Comfort air temperature influence on heating and cooling loads of a residential building

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Abstract. The paper presents the thermal behavior and energy loads of a two-level residential building designed for a family of four, two adults and two students, for different inside comfort levels reflected by the interior air temperature. Results are intended to emphasize the different thermal behavior of building elements and their contribution to the building’s external load. The most important contributors to the building thermal loss are determined. Daily heating and cooling loads are computed for 12 months simulation in Bucharest (44.25ºN latitude) in clear sky conditions. The most important aspects regarding sizing of thermal energy systems are emphasized, such as the reference months for maximum cooling and heating loads and these loads’ values. Annual maximum loads are encountered in February and August, respectively, so these months should be taken as reference for sizing thermal building systems, in Bucharest, under clear sky conditions.

1. Introduction

As emphasized by Perez-Lombard et.al. [1] in a review article from 2008 regarding energy consumption in buildings, the growth in population is accompanied by a rapid increase in energy demand and especially an increase in time spent in buildings and comfort levels inside buildings. The increase rate in building energy consumption was reported at an average rate of 1.5% per annum in Europe and even 4.2% per annum in Spain, reaching in 2004 a value of 37% from total final energy in EU. As reported by [1] citing the International Energy Outlook report, the building energy consumption is forecasted to grow by 34% in 20 years and the most important contribution is associated to heating, ventilation and air conditioning systems, both in residential and non-residential sectors.

The energy loads for house cooling and heating are obviously directly related to geographical location, ambient conditions in terms of exterior air temperature, wind speed and solar irradiation reaching wall surfaces [2], but also to interior air desired temperature level.

Jylha et al. [2] studied a residential building of 133 m² located in southern Finland targeting interior air temperatures of 21.5ºC and 23ºC for heating and 25ºC for cooling, depending on house occupancy. They have used a simulation program for modeling buildings loads, such as HVAC systems, human internal loads, equipment and lighting loads and time-variant solar loads. They have computed heating and cooling demands using different heating and cooling systems, and found that 159.5 kWh·m⁻²/year are required when direct electricity heating and mechanical space cooling systems are used. The lightening loads were evaluated at 24.9 kWh·m⁻²/year. The presented results emphasized a heating
duration from September to April and a cooling period from May to August. They have also predicted the demands on long term on a basis of climate change forecast.

The influence of climate change by considering future climate scenarios on the heating and cooling demands was also studied by Berger et al. [3], for four sample office buildings in Vienna, Austria. They have concluded that the influence of decreasing the internal load by two of its components, energy efficient IT equipment and artificial lightening, is more important on the energy net demand than that of a changing climate, even if a reduced internal load implies lower cooling demand, but also higher winter heating. The authors concluded that the internal load is the most important factor influencing the cooling demand.

Marr et al. [4][3] studied the influence of opening windows and doors on the natural ventilation rate of a residential building showing the importance of openings and exterior-to-interior air temperature difference on the air exchange rates. Fabi et al. [5] proposed a simulation tool for generating a probabilistic approach to model the human behavior related to windows opening and closing. More precisely, the author proposed four models of occupants’ interactions with windows and simulated the energy performance for a bedroom and a living room.

Dong et al. [6] devoted a recent study to the influence of occupancy behavior on residential buildings heating and cooling consumption showing that their behavior can influence up to 30% and 50% respectively from heating and cooling loads. The conducted study targeted low-income families in residential buildings. The occupants’ behavior was also studied by few other papers [7]-[9], underling its importance in energy building equipment and real life. Dar et al. [7] analyzed the most important parameters related to human behavior inside a building that affects heating and energy performance of the building. These are: occupancy behavior, appliance use and family size. Fabi et al. [8] emphasized this aspect from the point of view of heating set point preferences and its influence on indoor air quality and heating demand. Dong et al. [9] proposed a methodology for integrated building heating and cooling control to reduce energy consumption and maintain indoor temperature set-point showing that the heating energy consumption could be saved by 30.1%, while cooling energy by 17.8%.

Angrisani et al. [10] studied microcogeneration in low energy demand buildings and analyzed a residential building and an office one. The residential building was composed of six 100 m² flats disposed in a three floors south oriented roof building. The simulation was performed by TRNSYS software. They have found that for one flat occupied by four persons (two adults and two students) the average annual electricity demand is 3100 kWh/year, coming out 31 kWh·m⁻²/year, and the heating period was considered from October to April in Turin, Italy. The thermal energy demand was reported to be 55 kWh·m⁻²/year for an interior air temperature of 20ºC. They have proposed a microcogeneration system for the building sharing the loads with an office one.

Hanafizadeh et al. [11] proposed a combined cooling, heating and power (CCHP) system for a commercial 26 storeys building in Tehran, Iran. They evaluated electrical, heating, and cooling loads for a typical day in each season during the year in order to properly size the CCHP system. Comfort temperature was chosen 23ºC in January (when the exterior temperature is -4ºC) and 25.5ºC in July (for an ambient temperature of 36.8ºC). The heating and cooling demands were considered to be 12200 kWh for heating in the winter, from November to March, and 22300 kWh for cooling, from May to September.

Mago et al. [13] combined a heating and power system (CHP) to an organic Rankine cycle (ORC) in order to recover the surplus exhaust heat to generate extra electricity for a typical office building of 511 m² floor area. They have studied the same building located in six cities in U.S. under different climate conditions. The authors concluded that the CHP–ORC system performance strongly depends on the location mostly due to the variation of building thermal load. They also suggest coupling ORC to a CCHP system to use exhaust heat for cooling purposes.

A study devoted to cooling demands in residential buildings was developed by Dabaieh et al. [14] for the hot dry climate specific to Cairo, Egypt. They proposed a vault roof (covering 25 m² from a
total roof surface of 25.32 m²) with high albedo coating instead of typical flat non-insulated roofs for decreasing the cooling demand (by 826 kWh/summer season) and inside temperature (by 1.5°C in August), proving that roof shape, material and construction is very important.

Another study devoted to cooling demands in residential buildings was conducted by Wang et al. [12] who compared three types of cooling systems and made recommendations best suited to cold and hot climates.

Concluding the state of the art, there is a focused research on determining energetic demands of buildings and on finding ecologic solutions for sustaining the required heating and cooling demands. These demands are very important to be determined as they are used to size the energetic systems of the building. The heating and cooling loads depend, among other factors, on comfort conditions selected inside the building. As one may notice, different inside air temperature levels were chosen by the authors, influencing the internal load of a building and consequently dictating the cooling demand.

This paper targets the simulation of daily heating and cooling demands of a two-storeys residential rural building located in Romania, Bucharest (44.25°N latitude) depending on interior air temperature setting value, continuing a previous work on the subject [15]. Heat gains and losses through building’s walls, as well as household occupancy and lighting system loads are computed as time dependent variables, according to heat transfer laws and valid structural design norms. Weather data are considered on a time step of ten minutes; exterior air temperature measured data are employed [16], while the solar irradiation is computed by using Hottel and Worte model [17] for clear sky conditions. Hourly heat transfer rates exchanged by each room of the building are emphasized. They put into evidence the effect of room orientation, number of exterior walls and floor level on the thermal exchange. Also, the thermal behavior of each type of building element is emphasized. Cooling and heating loads are determined for different interior air temperatures. The maximum annual values determine the reference months for sizing energy systems. These results are useful when designing a house for minimum energy consumption, keeping in mind the thermal behavior of building elements.

2. Building description
The studied residential building is composed by two storeys, as presented in figure 1. The ground-floor has a living surface of 73.65 m² and is divided into a distribution hall, a kitchen, a bathroom, a bedroom and a living-room, as presented in figure 2. The first-floor, of 59.05 m², is composed by two bedrooms and a bathroom, and the distribution hall. Between the two levels, a stairs hall exists.

The structure of building elements is presented in table 1. The walls are made of autoclaved aerated concrete brickwork and exterior insulated with 10 cm polystyrene. Windows are thermo-insulated and double glazed ones. The roof is in V shape, East-West oriented.

In order to compute the heat rates by each element of the building, the following code is introduced: an element will be denoted by the letters specified in table 1, its orientation and the room number as presented in figure 2. For example, the exterior wall of the ground-floor living room, which is room number 2, is oriented towards West direction. Thus, it will be denoted by PE-W-2. In the same manner, the exterior window of the first-floor bathroom is denoted FE-E-10. These notations will be used in Results section.

3. Mathematical model
In order to compute the heating or cooling demand of the building, one should sum up the external and internal loads. The external load counts for all heat exchanges between the building and exterior air, through all building elements (walls, doors, windows, roofs, basements). The internal load considers sensible and latent heat rates corresponding to perspiration and exhalation of occupants, humidity sources, heat gains from electronic equipment, appliances and artificial lightening [18].

3.1 External load
The heat exchange rates between the above described building and the ambient are computed on a 10 minutes time basis. The sign convention is the following: heat rates entering the system (i.e. the
building) are positive, while heat rates exiting the system are negative. Thus, all heat gains counting in the cooling load are positive quantities and all heat losses counting in heating load are negative.

The following input data are considered: exterior air temperature $t_E$, as measured and reported by [16], solar irradiation on a horizontal plane $I_T$ and on a tilted plane $I_{Tt}$ as computed using Hottel and Woertz model applied at 44.25 N latitude in clear sky conditions [19]-[20].

The heat gains and losses are computed according to standard norms [21]-[22]. Heat rates exchanged through exterior building elements (exterior walls, windows and doors) and interior ones (interior walls, doors, floors, ceilings) are computed taking into account thermal inertia for the walls.

**Figure 1.** Street view of the two-storeys residential building.

![Street view of the two-storeys residential building](image1)

**Figure 2.** Building plans for the ground-floor (a) and first-floor (b).

![Building plans for the ground-floor and first-floor](image2)
Table 1. Structure of the building elements.

| Nr. | Wall                  | Notation | Structure, from exterior to interior | Thickness cm |
|-----|-----------------------|----------|--------------------------------------|--------------|
| 1   | Exterior Wall         | PE       | exterior coating                     | 0.5          |
|     |                       |          | expanded polystyrene (as insulation) | 10           |
|     |                       |          | interior mortar coating              | 3            |
|     |                       |          | autoclaved aerated concrete brickwork | 25           |
|     |                       |          | interior mortar coating              | 2            |
| 2   | Interior wall         | PI       | interior mortar coating              | 2            |
|     |                       |          | autoclaved aerated concrete brickwork | 25           |
|     |                       |          | interior mortar coating              | 2            |
| 3   | Floor/basement        | PPS      | woodline parquetry                   | 2            |
|     |                       |          | dig                                   | 5            |
|     |                       |          | extruded polystyrene                 | 10           |
|     |                       |          | reinforced concrete                  | 15           |
|     |                       |          | gravel                                | 10           |
|     |                       |          | soil                                  | 10           |
| 4   | Ceiling above the ground floor | PPP | woodline parquetry                   | 2            |
|     |                       |          | dig                                   | 5            |
|     |                       |          | reinforced concrete                  | 12           |
|     |                       |          | interior mortar coating              | 2            |
| 5   | Mansard ceiling       | PPE      | dig                                   | 5            |
|     |                       |          | extruded polystyrene                 | 10           |
|     |                       |          | reinforced concrete                  | 12           |
|     |                       |          | interior mortar coating              | 2            |
| 6   | Exterior window       | FE       | double glazed                        | 7            |
| 7   | Exterior door         | UE       | Metallic, interior insulated         | 8.7          |
| 8   | Interior door         | UI       | Wood                                 | 2            |

Their sum represents the total heat rate exchanged between the building and the environment:

\[
\dot{Q}_e = \dot{Q}_{PE} + \dot{Q}_{FE} + \dot{Q}_i
\]  

where: \( \dot{Q}_{PE} \) is the heat rate, in W, exchanged by the exterior walls (denoted PE according to table 1), characterized by a certain thermal inertia (elements opaque to solar radiation); \( \dot{Q}_{FE} \) is the heat rate, in W, exchanged by the exterior windows (FE according to table 1), elements without thermal inertia; \( \dot{Q}_i \) is the heat rate, in W, exchanged between the interior elements (interior walls).

3.1.1 Heat rates exchanged by the exterior walls. The considered global heat transfer consists of external and internal convection and wall conduction. The wall thermal inertia involves a phase shift \( \varepsilon \) between the time for computing the inside wall temperature and the exterior air temperature. When computing the heat rate at time \( \tau \), the exterior air temperature will be taken at time \( \tau - \varepsilon \). Temperature oscillations are considered by introducing a damping coefficient, \( \eta \), which depends on wall structure. The heat rate is then computed as [21]:

\[
\dot{Q}_{PE} = k \frac{A(T_{ESm} - T_i)}{A} + \alpha_i A (T_{ES} - T_{ESm}) \eta
\]

where: \( A \) is the wall heat transfer surface, in m\(^2\); \( k \) is the global heat transfer coefficient, in Wm\(^{-2}\)K\(^{-1}\), computed as:
\[ k = \left( \frac{1}{\alpha_i} + \frac{1}{\alpha_e} + \sum \frac{\delta_j}{\lambda_j} \right)^{-1} \]  
\( \delta \) and \( \lambda \) are the wall thickness, in m, and thermal conductivity, in Wm\(^{-1}\)K\(^{-1}\), respectively, for the wall structure specified in table 1; for exterior walls, the term \( \sum \delta_j/\lambda_j = 3.165 \) Wm\(^{-2}\)K\(^{-1}\); \( \alpha_i \) is the interior convection heat transfer coefficient (8 Wm\(^{-2}\)K\(^{-1}\) for walls and 5.8 Wm\(^{-2}\)K\(^{-1}\) for ceilings); \( \alpha_e \) is the exterior convection heat transfer coefficient (17.5 Wm\(^{-2}\)K\(^{-1}\)).

The heat exchange is considered between the interior air at temperature \( T_i \), in K, and the sunny exterior air temperature \( T_{ES} \), in K. The last one is computed based on energy balance on wall surface:

\[ T_{ES} = T_e + I_{\alpha} \alpha / \alpha_e, \]
where \( \alpha = 0.91 \) is the solar energy absorption coefficient for the wall exterior coating. The temperature oscillations are considered by the last term in equation (2); \( T_{ES} \) is the daily mean sunny exterior air temperature, computed in the same manner as \( T_{ES} \): \( T_{ES} = T_{Em} + I_{\alpha} \alpha / \alpha_e \).

The solar irradiation \( I_{\alpha} \) incident on the wall surface is computed taking into account its orientation with respect to East-West axis specified by the solar azimuth angle (0° due to South orientation).

The phase shift \( \varepsilon \) and the damping coefficient \( \eta \) are computed based on an algorithm presented in a Romanian norm for computing thermal stability of building elements [23]:

\[ \frac{1}{\eta} = 0.9e^{\sum_{k=1}^{n} s_{j} (s_j + B_j) (s_j + B_j - 1) (s_j + B_{j-1}) \left( \frac{B_j + \alpha_e}{s_j + B_{j-1}} \right)} \]  
\[ \varepsilon = \frac{24}{360} \left( 40.5 \sum R_{ij} - \arctg \frac{\alpha_j}{B_j + \alpha_j} + \arctg \frac{B_j}{B_j + \alpha_j} \right) \]  
[in hours]

where, for each wall layer \( j \):
\( R=\delta/\lambda \) is the layer thermal resistance; \( s = 8.5 \cdot 10^{-3} (\delta \rho) / \lambda \) Wm\(^{-2}\)K\(^{-1}\) is the layer heat assimilation coefficient; \( \rho \) is the layer material density and \( c_p \) its specific heat;

\[ B_j = \left\{ \begin{array}{l} s_j / (\delta / \lambda) s_j^2 + B_{j-1} \left[ 1 + (\delta / \lambda) B_{j-1} \right] \quad \text{if} \left( \delta / \lambda \right) > 1 \\ s_j^2 + B_{j-1} \left[ 1 + (\delta / \lambda) B_{j-1} \right] \quad \text{otherwise} \end{array} \right. \]

For the exterior wall structure specified in table 1, \( \eta = 0.0041 \) and \( \varepsilon = 11.7942 \) hours. For the ceiling, \( \eta = 0.0116 \), \( \varepsilon = 6.7618 \) hours.

Similarly, but without thermal inertia, heat rates exchanged through open exterior doors were computed and added to the total exterior load:

\[ \dot{Q}_{thermal} = k_{UR} A_{d} n_o (T_e - T_i) \]  

The coefficient \( k = 0.36 \) Jm\(^2\)K\(^{-1}\) was considered and the number of air exchanges per hour \( n_o \) was set as 1 at 7 AM (as people leave the house), and respectively 2 at 2 PM and 6 PM.

3.1.2 Heat rates exchanged by the exterior windows. These heat rates represent the contribution of two components, namely \( \dot{Q}_{solar} \) due to solar direct, \( I_{solar} \), and diffuse, \( I_{diffuse} \), radiation falling on window surface and \( \dot{Q}_{thermal} \) due to temperature difference between exterior and interior air:

\[ \dot{Q}_{FE} = \dot{Q}_{solar} + \dot{Q}_{thermal} \]

where:

\[ \dot{Q}_{solar} = c_1 c_2 c_3 (A_{GS} I_B + A_{GT} I_D) \]  

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where:

\[ \dot{Q}_{solar} = c_1 c_2 c_3 (A_{GS} I_B + A_{GT} I_D) \]
in which:  \( c_1 = 0.9 \) for double glazed window;  \( c_2 = 0.6 \) for light colored interior blinds;  \( c_3 = 0.6 \) for metallic windows [21];  \( m \) is a heat accumulation coefficient whose hourly values are taken from [21]; the sunny glass surface  \( A_{GS} \) was considered equal to the total glass one  \( A_{Gt} \), considering no shading on window surface.

\[
\dot{Q}_{\text{thermal}} = k_G A_{Gt} (T_{ESG} - T_i)
\]  \( (10) \)

For double glazed windows,  \( T_{ESG} = T_e + 2A_{GS}(1 - A_{Gi}) \frac{H_i}{\alpha_e} \). The global coefficient of heat transfer is  \( k_G = 2.56 \text{ Wm}^{-2}\text{K}^{-1} \).

### 3.1.3 Heat rates exchanged through interior elements

This heat transfer is considered through interior walls, doors, floors, and is computed as:

\[
\dot{Q}_i = k_R A_R (T_R - T_i)
\]  \( (11) \)

where the subscript  \( R \) refers to the studied interior element.

The temperature difference  \( (T_R - T_i) \) is computed as [21]:

- \( (T_R - T_i) = 2\text{K} \) if the wall of the next room is N-W, N or N-E oriented;
- \( (T_R - T_i) = 3\text{K} \) if the wall of the next room is E oriented;
- \( (T_R - T_i) = 4\text{K} \) if the wall of the next room is S-E, S or S-W oriented;
- \( (T_R - T_i) = 5\text{K} \) if the wall of the next room is W oriented.

The global coefficient of heat transfer,  \( k_R \), is computed by applying eq. (3) using  \( \alpha_i \) instead of  \( \alpha_e \).

The term  \( \sum \frac{\delta_i}{\lambda} = 0.876 \text{ Wm}^{-2}\text{K}^{-1} \) for interior walls structure,  \( 2.706 \text{ Wm}^{-2}\text{K}^{-1} \) for the floor,  \( 0.21 \text{ Wm}^{-2}\text{K}^{-1} \) for the floor above ground floor,  \( 2.394 \text{ Wm}^{-2}\text{K}^{-1} \) for the ceiling and  \( 0.431 \text{ Wm}^{-2}\text{K}^{-1} \) for the interior doors.

### 3.2. Internal load

The internal loads are released by sensible and latent heat of occupants, electric equipment and appliances, and sensible heat of artificial lightening. Sensible heat represents radiative and convective heat, while latent heat is heat gain from moisture transfer.

The total (sensible and latent) heat gain due to occupants activity is computed as:

\[
\dot{Q}_H = \dot{q}_H n_H
\]  \( (12) \)

where  \( n_H \) represents the number of occupants inside a room,  \( \dot{q}_H = 368 \text{ kJ hr}^{-1} (102 \text{ W}) \) corresponding to the average metabolic rate of an adult male at rest.

The heat gain due to humidity sources is:

\[
\dot{Q}_w = \dot{m}_w h_w = (\dot{q}_w n_H + \sum \dot{m}_{w_i}) h_w
\]  \( (13) \)

where  \( \dot{q}_w = 0.0632 \text{ kg humidity hr}^{-1} \) is the average amount of water vapors eliminated by human respiration and perspiration,  \( \sum \dot{m}_{w_i} \) is the total amount of water vapors absorbed or condensed on different elements inside the room,  \( h_w = 2500 + 1.88 t_i \) in Jkg\(^{-1}\), is the water vapor enthalpy at interior air temperature  \( t_i \) in °C.

The heat gain due to artificial lightening:

\[
\dot{Q}_{LS} = a \cdot n_{LS} P_{LS}
\]  \( (14) \)

where  \( a \) is a simultaneous coefficient showing the percent of light on,  \( n_{LS} \) is the number of light sources,  \( P_{LS} \) is the power of each light source (60 W for bulbs).

The number of occupants and the periods of operation for light sources were estimated as time-dependent considering that the building is occupied by a family of four, two adults and two students,
and the simulation is done for working days. Different time periods for winter and summer activities are considered, as one can see reflected in Results section.

3.3 Total load
The total load is the sum of all above mentioned contributors:

$$Q_T = Q_E + Q_H + Q_W + Q_LS$$  (15)

According to the considered sign convention, a positive value represents the cooling demand, while a negative value represents the heating demand.

4. Results and discussions
The sensitivity of the heating and cooling loads to the thermal comfort level set inside the building is analyzed. The most sensitive contributor is emphasized and solutions for diminishing the building energy consumption keeping the same thermal comfort level are discussed.

4.1 Thermal behavior of the building
Firstly, an interior temperature of 25°C is targeted, for which the thermal behavior of the building has been analyzed without applying any cooling or heating load.

4.1.1. Influence of exterior walls.
Figure 3 reveals the external load of each room of the building in July (figure 3 (a)) and in January (figure 3 (b)). As one may see, in July all heat load values are positive, meaning heat gains for the building and thus contributing to the building cooling demand. Also, one might notice that the highest heat gains belong to rooms having exterior walls orientated towards East, West or South (bedrooms, living-room and kitchen), namely exterior walls facing the Sun along the day.

In January, the heat loads are predominant negative, contributing to the building heating demand. Although, there is a period of few hours in the middle of the day in which the external load is positive, depending on room orientation and number of exterior walls. As revealed by figure 3 (b), the two bathrooms and stairs halls at the ground-floor and first-floor have negative loads all day long; these rooms have two exterior walls each and the highest surface is North oriented without seeing Sun.

Contrary, the ground-floor kitchen, also having two exterior walls, has the highest exterior wall surface South oriented, seeing the Sun during the day, so that a positive external load is met for few hours. The rest of positive loads in January characterize rooms having only one exterior wall.

4.1.2 Influence of room orientation.
Another characteristic of the building thermal behavior is linked to the room orientation. Both figures revealed that East oriented rooms have a heat gain peak before noon, as Sun is climbing the sky and is seeing East walls of the building. Contrary, the West oriented rooms have the peak after noon, as Sun goes down towards West. The rooms with South oriented walls (the kitchen) encounter the peak exactly at noon, as the azimuth angle is zero.

The peak value is obviously lower in winter (January, figure 3 (b)) than in summer (July, figure 3 (a)) and it also appears closer to noon in winter and further from noon in summer. This is due to a shorter path of the Sun in the sky during winter, respectively late sunrise hours and early sunset hours, as comparing to summer longer path, earlier sunrise hours and later sunset hours.

4.1.3 Influence of room level.
Comparing the thermal behavior of the same dimensions and orientation rooms at the ground-floor and first-floor (for example East Bedrooms 3 to 9, West rooms 2 to 8, Bathrooms 5 to 10, or Stairs Halls 6 to 11), one may notice that in July (figure 3 (a)) the first-floor rooms have higher heat gains. This is due to the fact that the ground-floor rooms reject part of the heat gain through the floor, while the first-floor rooms are continuously heated through the ceiling.

In January (figure 3 (b)), the ground-floor rooms also have a better thermal behavior in comparison to first-floor ones, requiring slightly lower heating energy. External load losses are lower in absolute value for ground-floor rooms, while external load gains during the daylight are higher.
The only exception is the first-floor East oriented bedroom which has higher heat gains for few hours, due to direct Sunlight during morning.

4.1.4 Influence of building elements. Figure 4 emphasizes the contribution of each building element to the total external load of a room with small window. Two characteristics might be noticed. The first one is linked to thermal inertia of each contributor. Elements without thermal inertia (e.g. windows) present heat gains as long as they are directly heated by Sun. The East oriented window of the first-floor bathroom (element FE-E-10 in figure 4) presents heat gains from sunrise to noon, as much as the window is in direct sunlight. A different behavior is observed for elements with thermal inertia (e.g. external walls). The East oriented wall of the same room (element PE-E-10 in figure 4) begins rejecting heat inside at about 4 PM, attaining the peak around 8 PM, although it was subjected to direct
sunlight for the same period as the previously discussed FE-E-10 window. This is due to the fact that
heat is absorbed and stored by the wall, being released with a phase-shift computed by eq. (5). As
mentioned in paragraph 3.1.1, the phase-shift for the considered exterior wall structure is about 12
hours (more precisely, 11 hours and 48 minutes). It implies that heat captured around 8 AM by the
wall is released inside at 8 PM.

A particular aspect is emphasized by the North oriented wall, PE-N-10. The two peaks observed in
figure 4 correspond to the two very short periods during which this wall is seeing the Sun. In summer
time, Sun rises and sets behind the East-West line, so that there are two periods with direct sunlight on
a North oriented surface, in clear sky conditions.

Figure 4. Hourly heat rates through different building elements of one room
with small window, in July.

Figure 5. Hourly heat rates through different building elements of one room
with large window, in July.
The second important characteristic is the magnitude of heat gained by each element. Comparing windows to external walls and taking into account their surfaces, one may notice that windows are a more important contributor to heat gains inside the building.

This is also emphasized by figure 5, where a larger window room is presented. The gain through external window FE-E-3 of surface 1.44 m² is much higher than that through the 8.65 m² wall PE-E-3 on which it is mounted. When referring to 1 m² of element, the peak heat gain through an exterior window is about 313 Wm⁻², while the exterior wall contributes with 3.5 Wm⁻².

These results are useful when designing a house for minimum energy consumption, keeping in mind the thermal behavior of each type of element.

4.2. Cooling and heating loads
The above described external loads dictate the required cooling or heating profiles.

Summing up the heat rates exposed in figure 3 for all rooms, the building total external load is obtained. Internal loads corresponding to a family of four are added to the total external load and the corresponding daily profiles are presented in figure 6 for 12 months simulation.

Positive total loads need to be rejected from the building in order to maintain a constant set interior temperature, thus they represent the cooling load of the building. Negative total loads need to be brought from exterior, so they represent heating load of the building. As one may notice, heating is required during night from November to March, while cooling appears useful from April till October. The longest period for heating is needed in January, while the longest period for cooling is unavoidable in August.

Whatever the month is, three peaks are emphasized for each daily profile. The first one is put into evidence around 8 AM, the second appears at 2 PM while the last one is around 4 PM during winter and 7 PM during summer. They correspond to occupants’ activity hours inside the building and are considered through the internal load contribution. A step downwards is met around 10 PM in summer or 9 PM in winter corresponding to the moment when occupants are suspending their activity. The cooling load records a daily minimum around 5 AM and a daily maximum at 2 PM in the cooling season (from April to October). When analyzing the heating load during the heating season (from November to March), one observes that the maximum is recorded around 5 AM, too.

In figure 7 one may observe the monthly variation of the total building load at 5 AM (to be interpreted as heating maxima in the heating season), 2 PM (to be interpreted as cooling maxima in the cooling season) and other two hours during the day, namely at 12 AM (solar noon) and 8 PM. These

![Figure 6. Total hourly cooling and heating loads of the building over the year.](image-url)
maxima are essential in sizing thermal energy systems of the building. As revealed by these variations, February should be the reference month for sizing the heating system, while August should order the cooling system capacity.

An unusual behavior is met in May, as the cooling demand is higher than in June. This is due to the considered experimental data for ambient temperature. The four-year average of ambient temperature in May is higher than the one recorded for June. Thus, the computed cooling demand has higher values in May in comparison to June. Ambient temperature average data may be analyzed in Table 2.

4.3. Building energy consumption

The hourly loads previously determined reflect the daily energy consumption of the building which is presented in figure 8. As one may notice, there are five months requiring heating during night (blue bars in figure 8), even if there is a small heat gain during the day (red bars in the period November – March).

| Month, Hour | 9 AM | 12 AM | 2 PM | 4 PM |
|-------------|------|-------|------|------|
| January, 1st | -0.2 | 0.7 | 1.9 | 1.9 |
| February, 1st | -1.9 | 0.5 | 0.9 | 1.0 |
| March, 1st | 5.1 | 8.8 | 10.9 | 11.2 |
| April, 1st | 10.1 | 14.8 | 16.4 | 17.4 |
| May, 1st | 17.0 | 22.4 | 26.8 | 28.6 |
| June, 1st | 17.3 | 20.1 | 21.4 | 21.1 |
| July, 1st | 23.7 | 27.8 | 30.7 | 29.2 |
| August, 1st | 22.8 | 27.4 | 30.9 | 31.7 |
| September, 1st | 19.7 | 26.1 | 29.8 | 29.8 |
| October, 1st | 15.6 | 23.7 | 27.7 | 29.0 |
| November, 1st | 8.5 | 15.7 | 16.5 | 15.8 |
| December, 1st | 6.7 | 7.2 | 7.7 | 7.9 |

Figure 7. Total loads of the building along the year at: 5 AM (daily cooling minima, respectively daily heating maxima), 2 PM (daily cooling maxima), 12 AM and 8 PM.

Table 2. Four-year ambient temperature average $T_a$ [°C], after [16].
These results emphasize that for maintaining 25ºC inside the building, the energy consumption for cooling is more important than for heating. Maximum cooling energy is about 62 kWh/day in August, while the maximum heating one is 31 kWh/day in February. The subsequent annual cooling and heating energy consumption of the building is about 13073 kWh, corresponding to 98 kWh/m².

4.4. Influence of interior air temperature on cooling and heating demands

A change in thermal comfort level reflects in a change of external and internal loads. Figure 9 reveals the daily energy consumption for heating and cooling at different inside air temperatures. Setting an interior air temperature of 20ºC, results in maximum energy consumption for heating of 17 kWh/day in February, 81 kWh/day for cooling in August, and respectively a total of 15300 kWh/year, equivalent to 115 kWh/m². When the interior temperature is maintained at 24ºC, the energy consumption of the building is globally decreasing to 101 kWh/m², increasing the maximum heating load to 28 kWh/day and decreasing the maximum cooling one to 66 kWh/day.

In figure 10 the maximum daily cooling and heating loads are emphasized for air temperatures between 20 and 28ºC. As expected, higher inside air temperatures implies higher heating loads and lower cooling ones. Usually, the interior air temperature is set depending on the exterior air one. As previously mentioned, the two reference months considered when designing cooling of heating systems are August and February.

The maximum ambient temperature in August is +30.9ºC, while the minimum one in February is -2.03ºC. The values are taken as four-year average of measured data [14]. Figure 11 reveals the maximum loads to be used in sizing thermal systems as a function of the difference between ambient and inside air temperatures.

As a conclusion of the whole study, the annual energy consumption of 1 m² of living space if a same comfort level is maintained all year long is emphasized in figure 12, revealing the contribution of cooling and heating. However, targeting higher interior air temperatures in the cooling season and lower ones in the heating period, the building energy consumption can be diminished.

5. Conclusions

The thermal behavior of a two-level residential building designed for a family of four in Bucharest (44.25 N latitude) in clear sky conditions was analyzed. Results revealed that the most important contributor to the building thermal loss is the window, contributing to a heat gain during summer of about 313 Wm⁻², while the exterior wall contributes with only 3.5 Wm⁻² phase-shifted, for East orientated surfaces. Also, the number of exterior walls and their orientation with respect to East-West axis influence the contribution to the external load of the building.
Figure 9. Daily heating (a) and cooling (b) energy consumptions of the building along the year function on interior air temperature.

Figure 10. Maximum daily cooling and heating loads along the year, function on interior air temperature.

Figure 11. Maximum cooling and heating loads used for sizing thermal systems, function on temperature difference between ambient and interior air.
Figure 12. Annual energy consumption of 1 m$^2$ used for cooling and heating, function on interior air temperature.

Daily heating and cooling loads were computed for 12 months simulation, for different inside comfort levels reflected by the interior air temperature. The most important aspects regarding sizing of cooling and heating systems were emphasized: the maximum cooling and heating loads to be taken into account and also the reference months for which the exterior air temperature values should be considered. These are August and February, respectively.

Annual energy consumption per square meter of living space shared between cooling and heating was computed for different thermal levels.

As a further development of the present work, a model for forecasting solar radiation in cloudy conditions should be applied in cold season to size the building heating system in the most unfavorable conditions.

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