical parameters that were further used to evaluate the time evolution of the indoor environment quality and energy consumption of the building:

• the indoor and outdoor air temperature, θ_i and θ_e respectively (blue dots in Fig. 1b). The temperature of indoor air was measured using shielded thermocouples. We used thermocouples type E composed by a first wire nickel + 10% chrome and a second wire copper + 45% nickel. The E thermocouples theoretically introduce an error of ±1.7 °C. Before they were plugged to the acquisition system they were first calibrated. The steel shield is used to eliminate the effect of surfaces radiation to thermocouple, therefore they accurately measure air temperature. All thermocouples with the data logger were calibrated using an Ametek JOFRA CTC140A Compact Temperature Calibrator.

• the mean radiant temperature in living room, θ_{MR} (black dot in Fig. 1b). A black sphere thermocouple was used for the mean radiant temperature measurement. The black sphere temperature sensor was placed in the centre of the room at 1.30 m from the floor. The measurement system (temperature probe and data logger) were calibrated by means of an Ametek JOFRA CTC140A Compact Temperature Calibrator and the maximum measurement error of the thermocouple from the sphere was 1.3 %.

- the ventilation fresh air flow, measured in two different ways. In the first way, we measured the velocity of the air inside of the tube (marked with a blue diamond in Fig. 1b) that brings it from outside. Multiplying the velocity with section of the tube we obtained the flow. The velocity of the air was measured using a hot wire anemometer (model Testo 425) which has an accuracy of ± 5% of the measured air flow. As validation of the working method, we measured the airflow using a vane anemometer (Testo 417), which is a compact measuring instrument for flow velocities by means of an integrated 100 mm vane. The accuracy of this instrument is ± 1.5 % of the measured air flow.
- The sound pressure level (green rhombus in Fig. 1b). The sound pressure level was measured by means of Bruel&Kjaer Hand-held Analyzer Type 2250, which is a class 1 precision device. The sound meter was calibrated by means of a Sound Calibrator Type 4231 from Bruel&Kjaer for both calibration frequencies 94 dB and 114dB. For each of 13 ventilation scenarios, the sound pressure level was measured in the centre of each room.
- The lighting level (yellow triangles in Fig. 1b). For measuring the lighting level, we used the light meter LM-8102 with an accuracy of ± 5%. The lighting level was measured in the centre of each room at 1 m height from the floor, and in living room it was measured in nine points equally spaced one from another. The lighting level vas measured during one day at every hour starting from 6:00 until 19:00.

The air temperature from living room, SW bedroom, kitchen and the outdoor temperature, were monitored using a data acquisition system composed by one data logger DataTaker DT505 placed in SW bedroom (Fig. 1b) with an extension module to increase the input channels number. The heating source of the building is a wall mounted electric boiler. The energy consumption of the heating system was determined by measuring the electricity consumption of the boiler. This electricity consumption was measured by means of a second data acquisition system based on a data logger DT50. Beside the electricity consumption, DT50 also records: the indoor air temperatures from NW bedroom, water flow from the boiler and temperature difference between the warm water and return water pipes of the heating indoor network.

The measurements were carried out during the 26.01.2016 to 04.03.2016 period. The traducers were scanned every 5 seconds and the 5 minutes averages were recorded. The ventilation air flow was also measured for ten different supply voltages.

4. Variation of the physical parameters

In this paragraph we shall present different analyses (time variation and space variation indoors) for each of the monitored physical parameters of the indoor environment comfort: indoor temperature, the lighting level, the sound pressure level and the air flow; parameters presented in detail under methodology.

4.1. Variation of indoor temperature

The operation of the heating system of the experimental house is similar to the existing self-operation controllers used today (thermostat controllers). The indoor setup point of the air temperature was 23°C. However, during the experiment period, the air temperature varied between the 22.70 ÷ 23.75°C (Fig. 2a) with a median value of 23.3°C. This difference between the setup point and the actual recorded air temperature is due to several factors: (1) the variation of the climatic parameters, (2) the setup of the electric boiler on the minimum power (the smallest electric resistance available, power 2 kW) and (3) the inherent operation of the electro-mechanical bimetal thermostat used for the boiler automation.

Beside the time variation of the actual recorded values of the air temperature, we shall also present the air temperature variation inside the house. The few exceptions correspond with the moments when doors or windows were opened. During the measurements time, the outdoor temperature varies from -2.5 to 23.62°C, while the indoor temperature varies between 22 °C and 23.75 °C. The average temperatures inside the experimental house during the period 26.01.2016 - 04.03.2016 were: θ_{m_liv} = 22.80°C for living room, θ_{m_BSW} = 23.30 °C for SW bedroom, θ_{m_BNW} = 23.08°C for NW bedroom and θ_{m_kit} = 23.05°C for kitchen (Fig. 2b).

We notice that there are small differences from one room to another. The biggest temperature difference, 1.02°C, was noticed in 27.01.2016 at 21:15 between kitchen (23.13°C) and living room (22.11°C). We can see that the indoor temperature from the living room is always lower compared to the other rooms. The main reason is that the room has three external walls (including the inclined roof) and each of the two vertical walls have glazed surfaces.

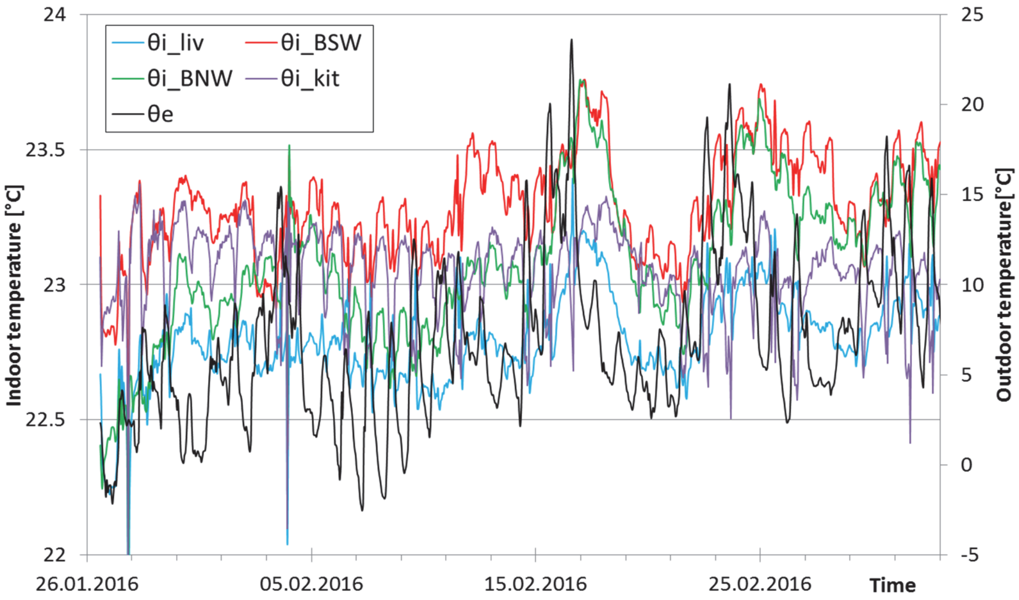
The orientation has an important role for temperature difference between rooms. As evidence, we can observe that the bedroom with a south orientated wall is the warmest room. The eastern zones of the building are disadvantaged because of the neighbouring building which shadows the external walls of bathroom, corridor and kitchen.

In 888 of 910 recorded values, the outdoor temperature was at least 5°C lower than set up indoor temperature, meaning boiler was operating most of time and the electricity consumption was recorded for space heating.

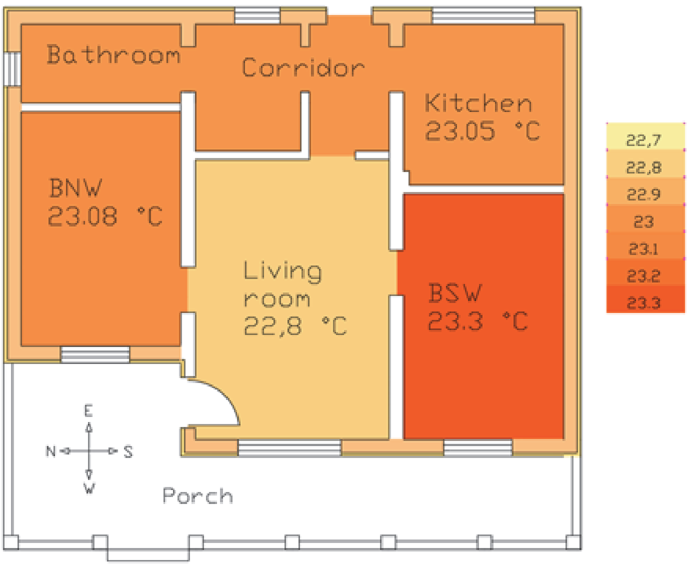
4.2. The lighting level variation

Lighting level was measured in nine points for the living room and in one point for each other room (Fig. 3a). The lighting level measurements were carried out in conditions of no artificial light. The lighting level was recorded in each room, each hour. During measurements, the light was off in order to understand the time variation of the outdoor lighting potential and house orientation. The time variations of the lighting level are different from one measurement location to another. The highest lighting level was found close to the NW corner of the living room (Fig. 1b). That point is the closest relative to the window on the west wall and is the closest relative to the glazed door on the north wall. The living room had the biggest glazing ratio, 0.32, while in other rooms the glazing ratios were: 0.08 for south-west bedroom, 0.12 for kitchen and 0.09 for north-west bedroom.

According with the measured values, between 19:00 to 06:00 the indoor lighting level is null. It rises between 07:00 and 10:00 maintain approximately constant value until 15:00. During this time, the variation of lighting level is largely due to the meteorological conditions. Another important factor that produces differences in lighting level between rooms is the neighbouring building D (Fig. 1a) which is placed at two meters from experimental building on the eastern side. The average levels of illumination within the 10:00÷15:00 were: E_{m_liv} = 233lx for living room, E_{m_BNW} = 85 lx for north-west bedroom, E_{m_BSW} = 105 x for south-west bedroom and E_{m_Kit} = 126 lx for kitchen. The highest values of the lighting level were recorded for all rooms at 16:00 (Fig. 3b) because the biggest window surface is placed on the west wall, resulting in a good lighting during the afternoon.



(a)



θi_liv – indoor air temperature in the living room;

θi_BSW – indoor air temperature in the SW bedroom;

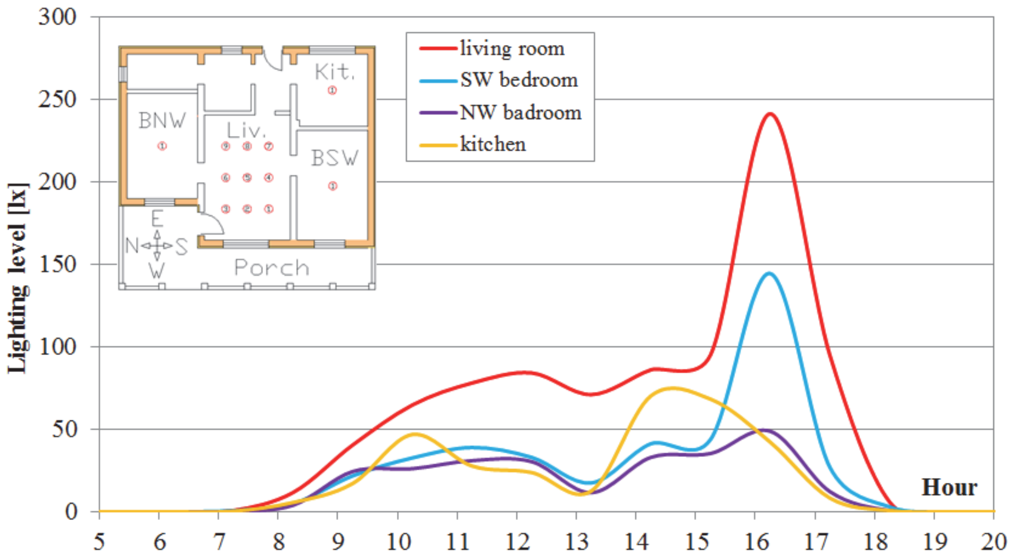
θi_BNW – indoor air temperature in the NW bedroom;

θi_kit – indoor air temperature in the kitchen;

θe – outdoor air temperature

(b)

Fig. 2. Indoor and outdoor temperature variations: (a) time variation, (b) room comparison



(a)

(b)

Fig. 3. Indoor lighting level variation: (a) daily variation, (b) room comparison at 16:00 hours

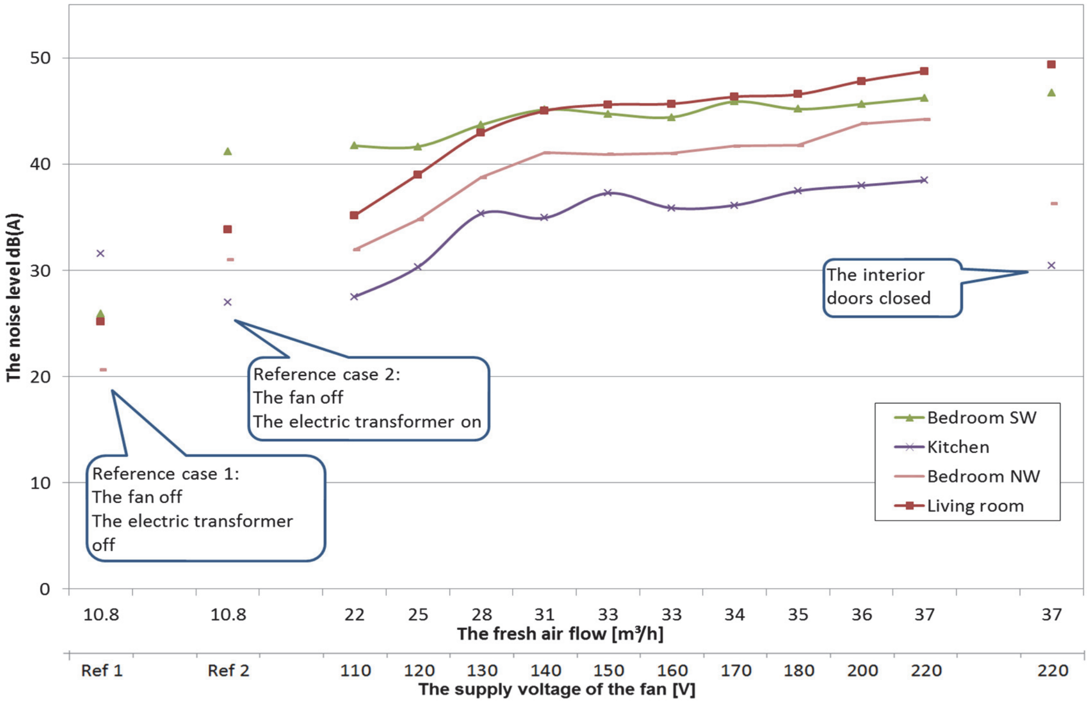
4.3. Sound pressure level and air flow variation

The experimental house is placed in the inner courtyard, 200 m away from road which represents the main outdoor noise source in the area; therefore, the local noise level is reduced. Consequently, the indoor noise level depends mainly on the noise generated by the ventilation system of the experimental building. The noise measurements were carried out for 13 different situations depending on the ventilation regime (Fig. 4a).

For air flow smaller than 30m³/h, the highest sound pressure level was found in the SW bedroom, while for higher air flows the living room becomes the noisiest place in the house (Fig. 4a). The noise level in the different rooms depends on the structure of the ventilation system. In the experimental house, the electric transformer of the ventilation system is located in the south west bedroom while the fan is placed in the living room. At higher air flow the noise generated by the fan overcomes the noise generated by the transformer. We can observe that between case 2 (transformer ON, fan OFF) and case 3 (transformer ON, fan ON 21.7 m³/h), the difference of the sound pressure level is less than 2.4 dB(A), concluding that at low airflow rate the main noise source is the electric transformer, while at higher ventilation rate the fan becomes the main noise generator.

Indoor noise mapping (Fig. 4b) shows how the noise level depends on the distance between measurement place and the noise source. Thus, the distribution maps of physical parameters (indoor temperature, luminance, noise level) are useful because this graphical representation represents the first indicator of the indoor poor comfort zones and of their main causes: the orientation of the rooms, neighbouring buildings, the place and the sizes of the windows, the place of building services equipment.

In the next paragraph, we will analyse correlation between the IEQ index (weighted average of the four comfort indexes) and the energy consumption in order to find how much the indoor environment quality affects the energy consumption of the house.



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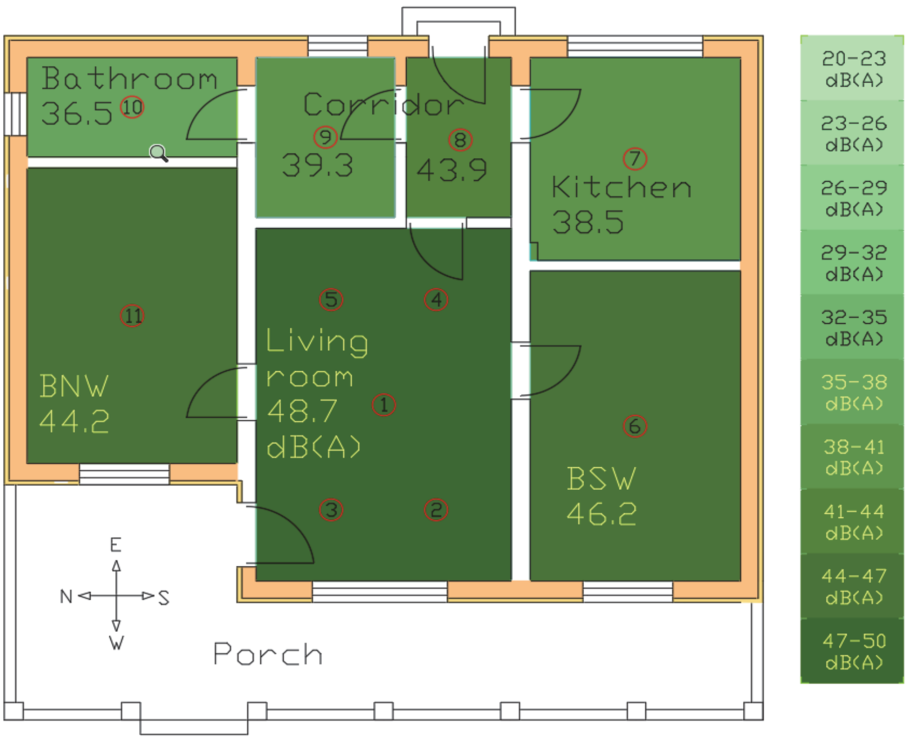


(b)

Fig. 4. Sound pressure variation: a) influence of the fresh air flow b) room comparison for during maximum ventilation rate

5. Indoor comfort indexes and correlation with energy consumption

In this paragraph, we will present the time variation of the four types of comfort indexes and the correlation between the indoor environment quality and the energy consumption. The IEQ index is calculated as a weighted average of the four comfort types indexes (Eq. 6), thus the IEQ index represents a multivariate linear regression where the coefficients are normalised to sum 1. Several researches were carried out on the weighting schemas (the coefficients of this model) between the four comfort types (Heinzerling et al. 2013; Nimlyat and Kandar, 2015) and the subjectivism aspect of these schemes was highlighted. In order to decrease the subjectivism errors we choose to use a weighting schema obtained from questionnaires on a group of Romanian subjects with good understanding of the different types of comfort (Toderaşc and Iordache, 2016). The weights that we used are very close to one another (25.1% for thermal comfort, 24.1% for acoustic comfort, 26.4% for indoor air quality and 24.4% for the visual comfort) similar to those found by Marino et al. (2012).

The classification schemes for the IEQ ratings are only used, as a reader friendly tool, in order to understand if a specific value of IEQ is high or low. In different studies in the literature the comfort classes correspond to a certain comfort ambiance. For example if there is too noisy and people cannot understand each other the class for the acoustic comfort will be very bad (lower classification), or if the norm maximum value of the noise level is not overpassed than the class will be very good (class "A"). Some authors prefer to divide this classification schema into three classes, others in four or five classes. There are no well-established classification schemes for the comfort indexes. In this study we employed the classification schemes that were determined on residential building (Lai, et al., 2009) and also used in other researches (Catalina and Iordache, 2012).

Due to the indoor temperature set point, during the heating system operation, the indoor temperature ensures a good thermal comfort (Fig. 5a) relatively constant. During the measurements period, the indoor thermal comfort index, $I_{CT\_livingroom}$, was maintained at levels between 95 (-) and 143 (-), values that fit the thermal comfort index in class "A" for almost entire monitoring period. The acoustic comfort index in the living room, $I_{CA\_livingroom}$, is varying depending on the indoor and outdoor noise sources. The only noise source during measurements time was the ventilation system. The noise generated by ventilation system depends on the fresh air flow. For low fresh air flow, the $I_{CA\_livingroom}$ is placed in class "A" and "B", while for higher fresh air flow the $I_{CA\_livingroom}$ index drops in class "C". In Fig. 5b the acoustic comfort index is represented as a function of the fresh air introduced for space ventilation. It can be noticed the higher the fresh airflow, the smaller the acoustic comfort index. Thus, the indoor acoustic comfort index is inversely correlated with the fresh air flow.

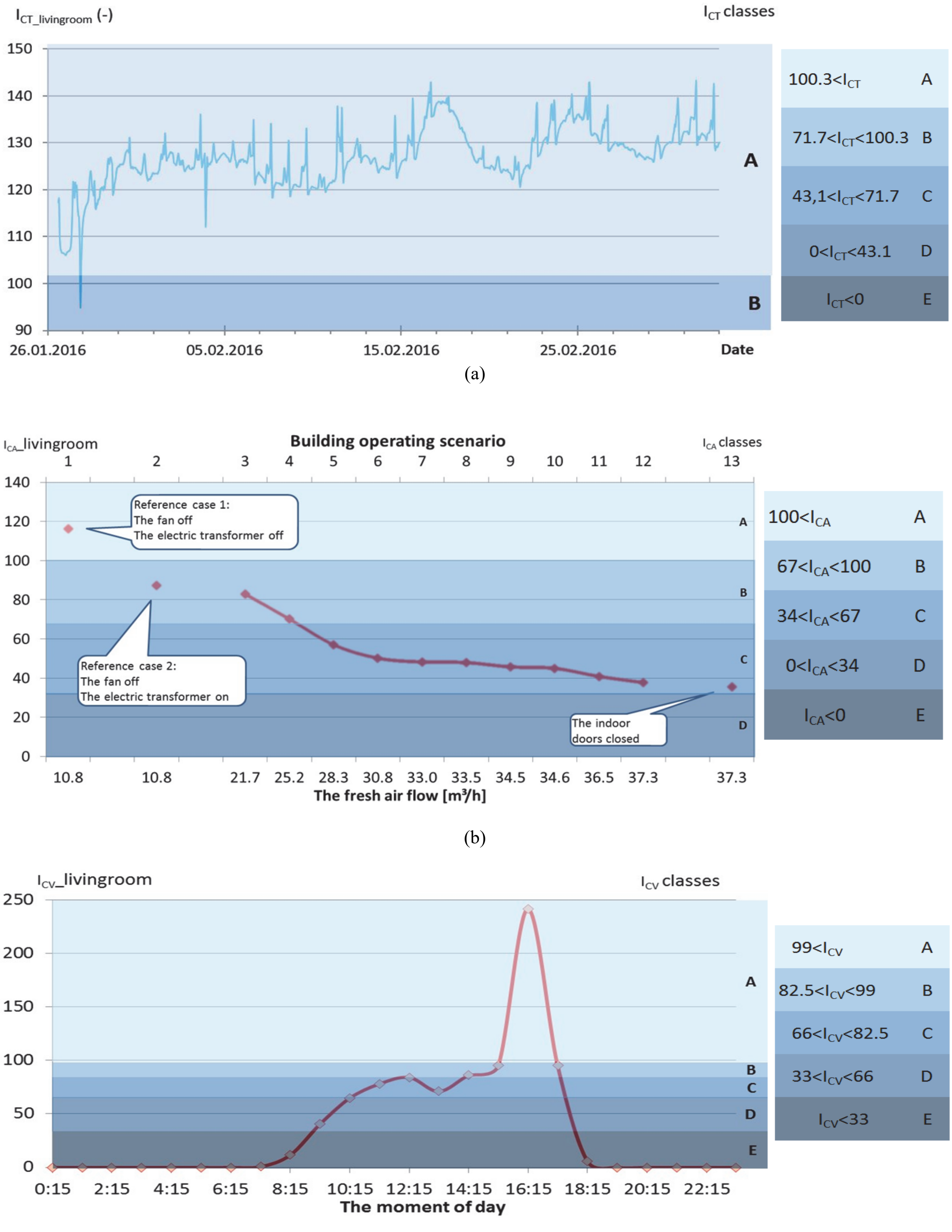
The visual comfort index in the living room, $I_{CV\_livingrom}$, varies (Fig. 5c) during daytime similar with the lighting level inside the living room, which in our study depended only on the natural light. The index is placed in class "E" from 18:00 to 09:00 (night-time, morning and evening), in classes "B" and "C" from 10:00 to 17:00 (most of the daytime) with a maximum peak at 16:00 when the index in placed in class "A". This visual comfort index variation is specific to the building and its position relative to the neighbours in urban environment, as well as the room window orientation (living room window oriented towards west).

The analysis of the indoor air quality index inside the living room, $I_{IAQ\_livingroom}$, shows that whatever the fresh air flow introduced with the existent ventilation system, the indoor air quality index did not exceed the value 27 (-), corresponding to the class "D" of indoor air quality (Fig. 5d). The indoor air quality index can be used in order to evaluate the performance of the ventilation system during its operation. In this case, the small values of indoor air quality index show that the ventilation system operates poorly and its refurbishment should be considered. The graphical variation of the indoor environment quality index in the living room, $I_{IEQ\_livingroom}$, (red curve in Fig. 6) underlines the existence of three different states corresponding to three different IEQ indexes:.

- I_{IEQ} in class "C", which correspond to the night time (18:00 - 10:00),
- I_{IEQ} in class "B", for most of the daylight period (10:00 - 15:30 and 16:40 - 18:00), and
- I_{IEQ} in class "A", corresponding the time interval 15:30 - 16:40.

IEQ index fits in class "C" in most of the measurement period, with values between 50 (-) and 60 (-). Class "C" is obtained during the night time because the value of I_{CV} (calculated based on natural lighting) is zero, resulting in overall lower values of I_{IEQ}. During the day, the I_{CV} value increases and the I_{IEQ} value is placed in class "B".

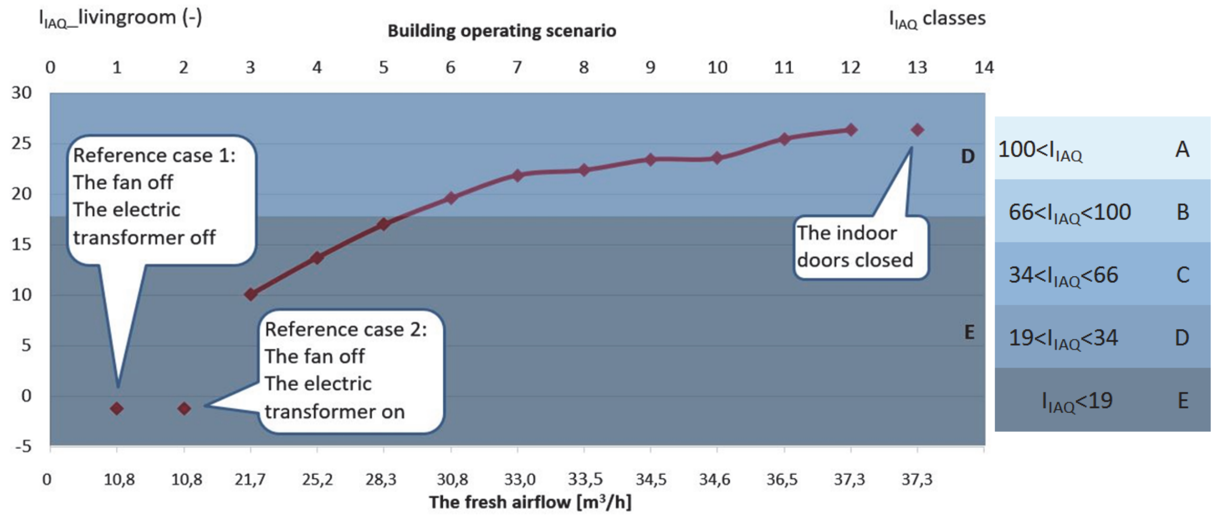
IEQ class "A" is obtained for a short period when the lighting level reaches its maximum value in the evening (west oriented window in the living room). Because in this particular case the indoor temperature, noise level and fresh air flow are characterized by reduced variation, the influence of daylight has the biggest impact on the overall I_{IEQ} variation (profile similarities between Fig 6 and Fig. 5c). This profile similarity is due to the similarity between the weights of the four individual comfort indexes that lead to the final indoor environmental quality index (Eq. 6). If the weights would be different from those measured in our previous study (Toderaşc and Iordache, 2016) resulting in a much lower weight for I_{CV}, than the similarity between the I_{IEQ} and I_{CV} profiles would be less noticeable. A discussion about weights can be found in (Heinzerling, 2013). One can also argue the use of the visual comfort during the night whatever the purpose of the room. For a usual domestic schedule, during the night time the visual comfort is not important (occupants sleep). When I_{IEQ} is calculated using a null weight for visual comfort during the night the indoor environment quality fits to class B instead of class C (black curve in Fig. 6). We investigated if there is any correlation between I_{IEQ} and the energy consumed by the heating system to maintain an indoor air temperature of 23°C. The correlation graph (Fig. 7) was based on a three months measurement period and it shows the experimental points form three different clouds.



(a)

(b)

(c)



(d)

Fig. 5. Variation of the indoor conform indexes: a) thermal comfort, b) acoustic comfort, c) visual comfort, d) indoor air quality

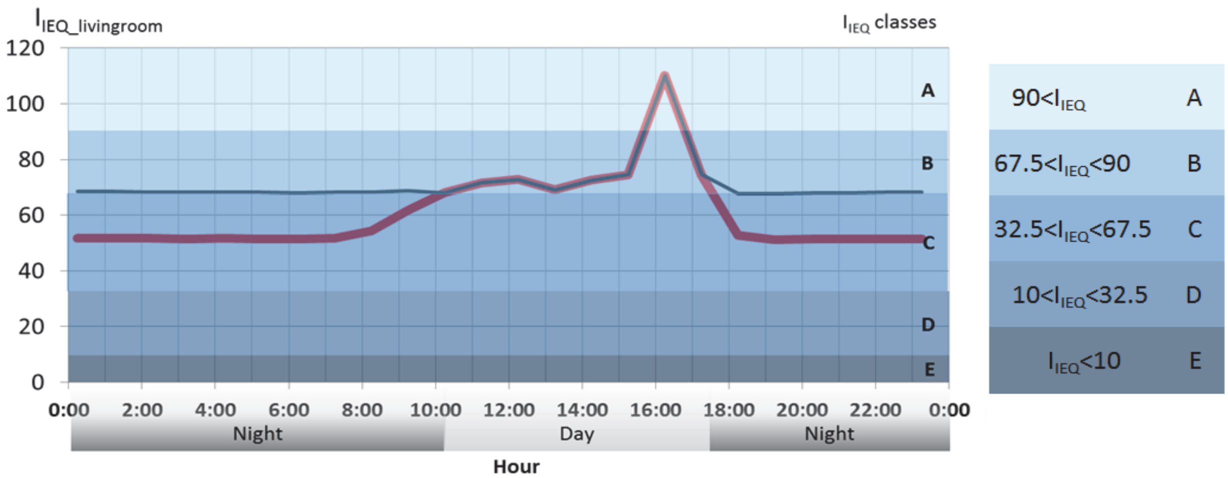


Fig. 6. Indoor Environment Quality index variation in time; red line - constant weights for IEQ index calculation; black line - variable weights for IEQ index calculation

The three-point clouds correspond to the three IEQ classes emphasized previously. The outdoor temperature fluctuated greatly during these months and consequently the energy consumption also varied in order to maintain a quasi-constant indoor environment quality. Thus, each point cloud presents an inverse correlation between the IEQ index and the energy consumption. The number of points characterizing each group corresponds to the number of hours when IEQ fits to the different classes.

We chose to use the Pearson's correlation coefficient (Wonnacott and Wonnacott, 1990), "r" due to the linear shape of the point clouds in order to evaluate the variation simultaneity between the energy consumption (EC) and the IEQ index (I_{IEQ}) (Eqs. 7-9.):

$$r_{I_{IEQ\_EC}} = \frac{\sum_{i=1}^{n}\left(I_{IEQ_i} - \bar{I}_{IEQ}\right)\left(EC_i - \overline{EC}\right)}{\sqrt{\sum_{i=1}^{n}\left(I_{IEQ_i} - \bar{I}_{IEQ}\right)^2 \cdot \sum_{i=1}^{n}\left(EC_i - \overline{EC}\right)^2}} \tag{7}$$

$$\bar{I}_{IEQ} = \frac{\sum_{i=1}^{n} I_{IEQ}}{n} \tag{8}$$

$$\overline{EC} = \frac{\sum_{i=1}^{n} EC}{n} \tag{9}$$

where $\bar{I}_{IEQ}$ (-) represents the average value of the hourly indoor environment quality index of a specific group of points, $\overline{EC}$ (-) represents the average value of the hourly energy consumption and EC (kWh/h) represents the energy consumption calculated according to the building energy performance norms (MC 001, 2006; EN13792, 2006).

The correlation coefficient was calculated for each of the three groups of points: $r_{I_{IEQ\_EC}} = -0.46$ for group C, $r_{I_{IEQ\_EC}} = -0.30$ for group B (daytime measurements) and $r_{I_{IEQ\_EC}} = -0.88$ for group A (afternoon measurements). These values prove there is an inverse correlation between the two parameters.

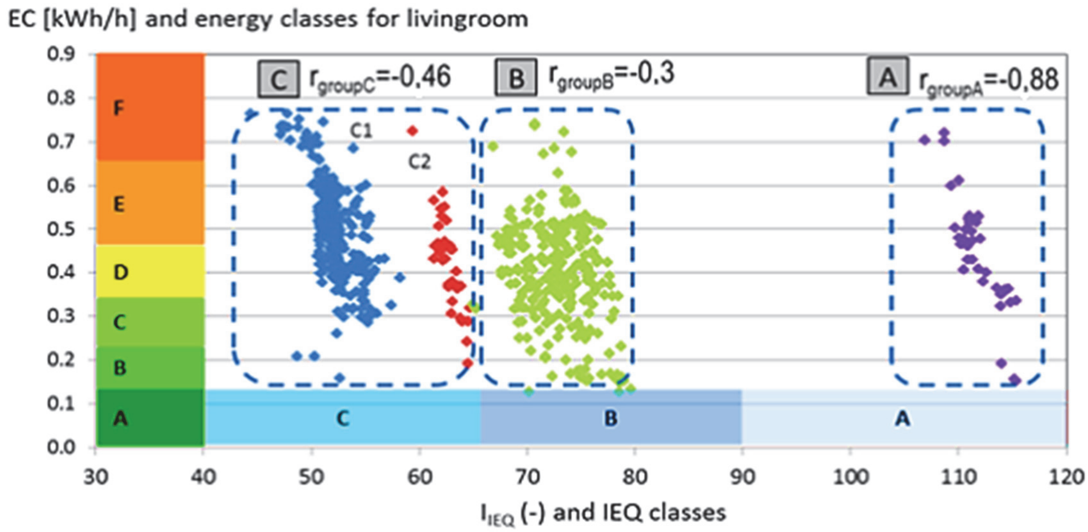


Fig. 7. The relationship between I_{IEQ} and EC

A comparison between the three groups shows a smaller correlation for group C due to the integration of two periods (night period and night-day transition period). If group C is split into two distinguished smaller groups, C1 for night-time measurements and C2 for night-day transition period measurements, the correlation coefficients for it are: $r_{I_{IEQ\_EC}} = -0.69$ for C1 and $r_{I_{IEQ\_EC}} = -0.86$ for C2 proving the high correlation between the two parameters. The high correlation coefficient obtained for group A is due to the high impact of the visual comfort over the entire IEQ index value.

The negative correlation sign shows the inverse variation of the two analysed parameters. In our case this shows the smaller the energy consumption, the higher the IEQ. This conclusion is opposed to the general perception that a better IEQ is obtained only with larger energy consumption. But it is also similar to the results obtained in other studies (Catalina and Iordache, 2012) and in good agreement with other comfort perception indexes (PMV, lighting level) variation as a function of the physical parameter (Lai et al., 2009).

Generally, we conclude the two parameters are highly correlated for both the night period (Group C - when visual comfort index has an extreme value, null) and the afternoon period (Group A) when the visual comfort has also an extreme value (over 200 (-)). For the rest of the day (Group B) the four indoor comfort indexes have more balanced values and weights and therefore the correlation between the two parameters is less visible.

6. Conclusions

The relationship between the indoor environment quality and the energy consumption was analysed during an experimental real-time monitoring campaign in a real house during a HVAC free operation mode (without human intervention) in order to understand the correlation degree between the two parameters (baseline study). The paper presents the time evolution of four physical parameters characterizing the indoor environment quality (indoor temperature, acoustic pressure level, lighting level and air quality) and their space mapping inside the house. Four indoor comfort indexes were calculated corresponding to these four physical parameters and their time evolution is also presented. Further the overall indoor environment quality index and energy consumption were determined and their correlation was investigated.

For this baseline experimental study, the IEQ and energy consumption were found to be inversely correlated, meaning the two indicators are changing in opposing directions; the higher the IEQ index the smaller the energy consumption. However, this correlation is different depending on the balance between the four indoor comfort indexes that form the overall IEQ index. During most of daytime hours we found the IEQ and energy consumption to be poorly correlated due to a relatively balanced influence between the four comfort indexes (superposed phenomena lead to unclear correlation). During evening and night-time, the correlation was much stronger because the visual comfort had extreme values (maximum lighting for evening - west oriented window room - and no lighting during night-time).

This research is an important development in the HVAC research field because it represents the baseline experimental study regarding how the IEQ index and energy consumption can be used as two estimators to select the optimal design solutions and operation strategies for the HVAC system.

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