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Energy consumption analysis in relation to the indoor environment quality index

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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). Nowadays because of technological progress, the comfort requirements are more demanding (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).

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

The indoor environment quality is an important factor that could explain the energy consumption and its time variation (Catalina and Iordache, 2012; Sarbu and Sebarchievici, 2013). The legislation in several countries aim to reduce the energy consumption and the carbon footprint without any decline of the indoor comfort and productivity (Pérez, et al., 2011; Virginia, et al., 2007)

Knowing that the energy efficiency of a building is affected to a large extent by the thermo-physical proprieties of the construction elements, the present legislations require that during the design stage the designers use such 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 and the setup values of comfort parameters may lead to a rational use of the energy or by contrary to a waste of energy (Toderaşc, et al., 2015). Other studies show that the optimized HVAC control algorithms, which use measured values of indoor comfort parameters, can create an increase of 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 also improve indoor environment quality and energy performance (Pereira, et al., 2014).

The overall indoor environment quality is estimated as a weighted mean of the four comfort parameters; the weights are most often determined by surveys (Heinzerling, et al., 2013). The differences between the four weights are caused by the peoples' subjectivism (Huang, et al., 2013). The main reasons for the different comfort perception are: 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).

Human behavioural proved to be an important factor influencing the building energy consumption (Toftum, 2010). Numerical simulations show that the energy consumption can vary up to 330% due to human behaviour (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) for building during the design stage.

Our study represents the first experimental monitoring study during the operation of a real building in order to experimentally understand the relationship between the two indexes: IEQ and EC. 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 research report presents firstly the methodology for IEQ and EC identification, followed by the experimental stage, the results (variation of measured comfort parameters, IEQ and EC) and the correlation between two indexes.

2. Method

We carried out a measurement and monitoring campaign for a real scale house. In our monitoring stage, we measured all the necessary physical quantities that underly 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.

The I_{IEQ} index was determined using equations (1) to (6) which are taken from the method described by (Catalina and Iordache, 2012). In order to calculate the indoor environment quality index, we first determined the four comfort indexes.

The first of the four types of indoor comfort is the thermal comfort, 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.

$$\mathrm{I_{CT}} = \begin{cases} 28{,}57 \cdot \theta_{OP} - 514;\ \text{pentru}\ \theta_{OP} \leq 21{,}5 \\ -28{,}57 \cdot \theta_{OP} + 800;\ \text{pentru}\ \theta_{OP} > 21{,}5 \end{cases} \tag{1}$$

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

where:

θ_{OP} [°C] represents the operative temperature

θ_i [°C] represents the indoor air temperature

θ_{MR} [°C] 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, Lpi (dB), (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).

$$I_{CA} = -0{,}33 \cdot L_{pi} + 200 \tag{3}$$

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 impacting 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). The indoor visual comfort index, I_{CV} (-), is calculated as a function of the lighting level, E (lx), (Eq. 5).

$$\mathrm{I_{CV}} = 0{,}33 \cdot \mathrm{E} \tag{5}$$

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}, μ_{CAI}, and μ_{CV} were determined by a survey study that we previous 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). The mentioned survey comprises a number of 115 questionnaires filled by students and professors of the Faculty of Building Services Engineering.

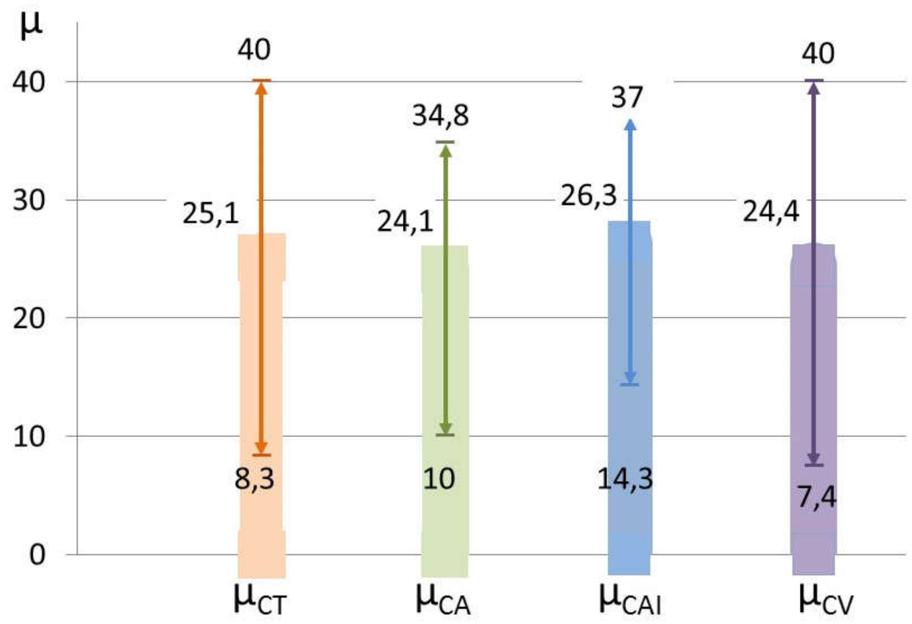


Fig. 1. The weights of the four different comfort types

Each person who filled a questionnaire had the possibility to give a note ranged from 1 to 100 for each type of comfort: thermal comfort, acoustic comfort, indoor air quality and visual comfort. In addition to questions about the importance of each type of comfort, the question form comprises questions about the age and the gender of the respondent. After processing the questionnaires, we found that the four types of comfort almost equal influences the comfort sensation. As seen in Fig. 1 the peoples appreciate that indoor air quality is the factor which has the most important influence on the indoor environment quality. But the difference between the most important comfort type and the least important comfort type is only for 2,2 points (Toderaşc and Iordache, 2016). The weights values obtained of four comfort types are comparable with the values obtained in some previous similar studies (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 four the physical parameters as well as the energy consumption.

3. Experimental campaign

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 from Fig. 2) is composed of: one living room, too bedrooms, one bathroom, corridor and porch (Fig. 4).

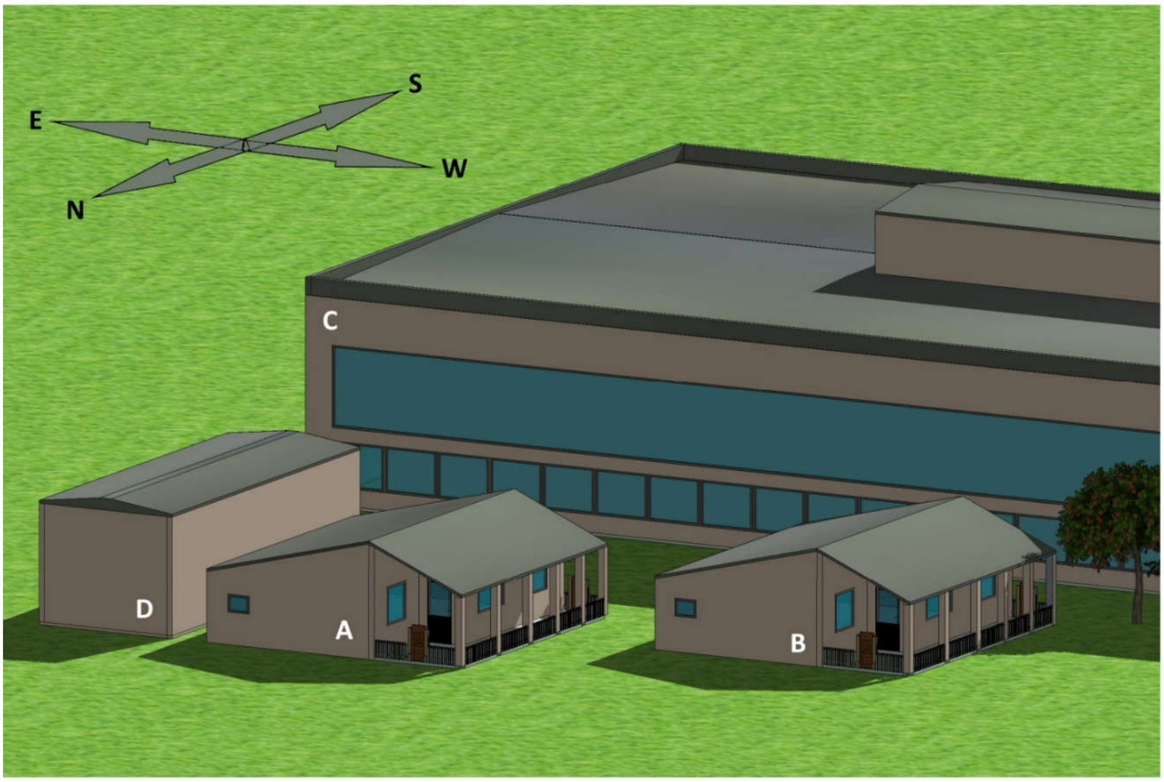


Fig. 2. The experimental building (A) and the neighbouring buildings (B, C, D)

The closest construction to the experimental building is placed at about two meters on the east side of it (building D in Fig. 2). 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 five meters on the west side (building B in Fig. 2), respectively at 8 m on the south side (building C in Fig. 2). The buildings B and C overshadow the experimental building too, but for short periods of time in a day.

The walls are insulated with 6 cm expanded polystyrene, the finishing touches being realized with decorative plaster. 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 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 window's grille from the southern facade. The windows equipped with evacuation grille are showed in Fig. 3.

a) b)

Fig. 3. The window kitchen a) and the bathroom window b)

The fan can supply 37 m³/h of fresh air, when it is working at full capacity. 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. In consequence, the flow varied from 22 to 37 m³/h and, as a result we obtained 13 operating scenarios of the building.
The Romanian legislation set the fresh air flow for housing depending on the number of the main rooms and the type of the room (I5, 2010):

Table 1. Air flows for housing ventilation

Number of main rooms in house	Extracted air flow [m³/h]				
	kitchen	bathroom	another bathroom	Toilet	
				simple	multiple
1	75	15	-	-	-
2	90	15	15	15	15
3	**105**	**30**	15	15	15
4	120	30	15	30	15
5 or more	135	30	15	30	15

According with the air flow values set by the Romanian norm (I5, 2010) and presented in Table 1, the minimum air flow for the experimental house, in order to satisfy the norm requirements is 105 m²/h. In this study, we intended to analyse how the indoor climatic parameters affect the indoor environment quality and the energy consumption. Although the 37 m³/h air flow realized by the installed fan is enough for our purpose, we brought in a second fan, placed in SW bedroom on the south wall. The second fan can ensure other 42 m³/h of fresh air, resulting in a max air flow equal with 79 m³/h when both fans are running.

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. 4). 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 ℃ (OMEGA®, 2015). 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 the thermocouple therefore to accurately measure air temperature.

- the mean radiant temperature in living room, θ_{MR} (black dot in Fig. 4). 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 ventilation fresh air flow. For each operating scenario, we measured the outdoor air flow 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. 4) 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%. In the second way, as a validation of the first way, 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 %.

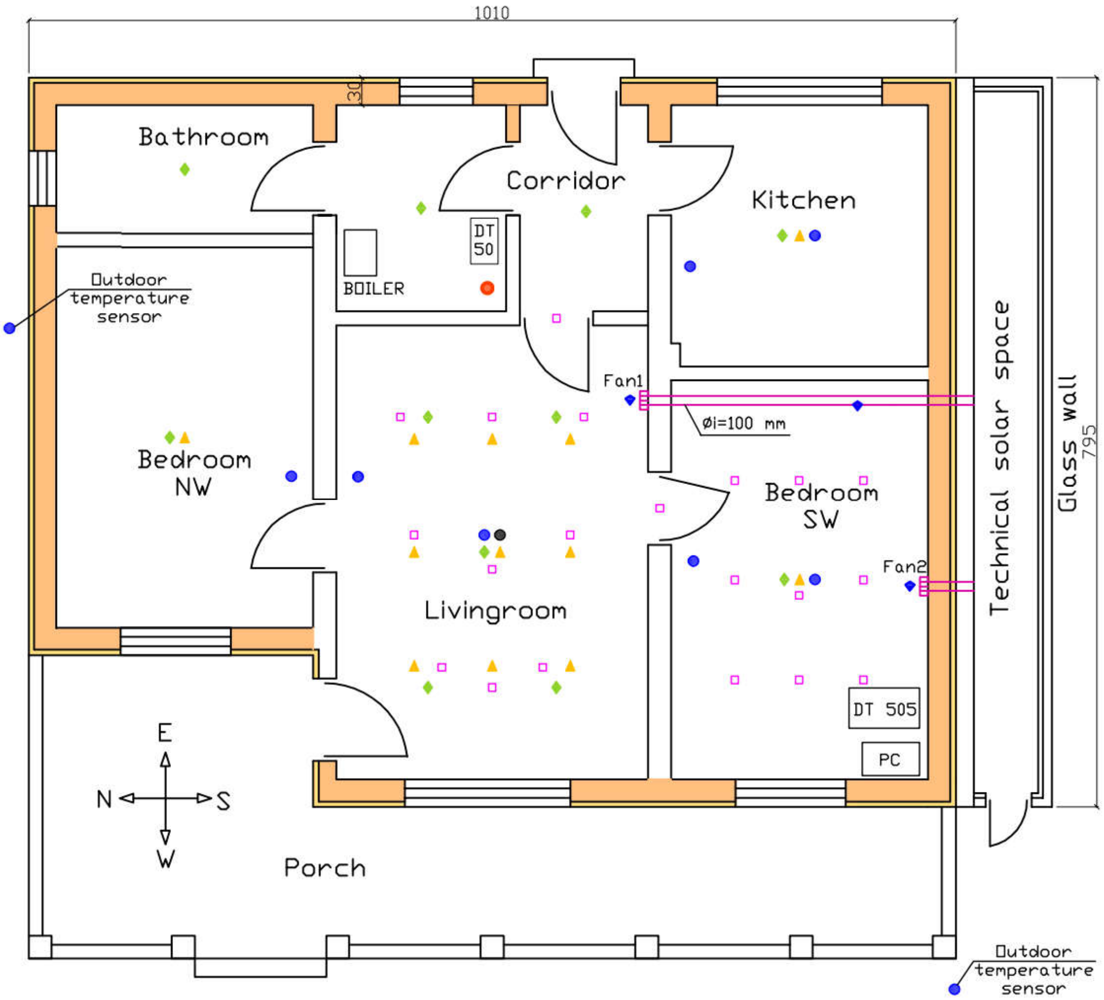


Fig. 4. The experimental house – first floor plan

Sensors locations: • – air temperature; • – mean radiant temperature; ♦ - quantity of fresh air introduced; ♦ – sound pressure level; ▲ – lighting level; □ - the air currents speed; • – energy transducer

- the sound pressure level in each room (green rhombus in Fig. 4). The sound pressure level was measured by means of Bruel&Kjaer Hand-held Analyzer Type 2250, which is a class 1 precision device. For each of 13 ventilation scenarios, the sound pressure level was measured in the centre of each room.

- the lighting level in each room (yellow triangles in Fig 4). 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 currents speed (violet squares from Fig 4). The speed of air currents was measured to find out if the air currents due to the fans are not producing any discomfort sensation. The velocity of the air was measured using a hot wire anemometer, model Testo 425. Sixty measurements of air current speed were carried out in twenty points from living room and north-west bedroom. The first set of twenty measurements were made when only the fan from living room (fan 1) was running. The second set of forty measurements were made when both fans were running at maximum power. Both in the living room and in the bedroom the speed of air currents varied from 0,01 to 0,05 m/s. The maximum current air speed 0,11 m/s was found next to the bedroom door. Using the measured values of the currents air speed, the percentage of people dissatisfied due to draught, DR, was calculated according to (ISO7730, 2005). The value obtained for DR is 2,40%, what it means that 97,60% of occupants are not bothered by draught. In these conditions the recommendations of (ISO7730, 2005) which indicate that 85% of the occupants must not be bothered by the draught are satisfied.

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. 4) with an extension module to increase the number of input channels.

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.

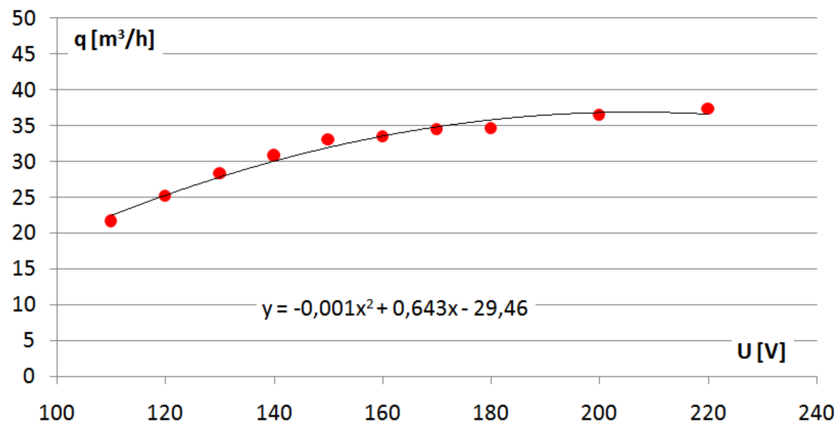


Fig. 5. The variation of airflow.

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.

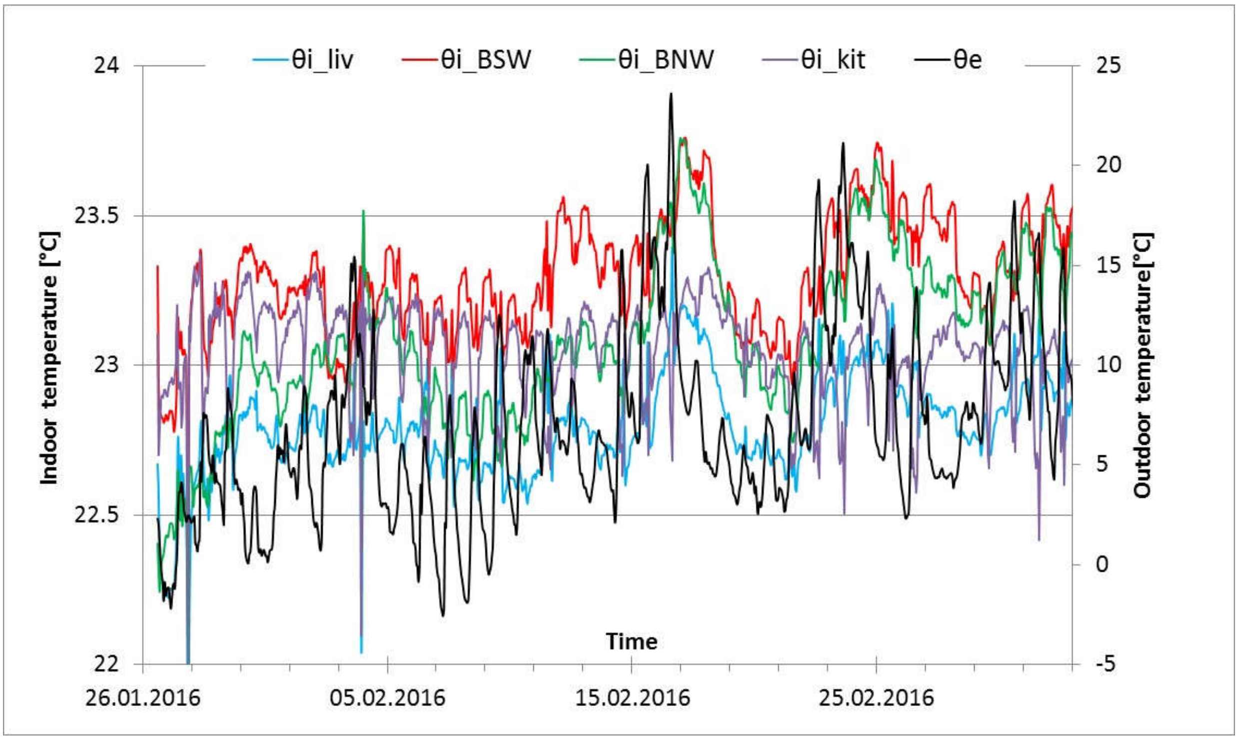
The ventilation air flow was measured for ten different supply voltages of the fan, each situation was further considered as a different building operation scenario (Fig. 5). Varying the ventilation air flow, we obtained 13 different operating scenarios of the building.

4. Results

With all measurement finished we were able to observe and represent as a graph the variations of indoor environment parameters in time. We also analysed the variation of the parameters in different zones of the building and the energy consumed for heating during measurements period.

4.1 The indoor temperature variation

The indoor temperature was maintained at about 23 ^{o}C (Fig 6). The average temperatures inside the experimental house during the period 26.01.2016 - 04.03.2016 were: θ_{m_liv}=22,80 ^{o}C for living room, θ_{m_BSW}=23,30 ^{o}C for SW bedroom, θ_{m_BNW}=23,08 ^{o}C for NW bedroom and θ_{m_kit}=23,05 ^{o}C for kitchen. We notice that there are not significant differences from a room to another (Fig. 7).



θi_liv – indoor air temperature in living room; θi_BSW – indoor air temperature in SW bedroom; θi_BNW – indoor air temperature in NW bedroom; θi_kit – indoor air temperature in kitchen; θe – outdoor temperature

Fig. 6. Indoor and outdoor temperature variations.

The indoor temperature varies simultaneously in most of the time for all rooms. 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 ℃. The biggest temperature difference, 1.02 ℃, was noticed in 27.01.2016 at 21:15 between kitchen (23.13℃) and living room (22.11 ℃). 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 neighboring building which shadows the external walls of bathroom, corridor and kitchen.

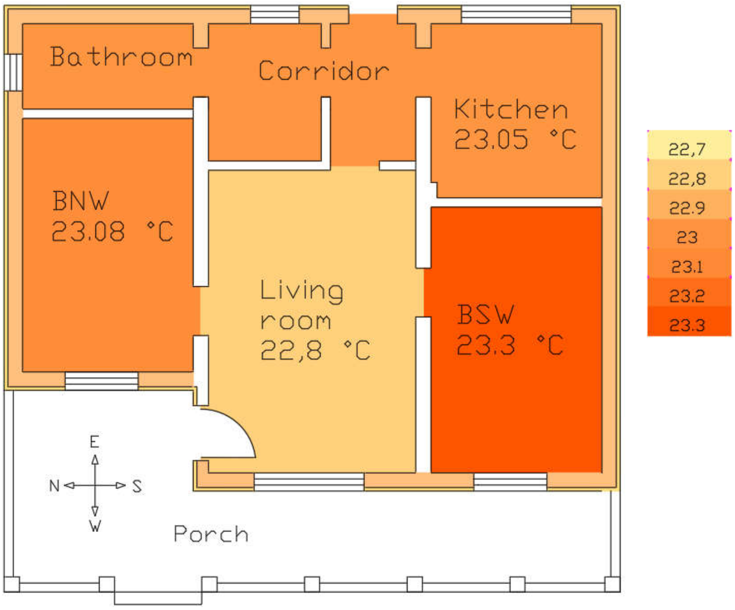


Fig. 7. The averaged indoor temperatures within 26.01.2016 - 04.03.2016 period.

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 living room and in one point for each other room (Fig. 8). 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 for our experimental house and its orientation.
The measurements show us that the lighting level varies from a measurement location to another and also varies in time for each location (Fig. 8). The highest light level was found close to the NW corner of the living room.

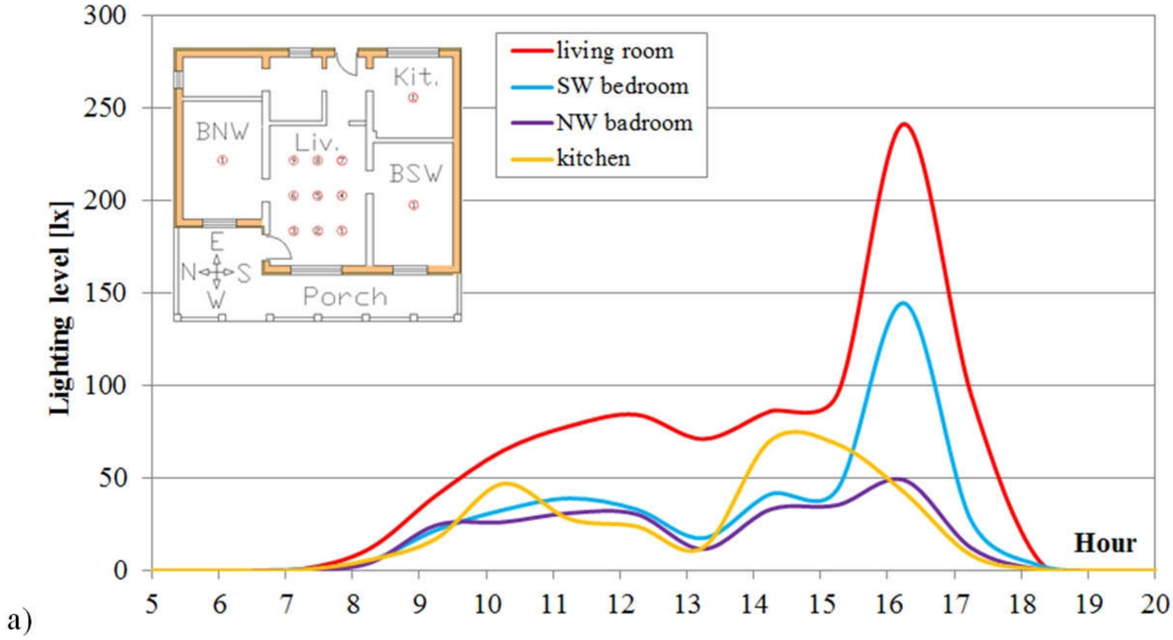


Fig. 8. Variation of the lighting level during the day.

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.

Fig. 9. Lighting level at 16:00 hours.

According with 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 (building D from Fig. 2) which is placed at two meters from experimental building on the eastern side.

The average levels of lighting level within the 10:00÷15:00 were: E_{m_liv}= 233 (lx) for living room, E_{m_BNW}= 85 (lx) for north-west bedroom, E_{m_BSW}= 105 (lx) 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. 8). This is because the biggest window surface is placed on the west wall, resulting in a good lighting in the afternoon.

4.3 The 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 of the experimental building. For that reason, the noise measurements were carried out for 13 different situations depending on the ventilation regime. The results are presented on the chart from Fig. 10.

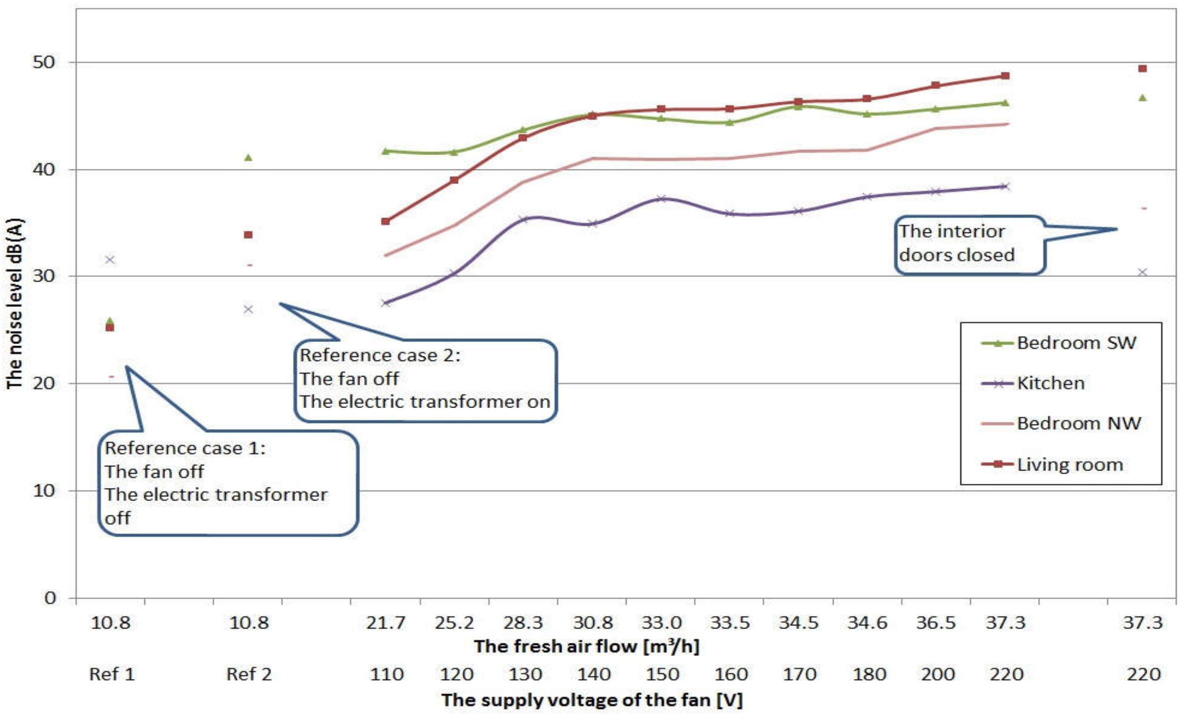


Fig. 10. The variation of the noise level depending on the ventilation regime.

When the fan runs at a low speed (less than 30 m³/h), the most disadvantaged area of the house from acoustic viewpoint is south west bedroom. However, when the airflow is higher than 30m³/h, the living room becomes the noisiest place in the house (Fig. 10). 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. 11) 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, lighting, 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.

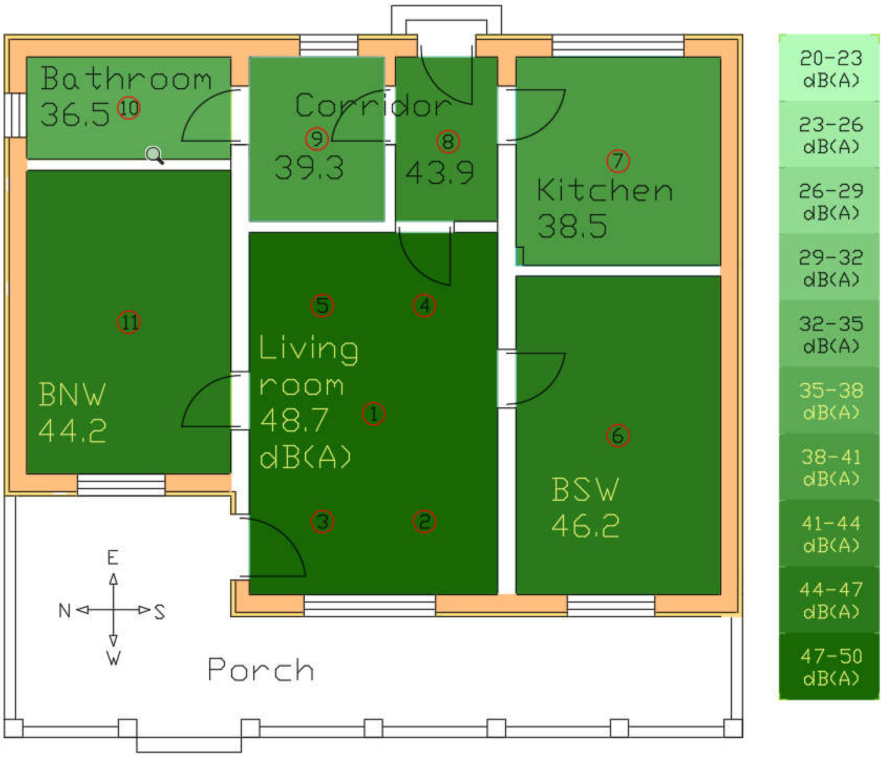


Fig. 11. Sound pressure level distribution during maximum ventilation rate (37,32 m³/h).

Next, we will put the IEQ index that is a weighted average of four comfort indexes in correlation with energy consumption in order to find how much the quality of indoor environment affects the energy that is consumed by the house.

5. IEQ and EC correlation

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. A classification scheme presented by (Catalina and Iordache, 2012), was used to discuss the obtained values of the comfort indexes.

Due to the indoor temperature set point, during the heating system operation, the indoor temperature ensures a good thermal comfort (Fig. 12) 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 conclusion, the indoor acoustic comfort index is inversely correlated with the fresh air flow (Fig. 13).

The visual comfort index in the living room, I_{CV}_livingrom, varies (Fig. 14) 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).

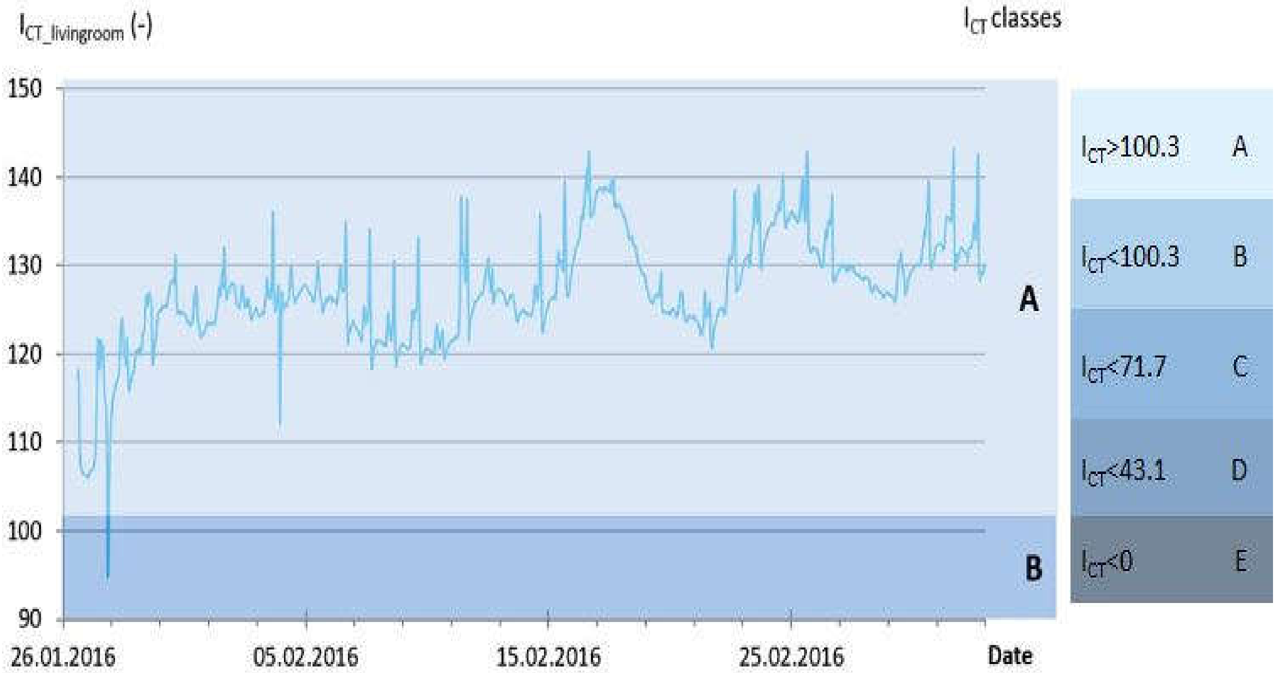


Fig. 12. The variation of the thermal comfort index

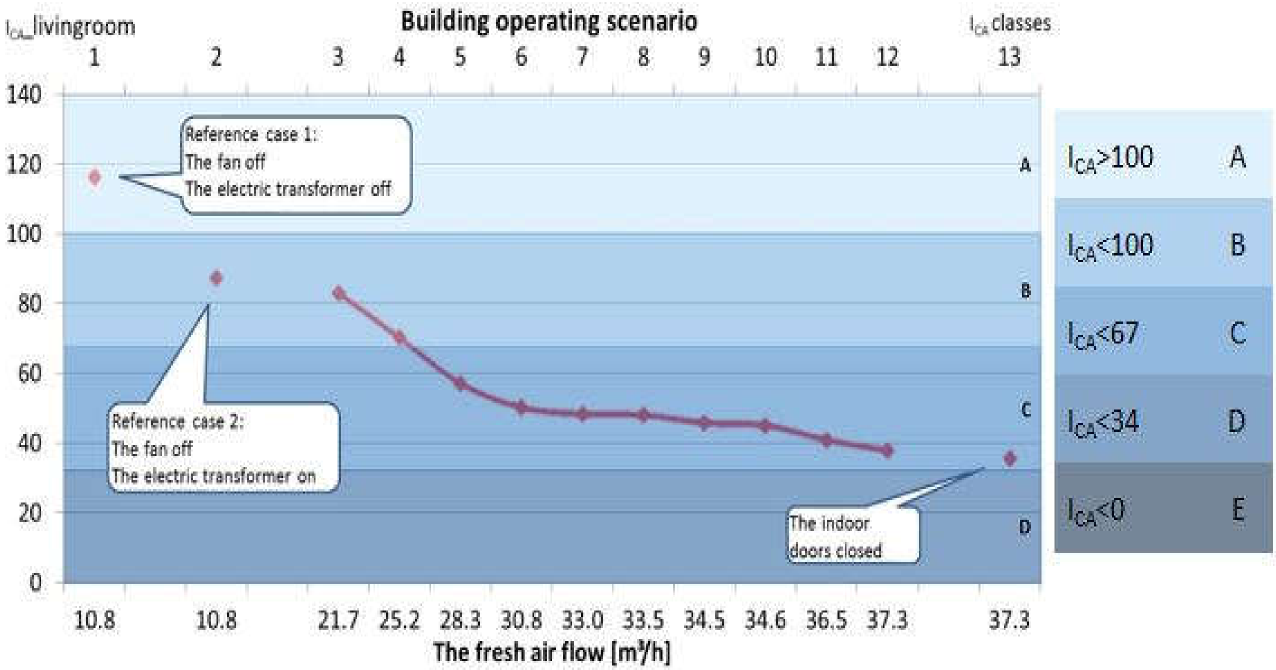


Fig. 13. The variation of the acoustic comfort index depending on the ventilation regime.

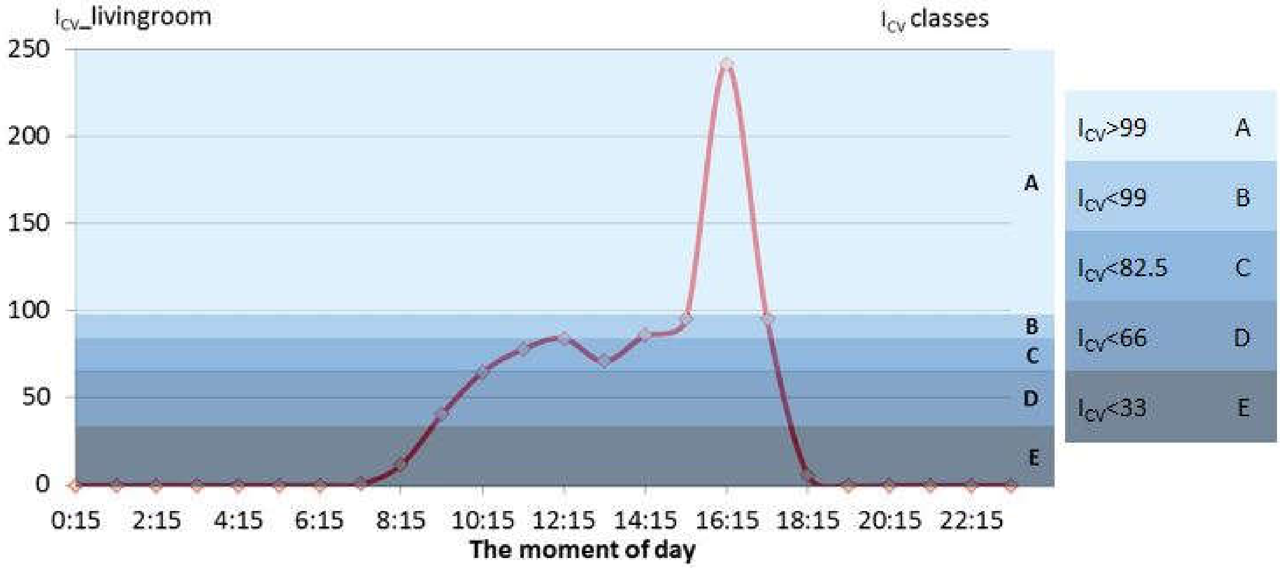


Fig. 14. The variation of the visual comfort index during of a day

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. 15).

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.

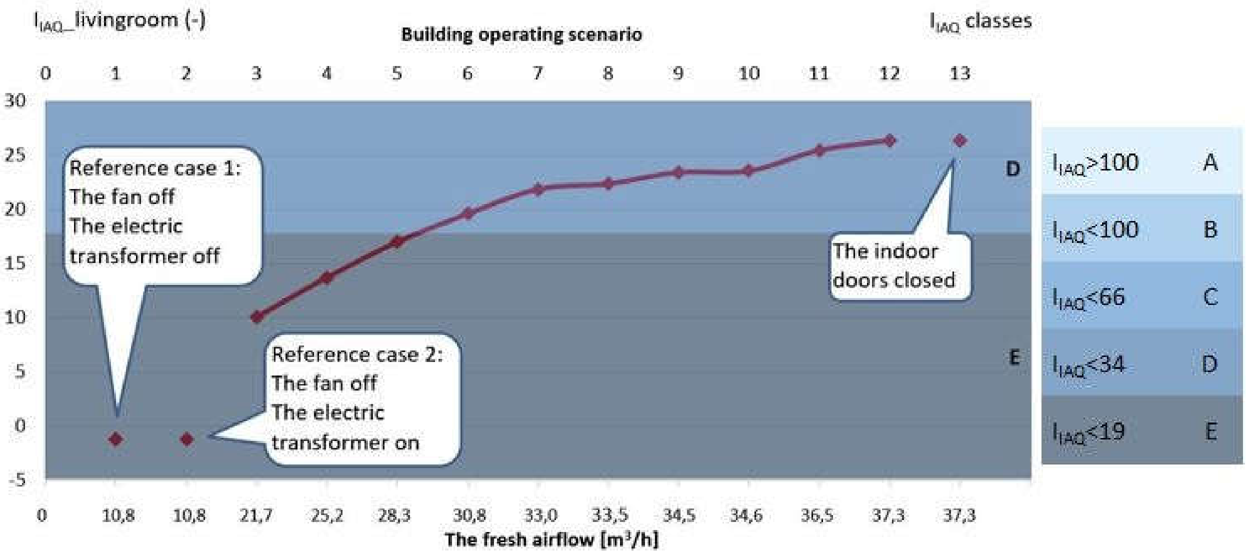


Fig. 15. The variation of the indoor air quality index depending on the ventilation regime

The graphical variation of the indoor environment quality index in the living room, IIEQ_livingroom, (red curve in Fig. 14) 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.

During the measurements predominate the moments when I_{IEQ} fits in class C, 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”. 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 16 and Fig. 14). 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).

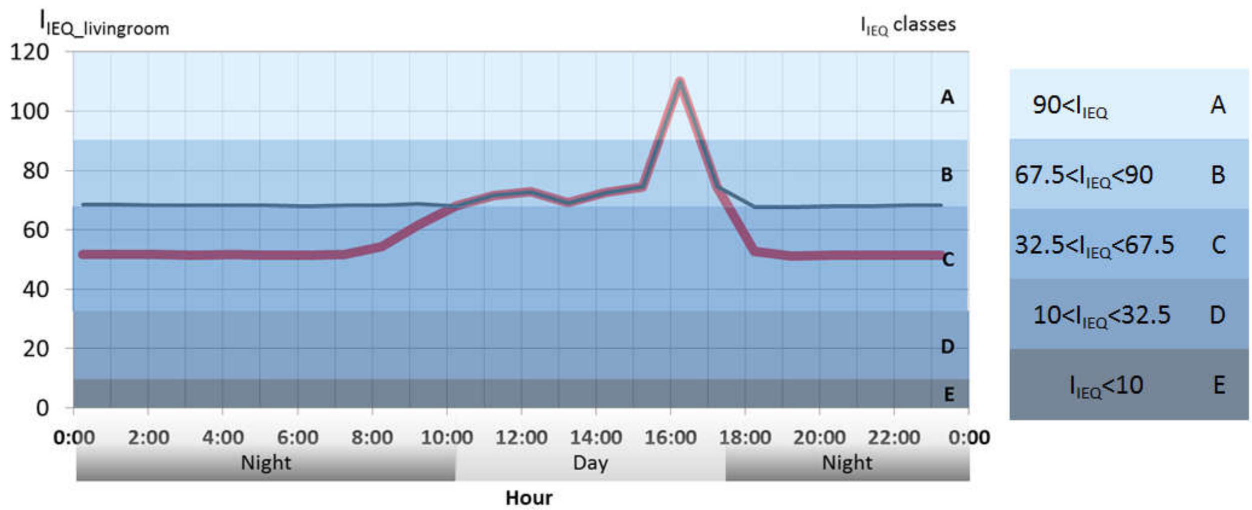


Fig. 16. Indoor Environment Quality index variation in time; red line – constant weights for IEQ index calculation; black line – variable weights for IEQ index calculation

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. Considering 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. 16).

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 20°C. The correlation graph (Fig. 17) was based on a three months measurement period and it shows the experimental points form three different clouds. 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.

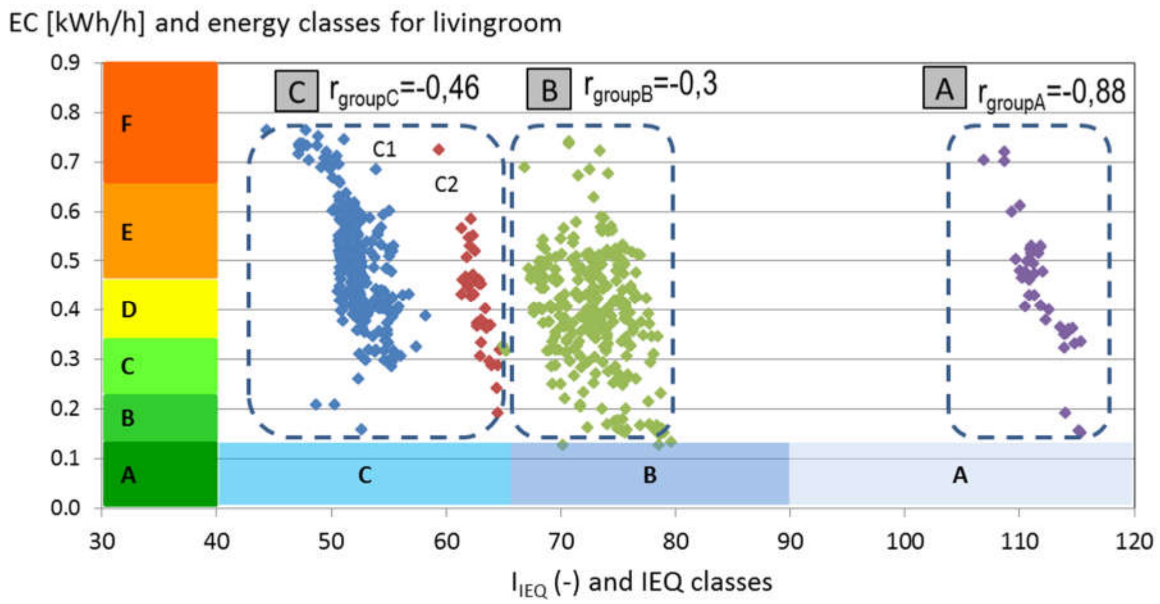


Fig. 17. The relationship between I_{IEQ} and EC. Group A corresponds to the afternoon measurements; Group B daytime measurements; Group C1 corresponds to the nighttime measurements; Group C2 corresponds to the night-day transition measurements.

In order to understand better how big is the energy consume to ensure the determined indoor environment quality for experimental house, we hourly measured the energy consume and we compared it with the energy scale for heating founded in (MC001/3, 2006) and presented in Fig. 18

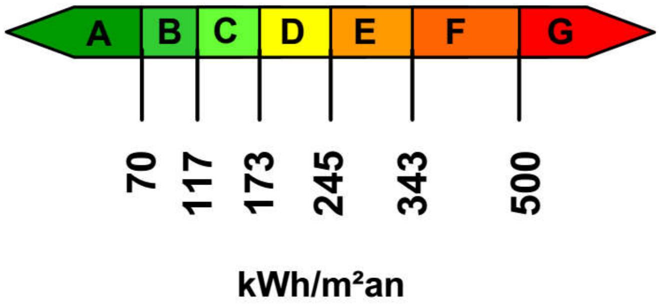


Fig. 18. The energetic scale expressed in kWh/m²year (MC001/3, 2006).

To draw up the chart from Fig. 17 where energy consume is expressed in kWh/h we converted the scale founded in (MC001/3, 2006) from kWh/m²an (mean kWh/m²year) to kWh/h. This conversion is valid just for the living room from the described experimental house. To make this conversion we divided the values expressed in kWh/m²an with the numbers of the hours from a year, 8760. In that way, the energy consume was expressed in kWh/m²hour. Next, we multiply the obtained values with the living room surface. Was thus obtained the scale for energy consume expressed in kWh/h, which is valid just for studied living room (Fig. 19).

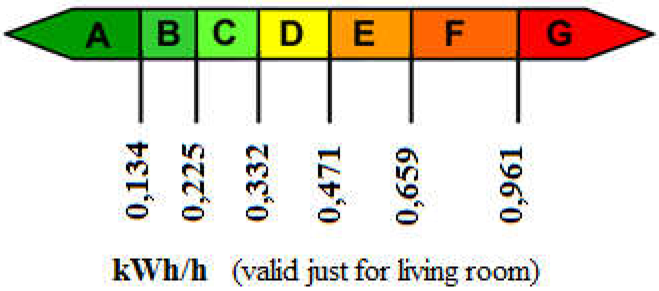


Fig. 19. The energetic scale expressed in kWh/h valid just for studied living room.

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

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

where:

$\overline{I_{IEQ}}$ (-) represents the average value of the indoor environment quality index;

$\overline{EC}$ (-) represents the average value of the hourly energy consumption.

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. 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.

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.

In order to find the influence of the fresh air flow introduced into the room on the I_{IEQ} value, 13 ventilation scenarios were made by varying the fan speed as previously described. The results obtained are presented in Fig. 20. As the fan speed was increased, the I_{IAQ} component of the I_{IEQ} increased, as expected. But, in the same time, the I_{CA} value decreased as a result of the increase of the noise level caused by the running of the fan. As a result, contrary to our expectations, the I_{IEQ} value decreased during all 13 scenarios. The problem was that the positive effect caused by the increase in the fresh air flow was overall lower than the negative effect introduced by the increase in the noise level. Better results should be obtained by using a more silent fan.

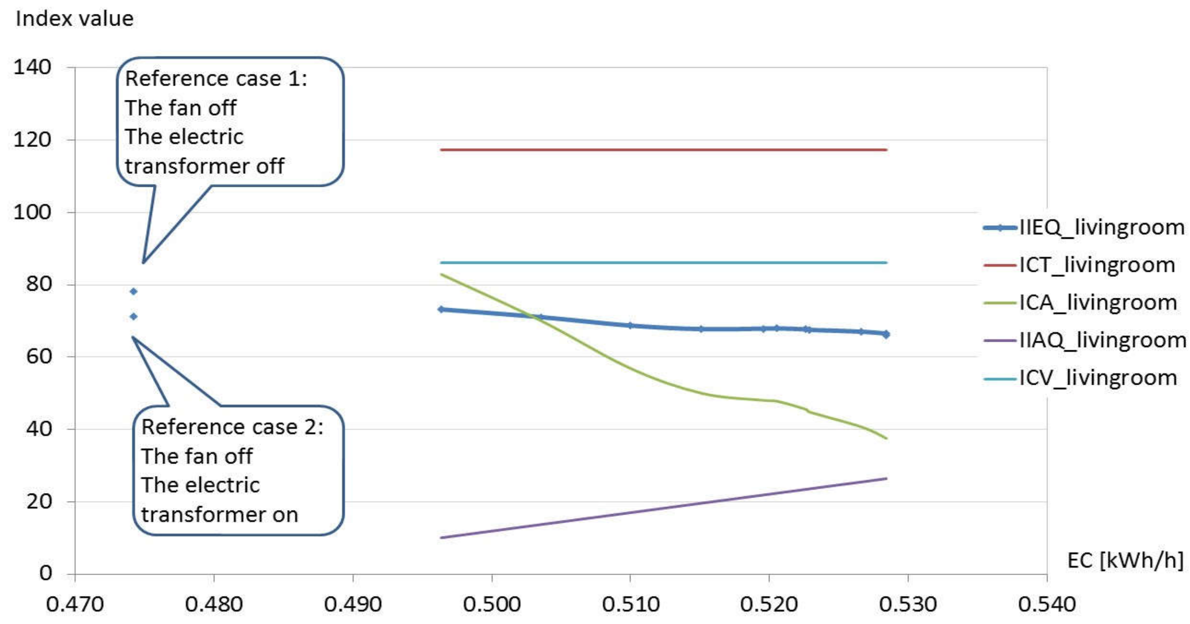


Fig. 20. The relationship between I_{IEQ} and EC in living room when varying the fresh airflow.

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 research report 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. 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).

The balance between the weights of the four indoor comfort indexes has a major influence upon the IEQ index and the correlation degree with the energy consumption. A change of any indoor comfort parameter (due to HVAC design or its operation) will lead to a new correlation different from the one obtained in this baseline study.

Starting from the idea that a good HVAC system designing do well can obtain the best balance between the indoor comfort and the energy consumption, we can sustain 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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