MULTI-PARAMETRIC ANALYSIS OF BUILDINGS – BUILDING SERVICES SYSTEM. CASE STUDIES AND APPLICATIONS IN BUILDINGS ENERGY PERFORMANCE

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ABSTRACT

The paper introduces the results of the simulations performed on an original calculation model, validated on the support of the INCERC full-scale experimental model. The calculation model is useful in the dynamic analysis of the buildings thermal behaviour as well as in assessing the heat / (sensitive) cold demand in view of maintaining the air-conditioned spaces at the required comfort temperature. The model is also able to quantify the effect of the modifications entailed by the façade upgrading works on the indoor microclimate or on the energy demand. The paper also includes examples of data obtained based on this calculation model used during the whole year or during the cooling period, in a real climate and for the dimensioning of the facility, on the whole building as well as on precincts in various locations.

The mathematical model developed is useful in the sensitivity analysis of the multi-parametric functions describing the building – building facilities system, in view of quantifying the simplifying hypotheses that may lead to the building energy performance (PEC) calculations fluidization. The mathematical model may also be used in buildings energy-related design calculations, in view of implementing innovative solutions involving improved energy efficiency values, with improved performance values as against the traditional solutions. The results of the multi-parametric analyses presented in this paper substantiate the necessity of the heat engineering analyses in the phase of buildings design as well as the transformation of the building – building facilities system design into an energy-related design interactive and convergent process involving a bijective relationship between the building members and the facilities maintaining the thermal comfort.

REZUMAT

Sunt prezentate rezultatele simulărilor pe un model de calcul original, validat pe suportul modelelor experimentale la scară naturală realizate de INCERC. Modelul de calcul este util pentru analiza dinamică a comportamentului termic al clădirilor şi pentru determinarea necesarului de căldură / frig (sensibil) în vederea menţinerii spaţiilor climatizate la temperatura de confort impusă. De asemenea, modelul poate cuantifica modificările pe care le produc reabilitările faţadei asupra microclimatului interior sau asupra necesarului de energie. Sunt prezentate exemple de date obţinute cu ajutorul acestui model de calcul, aplicat pentru întregul an sau pentru intervalul de răcire, pe o climă reală şi pentru dimensionarea instalaţiei, pe întreaga clădire şi pe incinte situate în diferite amplasări.

Modelul matematic dezvoltat este util în analiza de sensibilitate a funcţiilor multiparametrice care descriu ansamblul clădire – instalaţii, în scopul cuantificării ipotezelor simplificatoare care pot conduce la fluidizarea calculelor PEC. În acelaşi timp, modelul matematic este utilizabil în calcule de proiectare energetică a clădirilor, în vederea implementării unor soluţii inovatoare de eficientizare energetică, cu performanţe îmbunătăţite fată de soluţiile clasice. Rezultatul analizelor multiparametrice prezentate în acest articol fundamentează necesitatea analizelor termotehnice în etapa de proiectare a clădirilor şi transformarea proiectării clădirii şi a instalaţiilor aferente într-un proces interactiv si convergent de proiectare energetică, în care elementele de construcţie şi instalaţiile de menţinere a confortului termic sa aibă o relaţie biunivocă.

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1. Introduction

The mathematical models developed during the few last years within the Laboratory for Installations and Efficient Use of Energy of INCERC Bucharest emphasize the importance of the sensitivity analyses in rendering more efficient the use of energy and in quantifying the simplifying hypotheses implemented in the methods of calculating the Buildings Energy Performance (PEC).

In fact the analysis model the results of which are presented in this paper are focused both on the assessment of the condition of the existing buildings before the use of the energy-related upgrading technical solutions and after the implementation of these solutions. Therefore the direct beneficiaries of the results presented in the paper are the buildings energy auditors as well as the design engineers working on new buildings or on solutions of upgrading the existing ones.

Compared to the case of the buildings heating where the monthly calculation method provides results which are in very good correlation with the dynamic model using an hourly time pace [1], in the case of the buildings partitions analysis during the hot season, the use of the monthly calculation models generates significant deviations as against the hourly pace dynamic approach. While in the case of the buildings the parameter called "corrected number of degrees-days" has a special synthetic function related to the variation of the heating time of the occupied spaces, in the case of space cooling the use of the "degrees-days" parameter together with the monthly calculation models cancel two significant effects specific to the operation of the occupied spaces, as follows:

- damping and phase shift of the thermal waves crossing the opaque building members characterized by a thermal capacity and structural perturbation caused by the thermal bridges;
- disregard of the thermal "flywheel" effect generated by the indoor building members characterized by their own heat transmission mode, thermal capacity of the active zones and outline conditions connecting them to the thermodynamic outline field of the occupied spaces.

These simplifications associated to the model of electric analogy type used in the European standards taken over as national standards, SR EN 13791 and 13792 as well as in the buildings energy performance calculation methodology, Mc 001 2006, using the previously mentioned standardized methods, generate unacceptable errors both in the case of assessing the variation of the significant temperatures in the occupied spaces and in that of assessing their (sensitive) cooling demand. Both the temperatures variation and the variation of the cooling demand represent the result of the interaction between the natural outdoor environment, by the significant climatic parameters, with the occupied or unoccupied indoor environment. The random nature of the thermal load generated by the time variation of the climatic parameters entails a response with the same characteristic at the level of the space, a response "filtered" by the transfer function specific to the envelope and associated to the second order response of the indoor building members. The transfer function can be described by the electric analogue model only in the case of the models of the "regularly controlled thermal conditions – Kondratiev" used in simplified analyses and with well known limits [2]. The method used in this paper is based on the Unitary Thermal Response (R.T.U.) of composite structures [3], [7] which includes the thermal bridges effect [4] as well. The simplification included consists in using the one dimension heat transfer which, by the mediation of the surface temperatures and the generation of the isotherm heat transfer surfaces introduces an error of 2.6% at the most as against the heat transfer space model. The model of the convolution type between R.T.U. and the real parameters of the adjoining environment generates a virtual parameter called virtual outdoor temperature [5], [6] which preserves its time variation regardless of the resulting indoor temperature variation $\check{c}_i(t)$. This characteristic offers the possibility of analytically integrate the Kirchhoff – Fourier heat transfer equation specific to the indoor building members, associated to the heat balance algebraic equations of the air and of the envelope components. The model described avoids the use of a correction coefficient, at least debatable, included in the European standards taken over as national standards, namely the heat losses using coefficient, based on a simplistic processing of the monthly simplified model. In other words, this coefficient corrects the situations when values significantly over the set indoor temperature occur; they are not taken into consideration as a heat source in the altering of the inside energy of the indoor building members. From the phenomenological point of view, the effect mentioned above is obtained by interventions of the mechanical or natural ventilation type, which cannot be overlooked in the case of the daily functional profile of the spaces under analysis. The models described in the previously mentioned papers excessively use certain "intuitive" elements to the detriment of the analysis based on the heat balance equations which always are balance equations at the heat flow level, the result being the variation of the inside energy of a system (first law of the heat engineering). The adoption of the energy-related models overlooks the fact that any energy-related dimension represents a resultant of the integration operation during finite time lags that cannot be a priori selected. Even the intention of defining the time lags proves the lack of consistency of the models adopted in the regulations as they are based on the equality of the flows characterized as heat inputs in connection with those identified as heat losses. This hypothesis suggests the invariance at a certain moment of the inside energy and does not define a seasonal integration lag end. Moreover the methodology presented in code NP 048-2000 and taken over as a "simplified" method in Mc 001-2006, the spaces heating lag is defined by equalizing the reference reduced indoor and the outdoor temperatures representing the admissible parameters if a monthly calculation model is used. In the case of space cooling, such a condition defines only a sequence of space cooling lags and not a seasonal cooling period. The quasi-steady-state model used in the European standards will lead to cooling lags in the winter months as well, even in buildings with a traditional configuration (glazing rate < 0.30). The elements described above, together with the validation of the models conceived by the authors on the support of the INCERC experimental house and, at the same time, the lack of validation of the calculation models (referring to the experimental validation) developed in the European standards lead us to the conclusion that a phenomenological approach should be considered, backed up by the support of an easily usable software.

2. Sensitivity analysis with reference to the impact of the architecture solution on the energy demand for maintaining the indoor spaces at the required comfort parameters

A building structure representative for the buildings of the condominium type is analyzed; the characteristics of the closing members are presented in table 1.

The calculation is performed in two glazing variants:

- glazed surface and opaque surface corresponding to the conventional calculation building – Structure A (basic structure);
- the entire surface of the vertical envelope made of glazed building members, with very high quality glazing and joinery ($R_{glazing}$ = = 0,7 m^{2}K/W, corresponding to a joinery with no thermal bridges, with three glaze sheets, low-e treated) – Structure D.

Table 1.

Structural characteristics of the building under analysis

Building member		Thermal resistance m^2 K/W
Type	Description	
Outside wall	37.5 cm solid brick masonry with reinforced concrete floors	0.58
Outside window	Double, no special sealing	0.31
Terrace	14 cm reinforced concrete slab + 25 cm expanded slag	1.11
Floor over basement	Reinforced concrete slab with mosaic or linoleum floor	0.38
Wall towards staircase	25 cm solid brick masonry	0.56

In the first stage the analysis refers to the entire building, assessing the heat flow necessary for preserving the inside spaces at the comfort temperature if the building is air-conditioned. A real climate, representative for the Northern zones of the country is used in the simulation.

Figure 2.1 shows that during the hot season the rather low night temperatures allow structure A to preserve an indoor comfort microclimate without actually using the air conditioning / cooling systems. The situation changes in the case of the building with a glazed vertical envelope (structure D), which has a much larger quantity of energy for cooling. Nevertheless, it is obvious that even in the case of structure D (fig. 2.2) a continuous cooling lag is not possible, as the heat engineering behaviour of the building proves a sequence of the cool demand lags alternating with periods when the mechanical

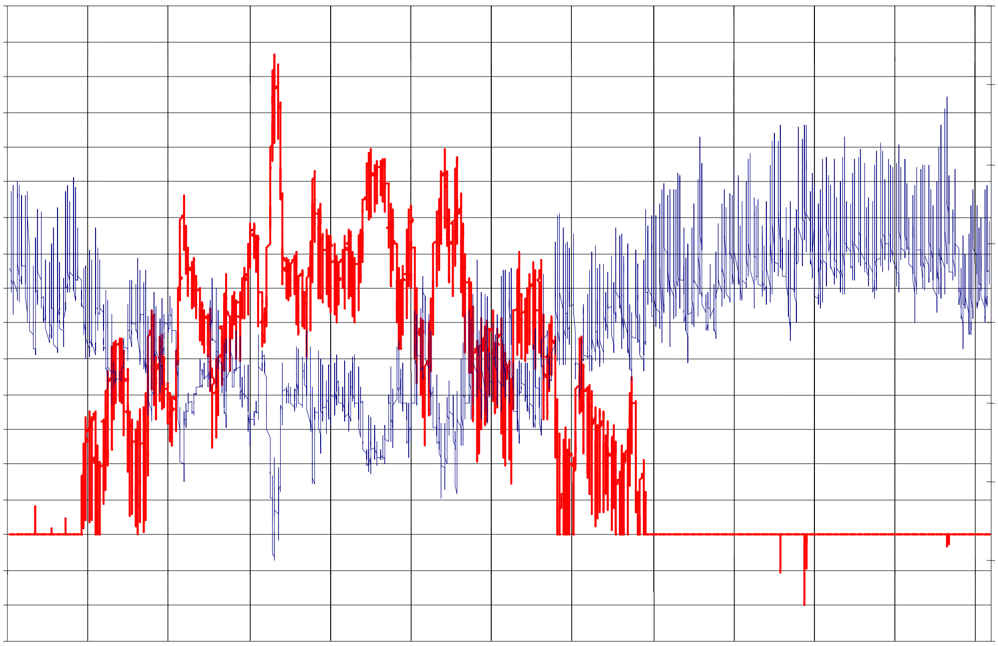

Figure 2.1. Heat flow demand for air-conditioning according to the outdoor temperature – structure A

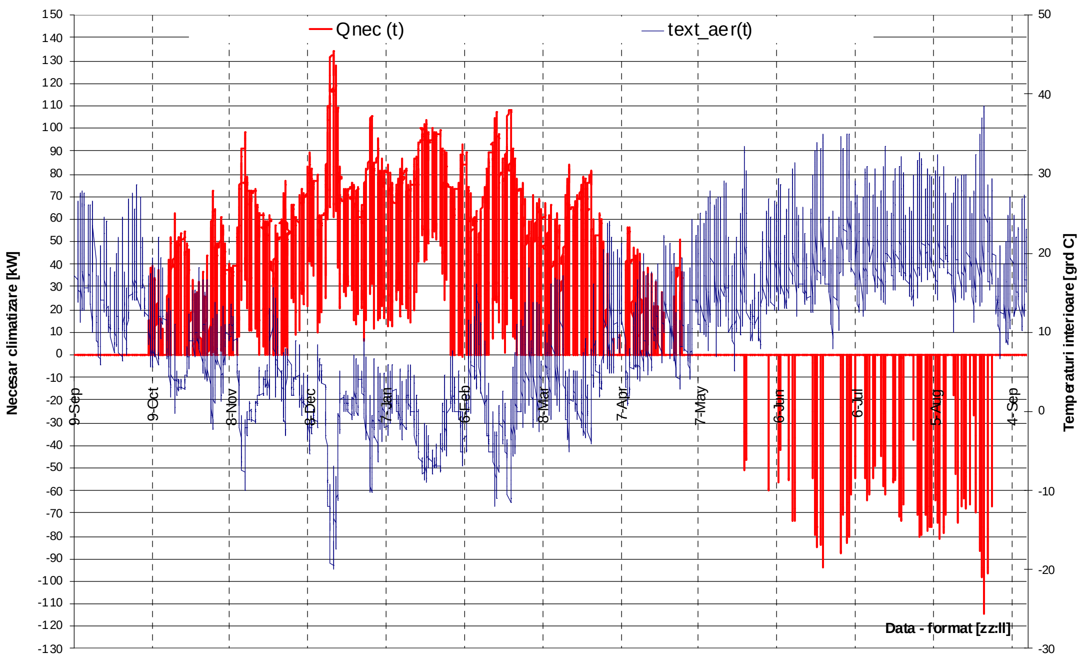

Figure 2.2. Heat flow demand for air conditioning according to the outdoor temperature – structure D

conditioning preserves a comfort indoor temperature.

Figures 2.1 and 2.2 show the difference between the curves of heat flow demand necessary for preserving the occupied spaces at the comfort temperature during the cold season, or in summer respectively. In the cold season there is a possibility to define an integration lag, noting that this lag results from the calculation (for instance it is defined by the intersection of the reduced indoor temperature curve with the reference outdoor temperature curve in the NP048 mathematical model and those derived from it). But in the hot season there is a possibility to use night cooling as the cold demand has a characteristic of the Dirac type both in the case of the usual envelope solutions and in the case of curtain walls. The characteristics of the cold demand that are presented prove the inconsistency of the “degrees-days” methods used in assessing the cold demand, as these methods have no physical support.

It is interesting to watch the rate of correlation between the heat / cold demand of the two structures and the outdoor temperature – figures 2.3, 2.4.

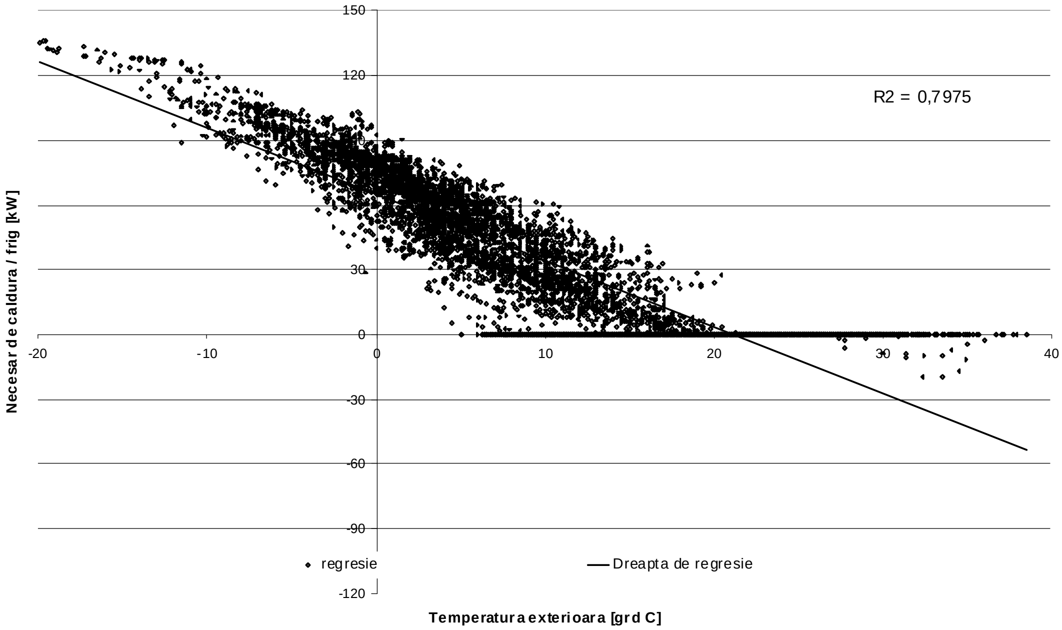

Figure 2.3. Correlation of the air conditioning energy demand with the outdoor temperature – structure A

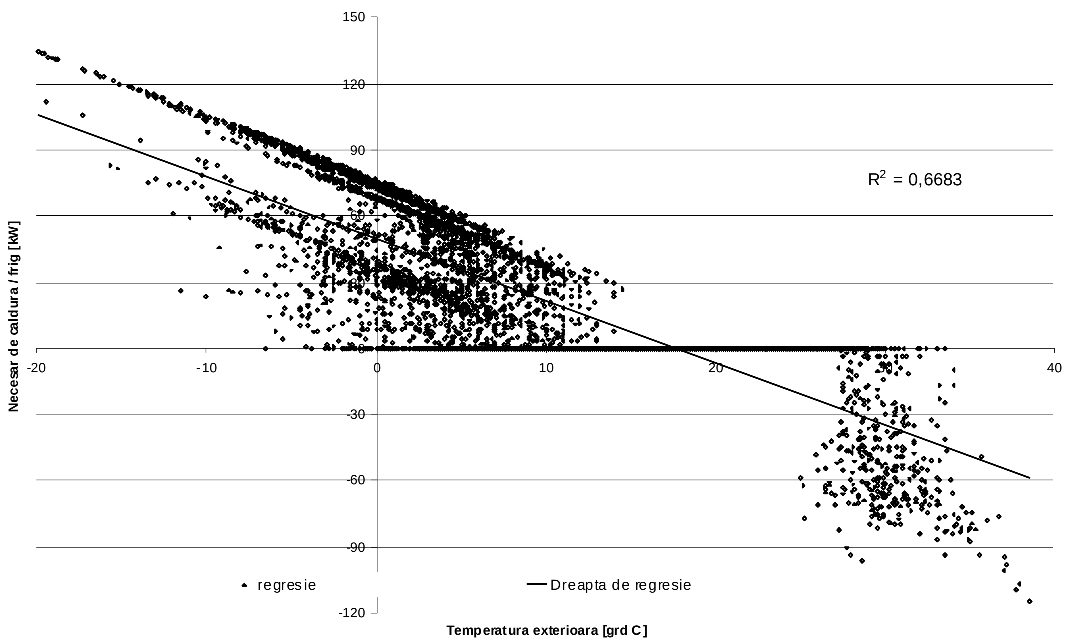

Figure 2.4. Correlation of the air conditioning energy demand with the outdoor temperature – structure D

The reduced correlation rate (0.66 ÷ 0.79) emphasizes the inaccuracy of the use of the heat steady-state conditions in assessing the buildings heat / cold demand. This remark is also valid, as figure 2.4 clearly shows, in the case of buildings with entirely glazed vertical envelope, where the phase lag is provided by the massiveness of the inside building members, by the building terrace.

Impact sensitivity analysis of the use of night ventilation on PEC (building energy performance) and indoor microclimate in occupied spaces

The use of night ventilation strategies or of ventilation in excess (in terms of the air demand for physiological reasons) of occupied spaces in the time lag when the outdoor air temperature allows the cooling of the inside building members; it is a well-known technique of reducing the energy demand used in buildings air conditioning.

In terms of buildings energy performance, natural ventilation at night or during the time lag when the outdoor temperature value is lower than that of the indoor air is the most recommendable solution. Natural ventilation reduces the energy demand for air conditioning and is efficient, according to the literature in the field, in rooms up to 6 meters deep (in the case of simple ventilation, ensured for instance by opening the windows on the same façade). This category includes most of the condominium apartments as well as one- family buildings. Natural ventilation may have an increased efficiency if the system starting air flow by natural draught was analyzed and implemented since the building design phase. There are various such solutions, from those of atrium type using chimney hoods to systems using hoods and ventilation shafts with a more reduced impact on the building architecture as a whole.

In the case of buildings in urban zones, issues related to security and to air pollution sometimes hinder buildings natural ventilation. It is therefore necessary to use mechanical ventilation (air filtering included), which requires both the assessment of the benefits of ventilation in terms of cold demand reduction and the energy consumption corresponding to the ventilation system operation. The evaluation of the ventilation energy consumption is irrelevant in the analysis of a virtual structure such as the reference building because of the variables that occur whose impact is hardly quantifiable. The energy consumption necessary in the ventilation of a building may be assessed only based on a statistical study on the systems and technologies currently used.

Moreover, the ventilation system should be designed in several variants and for each solution the load losses on the air treatment segments (filtering for instance) as well as on the transport and distribution segments. Only based on such an analysis, which is not the object of this paper, it is possible to determine the ventilators operating point, the system efficiency and the energy necessary for the operation of the mechanical ventilation system. Therefore, this paper analyzes the possibilities of reducing the energy consumption required for air conditioning, without taking into account the energy necessary for the operation of the mechanical ventilation system.

Figure 2.5 emphasizes the impact of night ventilation on the indoor microclimate, by reducing the resulting indoor temperature by about 2 degrees in the maximum temperatures lag. As the energy-related impact of using the night ventilation system, it is highly interesting in terms of PEC (building energy performance), we will further analyze the response of the same building (structure of A type, usual massiveness 1x), air conditioned, if the night ventilation system is used, if the ventilation is constant respectively, ensuring the air demand necessary for the physiological comfort.

Figure 2.6 presents the variation of these indoor temperatures. The modification of the refrigerating system operating lag as well as of the cold demand is noticed. By integrating the cold demand functions during one day, it is possible to obtain the conditioning demand, Q_{cold} = 424.4 [kWh/day] for a constantly ventilated building and Q_{cold} = 179.75 [kWh/day] for a reasonably ventilated building. **The resulting energy saving is of 57.65 %.**

Another very important aspect emphasized by the temperatures variation curves is the canceling of the effect of the building members inside massiveness. The consequence is **an approx. 17% higher peak load**, which will be implicitly reflected in the investment costs. It is necessary to notice that this

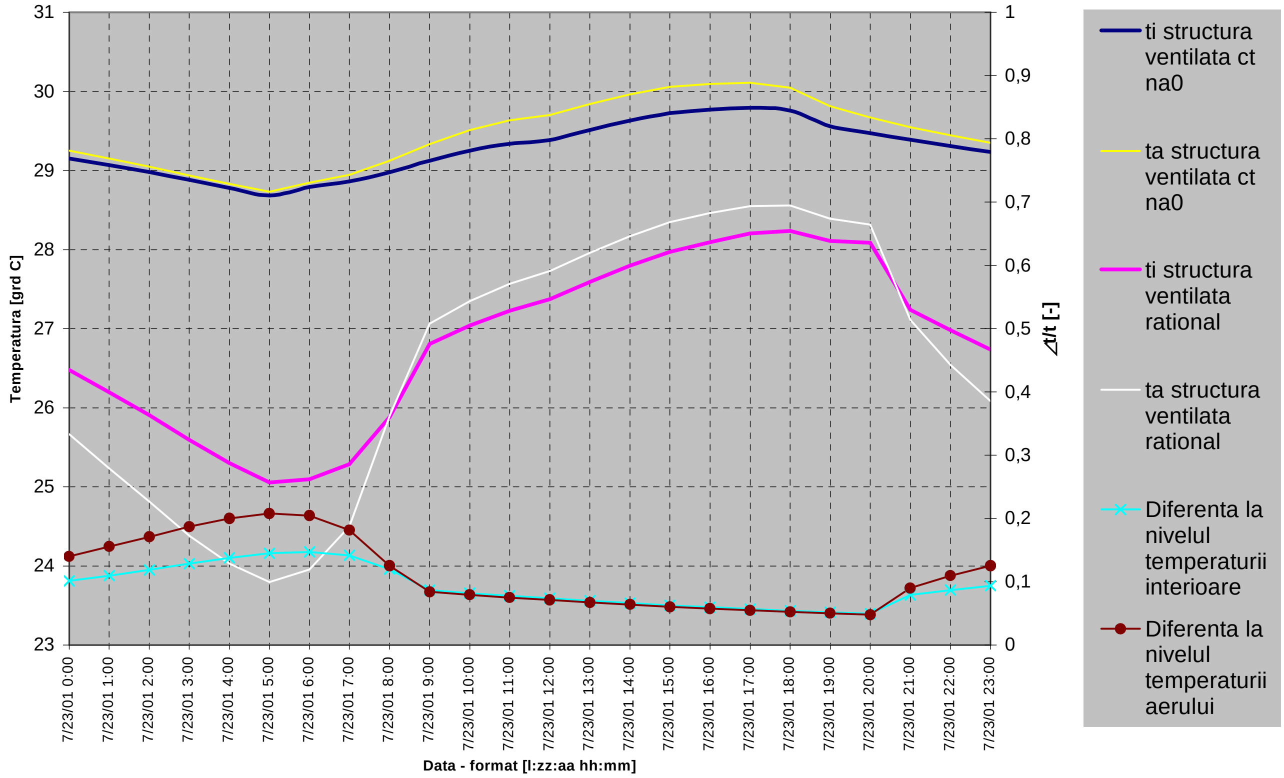

Figure 2.5. Indoor temperature and air temperature, in two situations of using the ventilation system: constant ventilation and reasonable ventilation Structure A, massiveness 1x

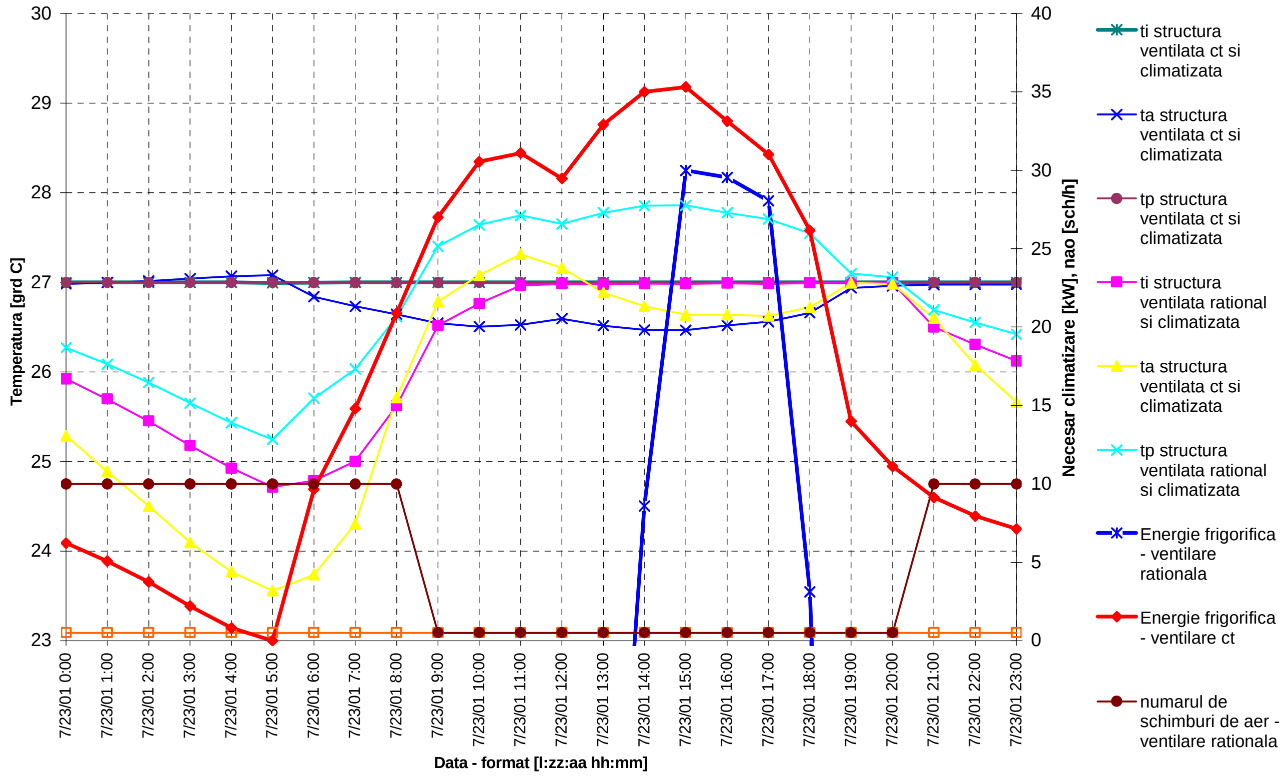

Figure 2.6. Relevant indoor temperatures and cold demand in two situations of using the ventilation system: constant ventilation and reasonable ventilation A type structure, normal massiveness of inside building members

load peak will be felt if the outdoor climate does not favour the operation of the heat pumps using as an enthalpy source the outdoor air, because it occurs in the lag when the outdoor air temperature is maximum and the heat pumps COP will be minimum.

Therefore, it is recommendable to provide a cold storage either by using the inside building members massiveness (by lowering at night the conditioning temperature by 2-3 degrees under the limit set for the building use period), or by using systems with phase change storage, if the night ventilation cannot be ensured because of certain conditions (outdoor air pollution, unfavourable climate – the PEC calculation emphasizes the night ventilation inefficiency, excessive moisture, indoor spaces security conditions).

Sensitivity analysis of the influence of the inside building members massiveness on the temperatures in the non-conditioned occupied spaces and on the cold demand if they are conditioned

In terms of the building heat engineering issues, the inside building members massiveness has the following effects on the temperature variation in the occupied spaces, during the hot season:

- ensures an increased inertia, perceived in the shortening of the conditioning lag and in the reducing of the maximum cold load;
- provides a higher efficiency of the night ventilation by increasing the heat storage;
- improves the thermal comfort by reducing the amplitudes of the indoor temperature resulted during a night-day cycle.

The paper further presents the results of the simulations for the A type usual building in three situations of considering the inside thermal massiveness. Zero thermal massiveness should be understood as the overlooking of the impact of the inside building members massiveness in the heat engineering calculations meant to assess the thermal comfort or the cold demand for conditioning the occupied spaces.

Conditions of very reduced thermal massiveness, close to zero, may occur in the case of lightweight structures like lattice girders, associated to partition walls made of multi-layer plaster plates – mineral wool – plaster plates.

Figure 2.7 presents the extremely important amplitude of the indoor temperature variation if the damping effect involved by the thermal balance at the level of the inside building members is overlooked. Especially for the massive structures,

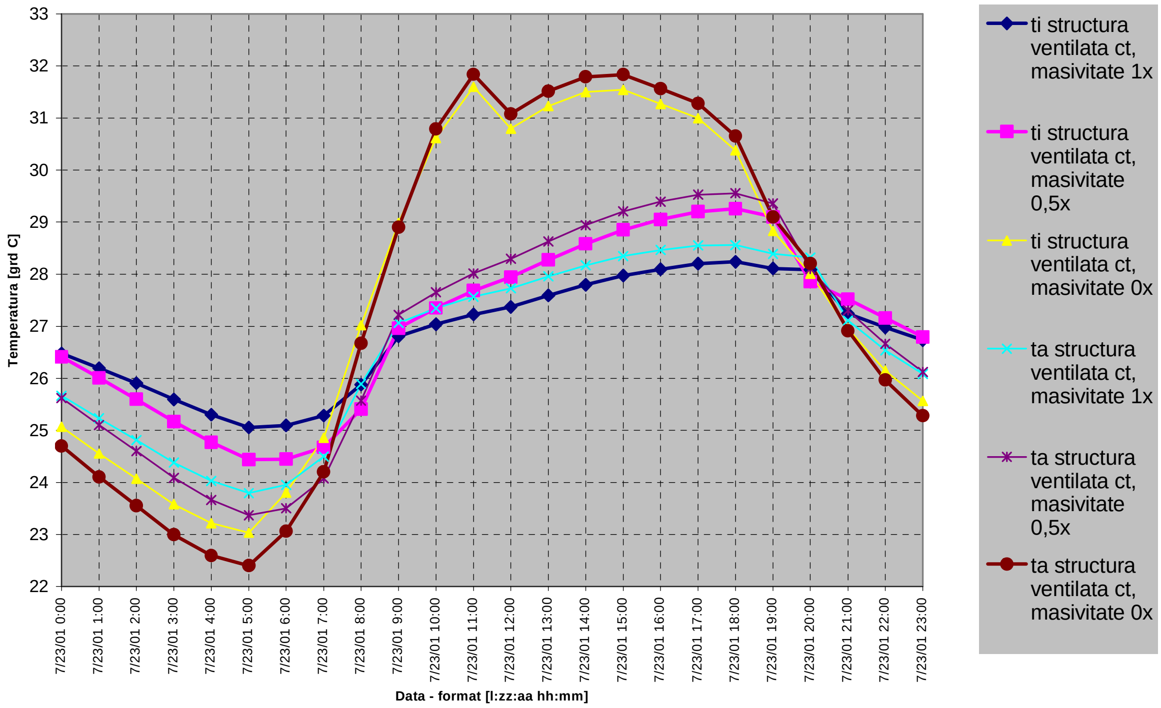

Figure 2.7. Indoor and air temperature in three variants of inside massiveness
Reasonable ventilation. Structure A

the intersection of the air temperature curve with the curve associated to the indoor temperature is noticed; this is generated by the effect of the average radiation temperature of the inside building members, namely of tempering the resulted indoor temperature.

In the case of constant ventilation (figure 2.8), the temperatures amplitude is considerably reduced, but at the same time the recorded temperatures increase (for instance in the case of the indoor temperature of structure A massiveness 1x a plus of over 1.5 °C is recorded).

Figure 2.9 emphasizes the reducing of the refrigerating system operating lag and the variation of the resulting indoor temperature as well as of the

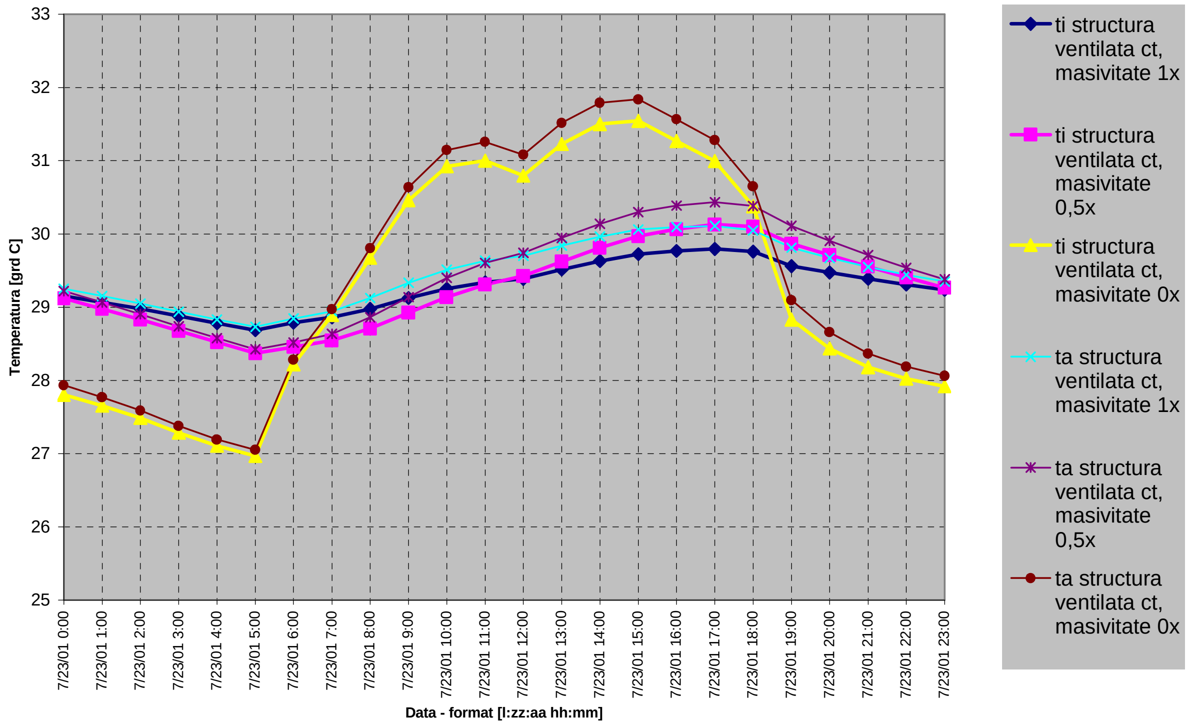

Figure 2.8. Indoor and air temperature in three variants of inside massiveness Constant ventilation. Structure A

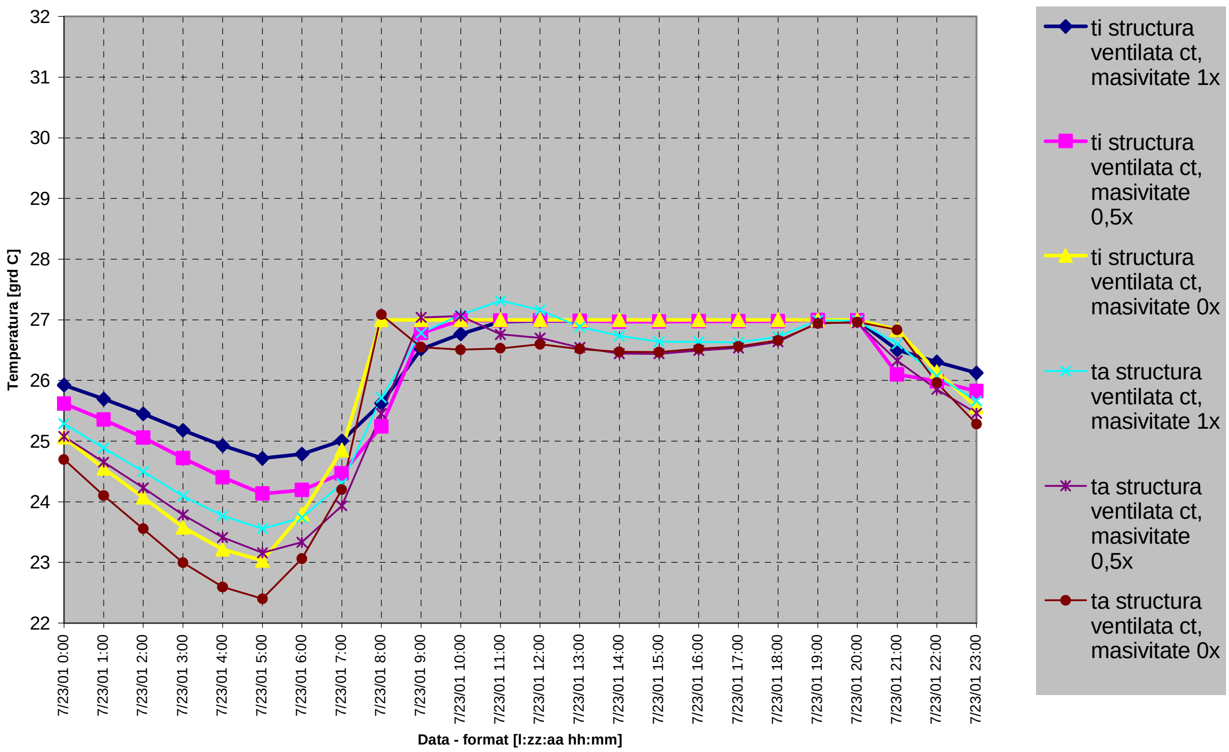

Figure 2.9. Indoor and air temperature in three variants of inside massiveness Air conditioning associated to reasonable ventilation. Structure A

air temperature, while figure 2.10 also presents the cold demand for buildings conditioning. The cold demand variation curves allow its integration during one day and the values centralized in table 2 are obtained. If the inside building members massiveness is overlooked, the cold demand for conditioning increases and the refrigerating source is oversized.

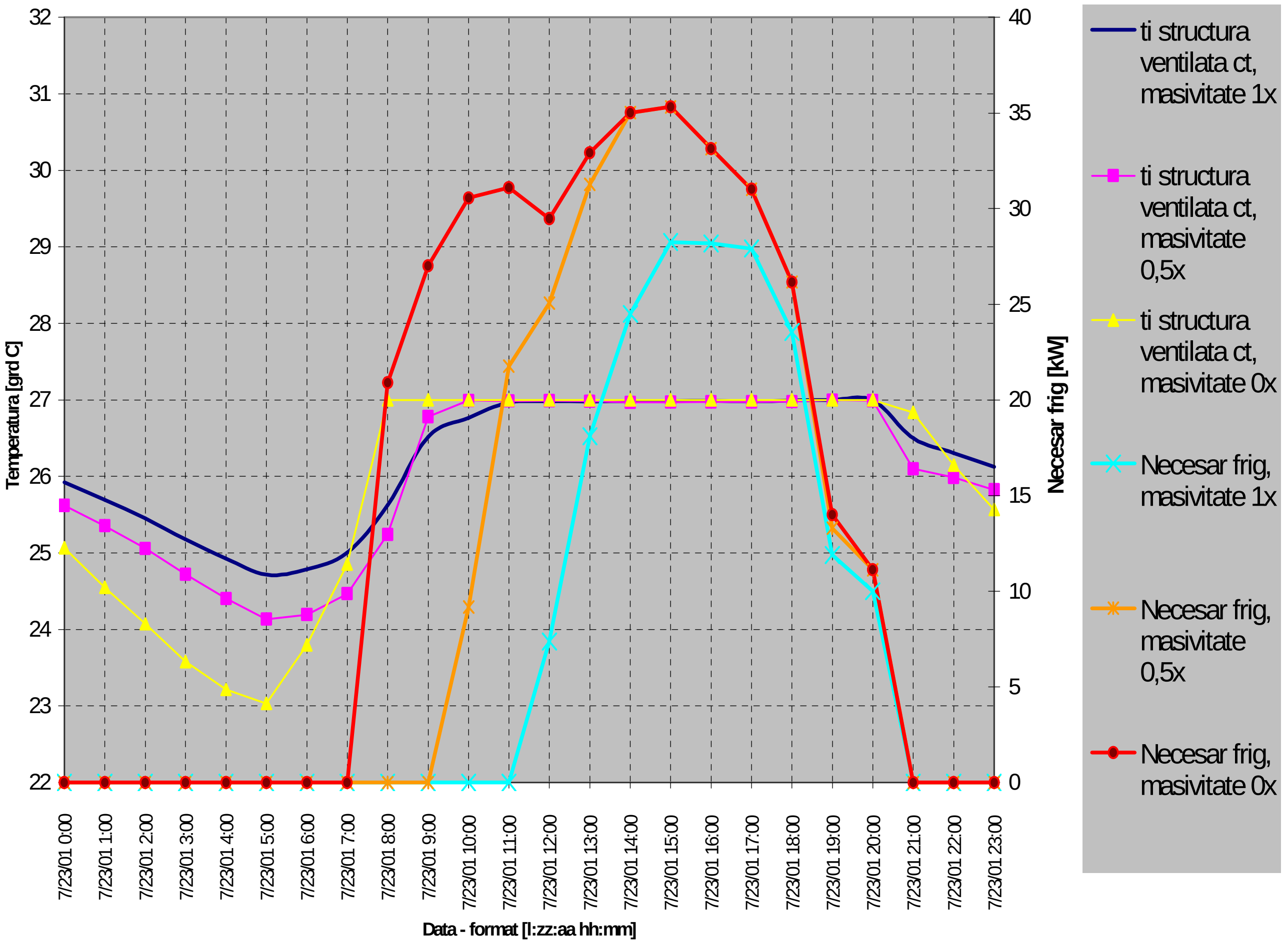

Figure 2.10. Indoor temperature and cold demand in three variants of inside massiveness. Air conditioning associated to reasonable ventilation. Structure A

Table 2.

A structure building conditioning – centralization of the PEC sensitivity analysis under the variation of the inside building members massiveness

	$Q_{refrigerating}$ [kWh/day]	Q_{max} [kW]	Energy consumption in excess [kWh/day]	Energy consumption in excess [%]	Source oversizing [%]
Usual massiveness building 1x	179.75	28.25	0	-	-
Reduced massiveness building 0.5x	272.30	35.31	92.55	51.49	25
Overlooking of inside building members massiveness – massiveness 0x	357.68	35.31	177.93	98.98	25

Sensitivity analysis concerning the location of the zones under analysis in the building structure and the selection of the calculation zones in view of sizing the conditioning system

The paper further presents the analysis of a usual average apartment (60 m^2 useful area) whose geometry is based on the reference building outline. The apartment is successively considered as located on the ground floor and on the highest floor, in the usual building (structure A) and in the structure with entirely glazed vertical envelope (structure D). The apartment is considered air-conditioned and the indoor comfort temperature considered is 27°C. The analysis is extremely interesting in terms of buildings heat engineering; the temperature and cold demand undergo important differences at the level of the zones under analysis, according to the location of the apartment within the building structure and the boundary conditions to be undergone result as well.

Figure 2.11 shows that for the usual structure, the reasonable ventilation of the space and the thermal mass effect of the soil allow the preservation of a thermal comfort temperature and the intervention of the cooling system is not necessary. The mechanical ventilation with a large number of air exchanges allows the preservation of the indoor space at the comfort temperature in the morning. Later, when the outdoor air temperature exceeds the value of the air temperature in the precinct under analysis the number of air exchanges decreases up to the minimum number physiologically necessary. The indoor heat releases, the outdoor inputs by ventilation and the inputs through the envelope are taken over by the inside massive building members. But in the case of structure D, the same conditions cannot ensure its independence of the cooling system – figure 2.12.

It is noticed that in the case of structure D the solar radiation received thanks to the generous glazing generates a thermal input which cannot be cancelled by the mechanical ventilation of the space and requires the intervention of the air conditioning system, especially during the first hours of the day when the direct solar inputs are very important because of the South exposure.

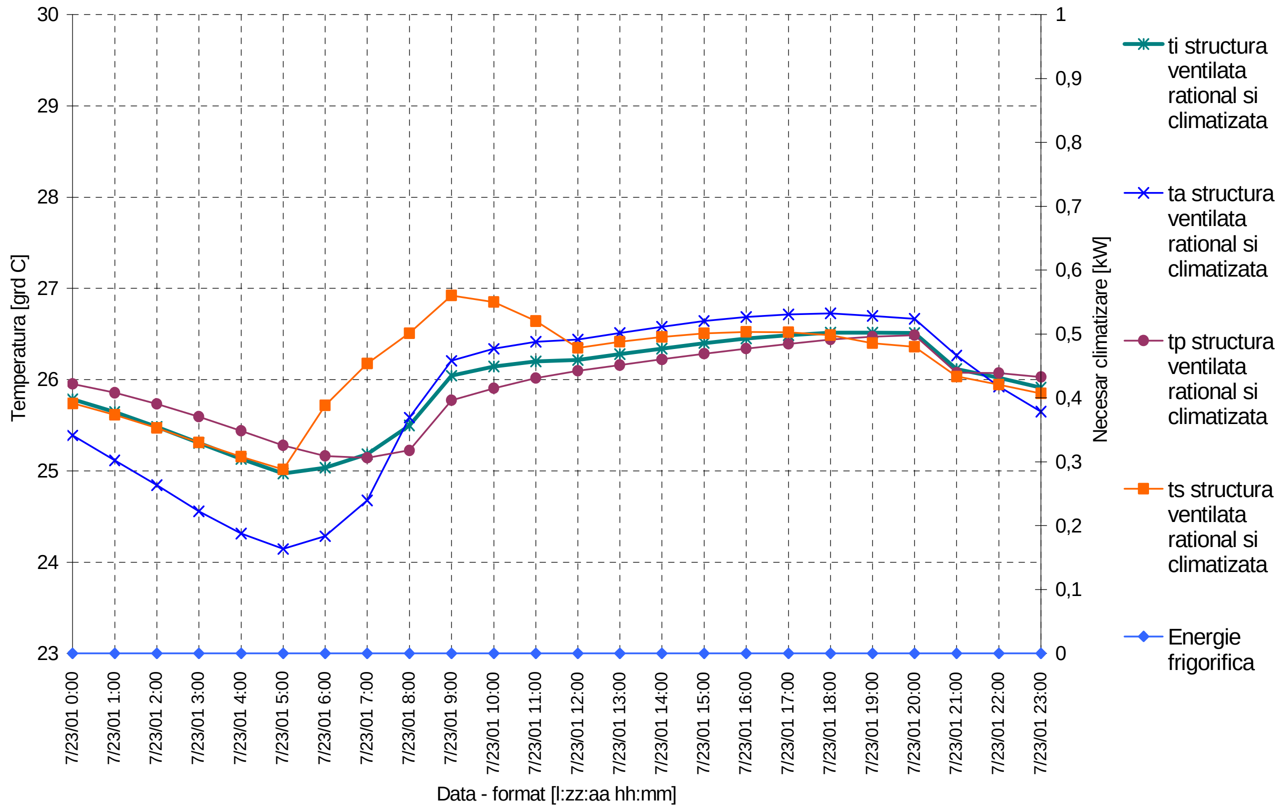

Figure 2.11. Relevant indoor temperatures and cold demand for air conditioning – structure A, apartment on ground floor, Eastward exposure

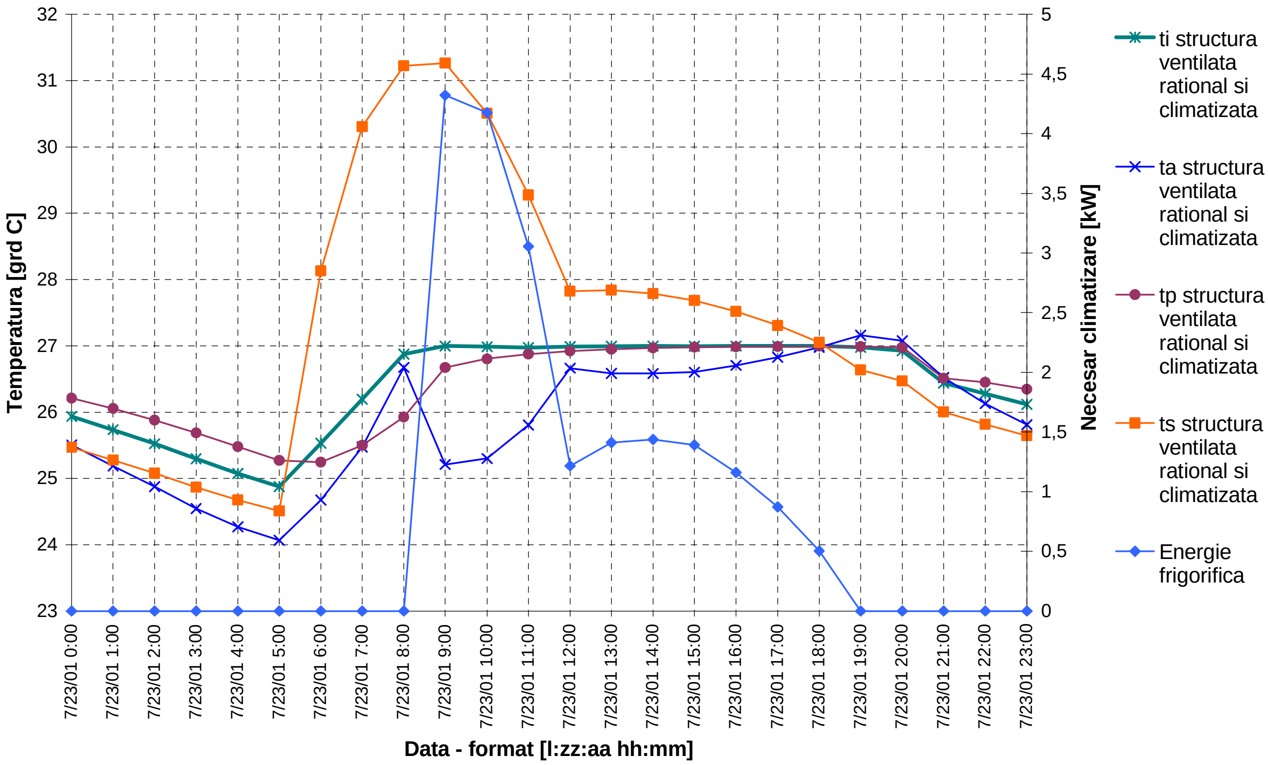

Figure 2.12. Relevant indoor temperatures and cold demand for air conditioning – structure D, apartment on ground floor, Eastward exposure

The same type of apartment located this time on the highest floor, is characterized by cooling demand in both types of structures. But this is considerably larger, in terms of amplitude as well as of energy, in the case of structure D (figures 2.13, 2.14). The load peak is of 2.5 kW (8,600 BTU/h) for structure A while for structure D the peak reaches 8 kW (27,400 BTU/h) and it is actually impossible to have it ensured by usual air conditioning systems of the split type.

Another issue, more important than the way in which this cold demand is ensured, is the high temperature of the radiant environments. This renders necessary a very reduced air temperature inside the precinct, in view of obtaining the necessary indoor temperature. As figure 19 shows, the time lag between 15h – 17h requires an air temperature of 21°C in order to provide a resulting indoor temperature of 27°C. This low temperature causes in a long term health problems to the users of this space, but it also may cause immediate effects by the thermal shock caused by sudden temperature modifications.

The aspect of the cold demand curves and of the relevant indoor temperatures at the level of the occupied spaces, as it results in figures 2.11 – 2.14, lead to the following remarks:

- in terms of indoor comfort, the supply of the air flow-rate required for physiological reasons at the temperature of 21°C is a problem;
- in terms of the design of the air conditioning system, the refrigerating demand will be different depending on the building zoning and on the way in which the zones are connected. From this point of view the diagrams presented in figures 2.12 and 2.14 are relevant; they present the cold demand and the hourly lag when the daily maximum is recorded. Thus, the refrigerating power will be minimum in the case of a model mono-zone analysis, in which all the occupied spaces are simulated as a sole main zone, the cold demand of certain zones will be compensated by other orientations / positions of the apartments. If the analysis is performed on small dimensions zones delimited by adiabatic surfaces, the cold demand resulted as a sum of the individual demand will be much higher, and the dispersion around the average value (obtained by previous analysis, in mono-zone conditions) will be inversely proportional to the dimensions of the simulated zones.

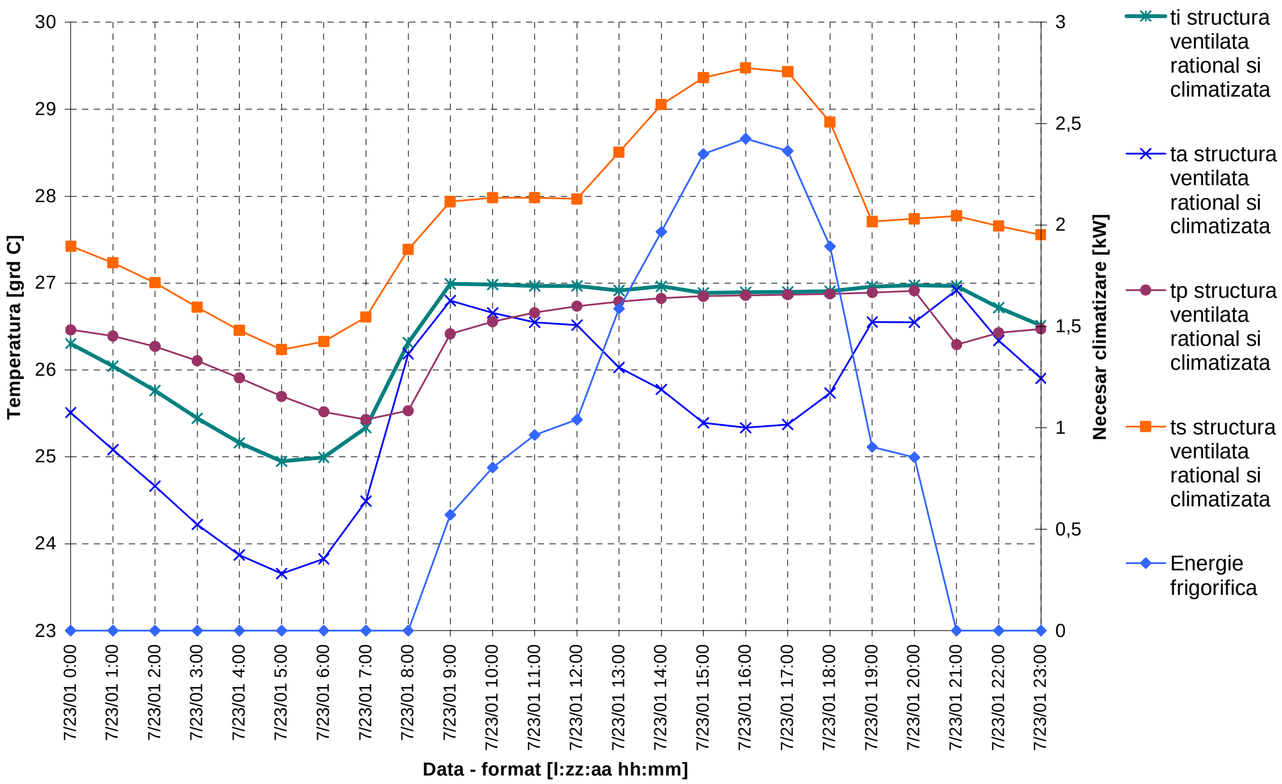

Figure 2.13. Relevant indoor temperatures and cold demand for air conditioning – structure A, apartment on highest floor, Westward exposure

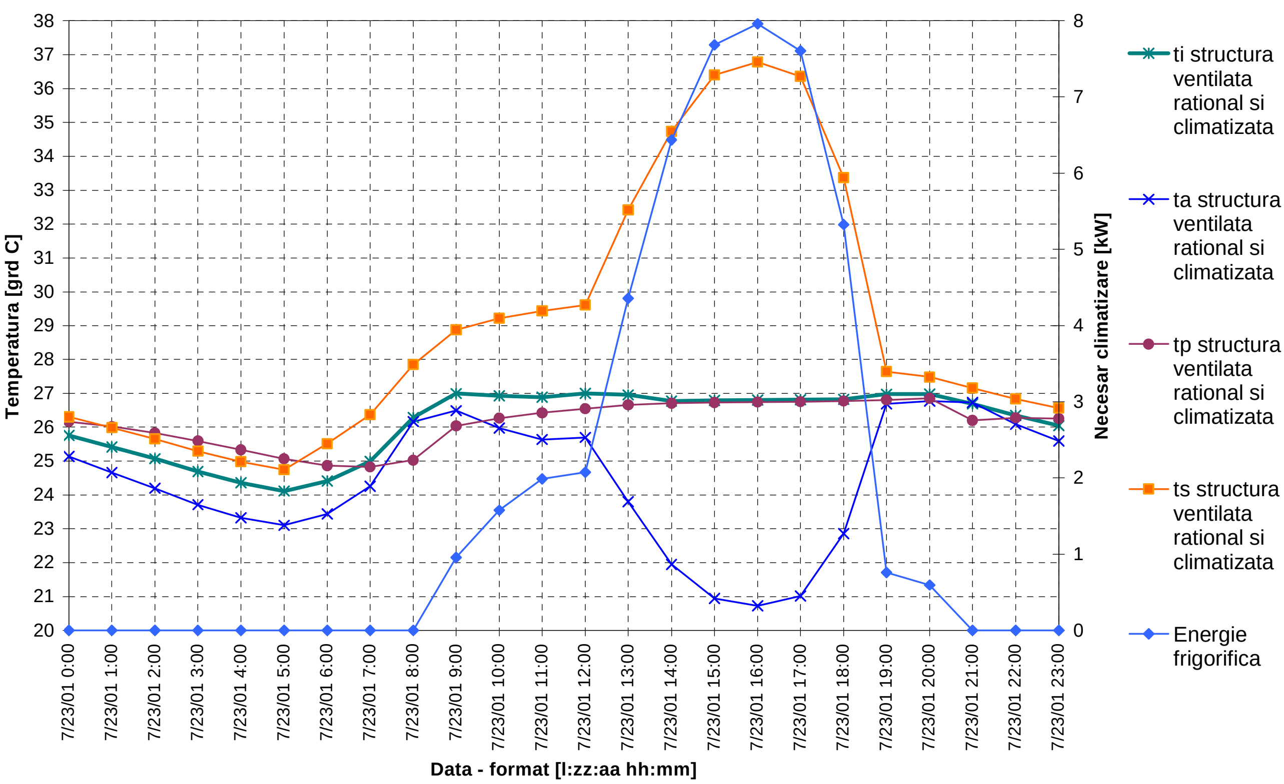

Figure 2.14. Relevant indoor temperatures and cold demand for air conditioning – structure D, apartment on highest floor, Westward exposure

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