Assessing the energy performance of existing buildings based on measurement data. Case study

A I Dumitrașcu¹, T M Hapurne¹, A L Kadhim-Abid¹ and I Bliuc¹
¹“G.M.Cantacuzino” Faculty of Architecture, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania

E-mail: aura.irina.dumitrascu@gmail.com

Abstract. Energy certification for existing buildings and selecting the most appropriate measures in order to classify these buildings as Near Zero Energy Buildings (NZEB), and therefore complying with specific regulation requirements, implies accessible models and methodologies capable of accurately reflecting the actual energy behavior of buildings and to ensure the optimal quality. Methods based on real data processing, resulting from the monitoring of indoor / outdoor environmental parameters and energy consumption over time, provide results comparable with real scenarios as well as the possibility of validating models and methodologies complying with existing regulations. The method of total heat loss / energy signature, based on the linearity relationship between energy consumption and environmental parameters, is widely used due to its simplicity of application. This method has been used to assess the energy performance for a single-family dwelling designed with a high level of energy efficiency. Results of the analysis revealed an appropriate level of thermal insulation characteristic to the building, reflected in low energy consumption for heating, but also a relatively low thermal inertia, which negatively impacts the energy performance. Comparison between the energy consumption/annual energy demands for heating, determined through various methods, recommends the regression approach as a useful tool for validating the various methods used when estimating the energy performance of existing buildings.

1. Introduction

Energy certification of existing buildings and the adoption of appropriate measures to increase their energy efficiency are one of the main requirements of the European Directive on Energy Performance of Buildings (EPBD, European Union 2003). Compliance with this requirement implies the existence of energy performance assessment methodologies for existing buildings capable of accurately indicating values related to the energy consumption for heating, lighting, ventilation / air conditioning, correlated with real values of environmental quality parameters, IAQ (Indoor Air Quality).

Methods for assessing the energy performance of existing buildings can be classified into two categories [1]:
- methods based on simulation models of building behavior as whole under the influence of environmental factors characterized by the standard values of the characteristic parameters;
- data-driven method (eg regression models) in which input and output data obtained through systematic records, through statistical processing, allow physical model characterization.

Methods related to the second category can not be applied to each building but may be applied to representative building types to provide relevant information on their compliance with the values of...
the results obtained by standard methods, as well as the possibility of estimating the influence of different parameters on energy performance [2].

Several data driven models have been developed, but the most commonly used is the total heat loss / energy signature coefficient.

Recent research has led to the improvement of these models in order to eliminate disadvantages (the difficulty of assessing the effects of thermal inertia and solar intakes) by considering the dynamic effect, which can be highlighted if there are data on the hourly or daily energy consumption correlated with the outdoor/indoormicroclimatic parameters [3].

2. Energy performance indicators

The energy consumption for operating buildings is influenced by a multitude of factors, the most important of which are: volume of the building, degree of thermal insulation of the envelope, ventilation, efficiency of the heating system, existence of solar energy utilization systems, the behavior of the users.

An essential condition for adopting the most appropriate measures for reducing energy consumption for heating is the use of indicators able to integrate the influence of all the above-mentioned factors. In this respect, there have been constant concerns that have led to the setting of performance criteria expressed by indicators, applicable in design or in the assessment of the building in use (post-occupation), providing solid criteria for energy optimization of the building system. Most important of them from this point of view are:

- the global thermal insulation coefficient \( G \), expressed in W/m\(^2\)K, which takes into account heat losses through transmission and ventilation, and allows characterization of the building in terms of volumetric compliance (area/volume ratio), thermal insulation of the building and its envelope; this indicator is used in design and allows the identification of solutions for reducing heat losses through transmission and ventilation;

- specific annual energy consumption for heating \( q \), expressed in kWh/m\(^2\) per year, which also takes into account the building's thermal mass, efficiency of the heating system and the solar inputs depending on orientation;

- the total heat loss coefficient \( K_{tot} \), in kWh/K, referred to as the energy signature or building constant, reflecting its true energy performance, integrating the user behavior; it also allows the evaluation of the influence of thermal mass and, corroborate with the value of \( G \), can also highlight the solar input.

This paper aims to assess the energy performance of a energy-efficient single-family home, characterized by the use of passive solar energy utilization systems and a high thermal insulation by analyzing the correlation between daily energy consumption and indoor/outdoor microclimate parameters.

3. Case study. Energy efficient individual dwelling

3.1 General presentation

The energy performance of a single-family dwelling was evaluated, a house known as the Sibelius wooden dwelling, located in Suceava (figure 1).
Figure 1. Single-family dwelling Sibelius.

From an architectural/functional point of view, the interior spaces revolve around the central green core. The living space (living room, dining room, kitchen, fireplace area, bathroom and annexes for central heating and storage) is situated at ground floor level. Upstairs there are two bedrooms, two bathrooms, a dressing room and a study/library area.

Structurally, the house has a wooden frame structure (pillars and glued lamellar beams) with exterior walls having the following structure:
- Cross Laminated Timber (CLT) - 66 mm;
- thermal insulation of natural cellulose fibers, pumped (120x240mm) - 290mm;
- 35 mm wood-fiber heat-insulating boards, labeled and flame retardant, treated against pests;
- polypropylene microfiber wind and moisture barrier mounted in 1mm system;
- decorative wooden boards, trimmed and fireproof, treated against moisture, ultraviolet radiation and pests, mounted vertically.

The roof has the following structure:
- Cross Laminated Timber (CLT) panels - 80 mm, mounted on wooden beams with 7 ° slope;
- thermal insulation of natural cellulose fibers, pumped (120x240mm) - 320mm;
- 52 mm wood-fiber heat-insulating boards, lacquered and flame retardant, treated against pests;
- wooden boards, ladder and fireproof, treated against moisture, ultraviolet radiation and pests 50x50 mm, mounted with 400 mm span;
- OSB 16 mm plywood;
- polypropylene microfiber waterproofing - 1mm.

3.2 Total heat loss/energy signature coefficient
The physical significance of this indicator can be explained by analyzing the energy equation for heating the building, which expresses that heat losses through transmission and ventilation, $Q_t$, to which the energy stored/restituted by dynamic effect $Q_d$ is added, are compensated by the energy supplied by $Q_s$ heat source and free, solar and internal input $Q_a$ [3]:

$$Q_t = Q_s + Q_d = Q_s + Q_a.$$  \hspace{1cm} (1)

The amount of energy required to compensate for the losses results:

$$Q_c = Q_s - Q_d + Q_a$$ \hspace{1cm} (2)

equation that can also be expressed as:

$$K_t G_x = Q_s - Q_d + Q_a$$ \hspace{1cm} (3)
where \( K_t \) is the total heat loss coefficient without considering the dynamic effect and free input, and \( G_z \), the number of heating days.

Value of the total heat loss coefficient is determined on the basis of actual operating data obtained by monitoring the monthly or daily energy consumption and indoor and outdoor air temperature, monthly or daily averages, using regression analysis.

To estimate the \( K_t \) value, the correlation between external climatic conditions - outdoor temperature values or number of heating days - independent variables - and the corresponding energy consumption as a dependent variable or function [4] is established.

The correlation is linear, expressed by the equation:

\[
y = a + bx
\]

where:
- \( a \) represents the intersection of the regression line with the Y axis, the physical significance being related to the constant consumption of energy for other purposes, other than heating;
- \( b \), the slope of the regression line, which gives the value of \( K_t \).

For a number \( n \), pairs of \( X_i, Y_i \) values - temperature and energy consumption records - the coefficients of the correlation straight line can be determined with the relations:

\[
\begin{align*}
    b &= \frac{(n \sum X_i Y_i - n \sum X_i \sum Y_i)}{(n \sum X_i^2 - (\sum X_i)^2)} \\
    a &= Y_m - bX_m
\end{align*}
\]

where \( Y_m, X_m \) represent the mean values of the variables \( X, Y \).

In order to evaluate the extent to which the determined regression reflects the correlation between the two variables, the correlation coefficient \( r \) is calculated with the relation:

\[
r = \frac{(\sum X_i Y_i - nY_mX_m)}{(\sum X_i^2 - nX_m^2)(\sum Y_i^2 - nY_m^2))}.
\]

The effective value of the correlation coefficient varies between -0.99 and +0.99 and represents the number of values of the dependent variable (energy consumption) whose variation can be explained by the regression correlation. A correlation is significant if the value of the coefficient \( r \) exceeds a certain value depending on the number of observations[4].

The total heat loss coefficient, \( K_{total} \), known as the energy signature or the constant of the building, is a quantification of the real performance of the building over a given period of time.

In order to collect necessary data for the assessment of the energy performance of the Sibelius dwelling for 41 days, between 15.02. and 27.03.2017, the following activities were carried out:

- hourly recordings of the outdoor temperatures values and indoor microclimate parameters;
- daily values of the energy consumption for heating and domestic activities.

Analysis of the average values for outdoor air temperatures and daily energy consumption indicates 3 days with very high energy consumption, compared to the general situation, the statistical analysis being performed with the elimination of the 3 values.
The correlation shown in figure 2 can be expressed using the equation:

\[ y = -7.83x + 134.24 \]  

(7)

Value of the total heat loss coefficient resulting from the correlation is:

\[ K_t = 7.83 \text{ kWh/K day} \]

For the determined correlation coefficient, the value \( r = 0.62 \), higher than \( r = 0.402 \), the minimum limit for 40 observations; this shows that 62% of the pairs of values follow the equation resulting from the regression analysis.

### 3.3 Evaluating the dynamic effect caused by the thermal mass of the building

The contribution of the dynamic effect on the energy requirement for heating is explained by the thermal mass of the building that determines thermal inertia, responsible for the behaviour of the building in a variable thermal regime. In a building with a high thermal mass a certain amount of energy is needed to heat it, but at the same time this heat becomes waste heat when the indoor air temperature is less than the temperature of the surface of the thermal mass elements. In existing buildings, measurement/recording of temperature variation in element mass is very difficult, if not impossible, for which reason indirect methods based on the relationship between outdoor air temperature differences and differences in energy consumption recorded in 2 consecutive days are applied, determined by the effective thermal capacity of the building, \( C_{ef} \). [3]. This can be defined and calculated by the ratio between the oscillation of the energy consumption for heating (thermal load) in 24 hours, \( Q \), at the oscillation of the average outside temperature, \( T_e \), during the same period and the oscillation frequency of these quantities (1/24h), applying the following relationship:

\[ C_{ef} = (Q_k - Q_{k-1})/(T_{e,k} - T_{e,k-1}) \]  

(8)

in which \( Q_k \) and \( Q_{k-1} \) represent the total heat demand (including the energy produced by the heating system and the internal and solar intakes) for 2 consecutive days, k-1 and k. Starting from equation (8) that approximates the effective thermal capacity, its value results as the inverse of the slope of the regression line which reflects the correlation between the temperature differences and the energy consumption differences \( Q_c \):

\[ C_{ef} = 1/p \]  

(9)

where \( p \) is the slope of the regression line resulting from the monitoring data.
Once the actual thermal capacity of the building has been assessed, the dynamic effect on the energy demand for heating is determined using the relation:

\[ Q_{\text{din}} = C_{\text{ef}} \left( T_{e,k} - T_{e,k-1} \right) \]  

where \( T_{e,k} \) and \( T_{e,k-1} \) represent the mean outdoor temperature values for 2 consecutive days.

In order to perform the dynamic correction, start from the energy balance equation (3). The dynamic correction is applied to the recorded energy consumption values:

\[ Q_{\text{cor}} = Q_s - Q_{\text{din}} \]  

Starting from equation (10) that approximates the effective thermal capacity, its value results as the inverse of the slope of the regression line which reflects the correlation between the temperature differences and the energy consumption differences \( Q_c \). For the Sibelius dwelling, the effective thermal capacity results as:

\[ C_{\text{ef}} = \frac{1}{p} = \frac{1}{0.138} = 7.24 \]  

where \( p \) is the slope of the regression line resulting from the monitored data (figure 3).

![Figure 3. Linear regression of the difference in heat load values for two consecutive days and the corresponding mean outside temperature difference. Determination of effective thermal capacity, C_{ef}.](image)

The correlation between the outside temperature and the energy consumption for heating, corrected with dynamic effect is given by the equation:

\[ Y = -10.373X + 150.3. \]  

Value of the total heat loss coefficient, corrected with dynamic effect is \( K_{\text{td}} = 10.37 \text{ kWh/K day} \).

### 3.4 Global Energy Performance Indicators. Comparative analysis

A global assessment of the building's energy performance can be performed knowing the value of the energy consumption/demand for indoor comfort over a year. This indicator can be calculated by different methods and then compared to the actual energy consumption recorded during a heating season.

Most common calculation methods are:

- based on the information provided by the project and according to the following relationship:

\[ Q_{\text{nec}} = 0.024 \times G \times V \times GZ_{\text{inc}} \]  

in which \( Q_{\text{nec}} \) represents the amount of energy required over a given period, in kWh;

\( G \), global heat loss coefficient, in W/m²K;
V, volume of the building, in m³;
- based on the MC001/2005 Building Energy Performance Calculation Methodology, which gives the value stated in the Energy Performance Certificate (CPE) of the building;
- based of the total heat loss coefficient, respectively the energy signature $K_{nt}$.

Table 1 shows values resulting from the above-mentioned methods and the actual energy consumption values for heating during the year 2015.

| Global indicators | Measuring unit | Values |
|-------------------|----------------|--------|
| Annual energy requirement estimated based on the Design Project information (equation 11) | kWh/year | 23281,48 |
| Annual energy consumption for heating, according to CPE | kWh/year | 11432,00 |
| Annual energy consumption estimated based on energy signature | kWh/year | 12330.00 |
| Annual energy consumption (based on bills per year, 2015) | kWh/year | 12304.00 |

Results from the estimation regarding the annual energy consumption based on the total heat loss coefficient, $K_{nt}$, reveals a value very close to the one invoiced by the electricity supplier, which shows a high degree of accuracy of the method. The difference between the estimated energy requirement based on project data according to equation (14) and the actual consumption value is significant (1097.00 kWh) and can be interpreted as a deficiency of the valuation method. At the same time, this difference may also mean that, for the building under consideration, energy needs can be heavily covered by solar and domestic inputs that have not been highlighted.

An estimate of the influence of solar intakes on energy performance implies the existence of detailed data regarding the variation of solar radiation intensity specific to the analyzed dwelling's surroundings and the application of multiple regression models.

4. Conclusion

The energy performance analysis for the single-family dwelling was assessed by the total heat loss coefficient, also known as building constant or energy footprint, resulting from processed data obtained by monitoring energy consumption level and environmental parameters on a relatively long period of time, 41 days. Regarding values of this indicator, the following conclusions can be drawn:

- the total heat loss coefficient, without considering the dynamic effect, has a relatively low value $K_t = 7.83$ kWh/Kday. This value indicates a high thermal insulation of the building and does not reflect the dynamic effects caused by thermal inertia and free inputs (solar and domestic);
- after applying the dynamic correction resulting from statistical calculations, the value of the total heat loss coefficient increases by 24.5%, from $K_t=7.83$ kWh/K to $K_t=10.37$ kWh/K day. This means that a significant part of the energy consumed for operating the heat source and solar intakes is intended to compensate for heat losses caused by the change in outdoor temperature within 2 consecutive days and, implicitly, by the increase in internal temperature of the shutters. The relatively low value $C_{ef} = 7.24$ kWh/K, representing the actual thermal capacity, reflects a reduced thermal inertia of the building.
- the method for assessing an energy performance analysis, based on the relationship between energy consumption and values on environmental parameters - linear regression - proves to reflect the real energy performance of the building. In this case, the annual energy consumption for heating, calculated based on the corrected heat loss coefficient, is considerably close to the actual data recorded. This method can therefore be a useful tool for validating assessment methods by calculating the energy performance of existing buildings.
5. References

[1] Vesterberg J 2014 A regression approach for assessment of building energy performance *UMEA Universitet, Departament of Applied Physics and Electronics Industrial Doctoral School 2014 Sweden*

[2] Hygh J S, DeCarolis JF., Hill B D and Ranjithan SR 2014 Multivariate regression as an energy assessment tool in early building design *Building and Environment* 57 pp165-175

[3] Danov S, Cipriano J and Marti-Herero J 2013 Approaches to evaluate building energy performance from daily consumption data considering dynamic and solar effects *Energy and Buildings* 57 pp110-118

[4] Moss K 2006 *Energy Management in Buildings* (London; New York: Taylor and Francis).

Acknowledgments

This research was undertaken as part of a research project supported by UEFISCDI, Model for a sustainable single-family dwelling integrating architectural concepts and high energy performance systems with minimal environmental impact, PN–III–P2–2.1–BG–2016–0074, Contract 61 BG din 01/10/2016.