HYGROTHERMAL RESPONSE OF A DWELLING HOUSE. THERMAL COMFORT CRITERIA

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ABSTRACT

The use of local natural materials in order to reduce the environmental negative impact of buildings has become common practice in recent years; such buildings are to be found in all regions of the planet. The high level of thermal protection provided by the envelope elements made from natural materials such as straw bale insulation, hemp insulation or sheep wool, and their lack of thermal massiveness require a more complex analysis on their ability to keep interior comfort without accentuated variations. This paper proposes a comparative analysis between different solutions for a residential building located near a Romanian city, Cluj-Napoca. The elements of the building envelope are designed in three alternative solutions, using as substitute to classical solutions (concrete and polystyrene, masonry and polystyrene), straw bales and rammed earth for enclosing elements. For this purpose there are conducted numerical simulations of heat and mass transfer, using a mathematical model that allows the analysis of indoor comfort, by comparing both objective factors (air temperature, operative temperature and relative humidity) and subjective factors, which are needed to define interior thermal comfort indices PPD and PMV. Finally, a set of conclusions are presented and future research directions are drawn.

Keywords: overall building assessment, transient heat and mass transfer, hygrothermal behaviour, natural local materials, architectural archetype

REZUMAT

Utilizarea materialelor naturale locale pentru reducerea impactului negativ al clădirilor asupra mediului a devenit în prezent o practică curentă; astfel de clădiri pot fi întâlnite în toate regiunile globului. Nivelul înalt de protecţie termică asigurat de elementele de anvelopă realizate din materiale naturale, cum ar fi baloturile din paie, izolaţia din cânepă sau lână de oaie, precum şi lipsa masivităţii termice impun o analiză mai complexă asupra capacităţii de a menţine confortul interior fără variaţii majore. Această lucrare propune o analiză comparativă a diferite soluţii pentru o clădire rezidenţială aflată în apropierea oraşului Cluj-Napoca, din România. Elementele anvelopei clădirii sunt concepute în trei variante de soluţii, folosind ca alternative la soluţiile clasice (beton armat şi polistiren, zidărie şi polistiren), baloturile din paie şi pământul bătătorit pentru elementele de închidere. În acest scop sunt realizate simulări numerice ale transferului termic şi de masă, folosind un model matematic ce permite analiza confortului interior, prin studiul comparativ al factorilor obiectivi (temperatura aerului, temperatura operativă şi umiditatea relativă), dar şi al factorilor subiectivi, necesari în definirea indicilor de confort interior PPD şi PMV. În final, este prezentată o serie de concluzii, şi sunt indicate direcţii pentru cercetările viitoare.

Cuvinte cheie: analiza globală a clădirii, transfer termic şi de masă în regim variabil, comportare higrotermică, materiale naturale locale, arhetip arhitectural

1. INTRODUCTION

The assessment of thermo-hygro-energetic behaviour of enclosing elements as separate partitions of the building envelope does not provide a complete image on the defining criteria of the building quality, expressed by indoor environment quality and energy performance, which are characterized by comfort parameters and interior air quality, respectively by the annual energy demand to ensure the optimal values of characteristic parameters. Therefore, towards adopting a strategy for optimal energy efficiency and comfort conditions improvement, it becomes necessary an integrated assessment by considering unsteady regime in the interaction between the building envelope and the environment, heating and air conditioning equipments, and user behaviour.

By considering the human perception, there has been developed a model that enables global assessment of the comfort degree (Fanger, 1967), which is assessed by using the indices Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). These indices integrate the effects of objective factors (microclimatic parameters) and subjective factors (nature of the activity, metabolic rate, thermal protection of clothing and individual characteristics).

In this paper it is globally analysed a dwelling house, whose envelope elements are made with traditional solutions by using straw bales, but also with classical solutions by using brick masonry, considering simulation models of hygrothermal phenomena for two variants of living space microclimate conditions. The authors' intention was to identify possible adverse effects on indoor climate conditions caused by lack of thermal massiveness of such building elements. To define the hygrothermal properties of these materials specific literature was consulted (Vasilache et al., 2010; Zhang, 2011). It is considered appropriate to complete those studies with a complex analysis of the envelope elements influence, comprising insulation made from natural materials, on indoor climate conditions, in order to get a full picture of the advantages and disadvantages of their use.

2. TRADITIONAL TECHNIQUES AND LOCAL NATURAL MATERIALS IN THE MODERN DWELLING

The concept of modern dwelling is defined by an evolutionary character, not being strictly tied to a specific architectural style, but to a continuous adaptation to dominant visions, which hold on to essential aesthetics, but which are also increasingly complying to the general theme of sustainable development. Among the simultaneously applicable criteria that principles of sustainable development are transmitting in architecture, there are provided the efficient use of space and of material and energy resources, the fulfilling of current needs of users, and the preservation of traditional culture, as a key factor in the continuity of collective consciousness. In this regard, the recurrence of archetypal elements is at present approached in studies that propose their integration into the modern dwellings (Corduban et al., 2011; Corduban and Polastri, 2013), in which the application of traditional techniques and local natural materials is developing only through the natural tendency of process optimization.

The object of the case study represents an individual dwelling located in a rural area, close to the city of Cluj-Napoca (Fig.1). Architectural and technical traditional particularities of the building are designed with the aim of improving the thermo-hygro-energetic behaviour. The porch has a main role in reducing direct solar radiation on the most exposed facade, through the shade provided during the hot period, and similar to the open porch on the north facade, also a secondary role in reducing convective heat transfer, by sheltering in the cold period. The third space, an enclosed vestibule incorporated in the south oriented porch, as intermediate room also has a role in reducing heat loss. To protect the thermal insulation made of natural materials from water by infiltrations, between insulation at lower floor and ground there is arranged a 50 cm layer of ventilated air. A similar technical solution it is chosen for solving the facades, having disposed under the wood finish a ventilated air layer of 5 cm, for limiting the heat absorption generated by solar radiation, and for preserving the thermal insulation and the lime plaster from the rain action.

The plan of the house meets the requirements of today's families, dividing the interior space as it is detailed in Table 1, and for a comparative analysis of residential environment quality and energy performance for different technical solutions, in Table 2 there are presented three options for the design of the envelope. The comparative analysis is performed for three variants of envelope, for each situation considering two sets of boundary conditions for indoor climate, with and without cooling in summer, resulting in six proposed scenarios presented in Table 3.

Fig.1. The architectural concept of the house – facades sights from SW, respectively N

Table 1. *Identifying the heated zones of the building*

Level	Room	Net area [m^2]	Orientation of the room
Ground floor	Bedroom no.1	11.99	on SW
	Bedroom no. 2	13.03	on NW
	Hall	17.86	from S to N
	Kitchen	24.57	on SE
	Bathroom	7.30	on N
	Storage space	3.65	on NE
Attic floor	Living room	50.75	entire area of the attic

Table 2. *The structure of the envelope elements*

Envelope variants	Envelope element		
	Exterior walls	Lower floor	Roof
A	Cob and lime based plaster, straw bales (40 cm), ventilated facade with wood finishing	Wood planks (3 cm), Straw bales (30 cm),	Cob and lime based plaster, straw bales (40 cm), wood weather board
B	Cob and lime based plaster, rammed earth (30 cm), straw bales (20 cm), ventilated facade with wood finishing	Wood planks (3 cm), Straw bales (30 cm),	Cob and lime based plaster, straw bales (40 cm), wood weather board
C	Classic plaster, hollow bricks masonry (37,5 cm), polystyrene insulation (10 cm)	Reinforced concrete slab (13 cm), polystyrene (15 cm)	Gypsum boards, extruded polystyrene (20 cm), metal tile roof

Table 3. *Cases subjected to numerical simulations*

Envelope variants	Without cooling in summer	With cooling in summer
A	I	II
B	III	IV
C	V	VI

3. ASSESSMENT OF UNSTEADY HEAT AND MASS TRANSFER

The analysis of heat and mass transfer phenomena has available a number of programs for numerical simulation (Tilmans and Van Orshoven, 2010; Holm et al., 2003), but most existing models do not exceed the limitations defined by a simplified manner of analysing the envelope mass transfer, assigning a certain moisture storage capacity inside buildings. Since variations in the moisture regime significantly affect heat transfer and therefore comfort parameters, namely the energy demand in the processes of heating and cooling indoor environment, in this study there has been used a model that includes the mass component, in order to represent a more realistic behaviour of the building. Thus, the performance of WUFI® Plus program has been used, whose mathematical model is based on equations of energy and mass conservation (Künzel, 1995), expressed through eq. (1) and eq. (2), and equations of the room energy and humidity balance, expressed through eq. (3), respectively eq. (4). The mathematical model of computational environment is completed by knowledge of boundary conditions consisting of inside and outside climate parameters.

$$\left(\rho c+\frac{\partial H_w}{\partial \theta}\right)\cdot\frac{\partial \theta}{\partial t}=\nabla\cdot(\lambda\nabla\theta)+ \\ +h_v\nabla\cdot\left(\delta_p\nabla(\varphi\cdot p_{sat})\right) \quad (1)$$

$$\frac{dw}{d\varphi}\cdot\frac{\partial\varphi}{\partial t}=\nabla\cdot\left(D_w\frac{dw}{d\varphi}\nabla\varphi+\delta_p\nabla(\varphi\cdot p_{sat})\right) \quad (2)$$

Where: φ is the relative humidity, [-]; t – time, [s]; θ – temperature, [K]; c – specific heat, [J/(kg·K)]; w – moisture content, [kg/m^3]; p_{sat} – saturation vapour pressure, [Pa]; λ – thermal conductivity, [W/(m·K)]; H – total enthalpy, [J/m^3]; D_w – liquid diffusion coefficient, [kg/(m·s)]; δ_p – vapour permeability, [kg/(m·s·Pa)]; h_v – latent heat of phase change, [J/kg].

$$\rho\cdot c\cdot V\cdot\frac{d\theta_i}{dt}=\sum_j A_j\alpha_j\left(\theta_j-\theta_i\right)+\dot{Q}_{Sol}+ \\ +\dot{Q}_{il}+n\cdot V\cdot\rho\cdot c\cdot\left(\theta_a-\theta_i\right)+\dot{Q}_{vent} \quad (3)$$

Where: ρ is air density, [kg/m^3]; α_j – heat transfer coefficient, [W/(m^2·K)]; θ_a – outdoor air temperature, [K]; θ_j – surface temperature, [K]; θ_i – indoor air temperature, [K]; t – time, [s]; A_j – surface area, [m^2]; c – air heat capacity, [J/(kg·K)]; n – air change rate, [h^{-1}]; Q_{sol} – solar input that leads directly to an increase in air temperature, [W]; Q_{il} – domestic heat gains of human activity, lighting and equipment, [W]; Q_{vent} – heat gained or lost through ventilation, [W]; V – volume, [m^3].

$$V\cdot\frac{dc_i}{dt}=\sum_j A_j\dot{g}_{wj}+n\cdot V\left(c_a-c_i\right)+ \\ +\dot{W}_{IMP}+\dot{W}_{Vent}+\dot{W}_{HVAC} \quad (4)$$

Where: c_a is absolute moisture ratio of outdoor air, [kg/m^3]; c_i – absolute moisture ratio of indoor air, [kg/m^3]; g_{wj} – moisture flux from the inner surface to the room, [kg/(s·m^2)]; W_{IMP} – moisture production, [kg/h]; W_{Vent} – moisture gains or losses due to ventilation, [kg/h]; W_{HVAC} – moisture gains or losses due to HVAC system, [kg/h].

4. RESULTS AND DISCUSSION

For the analysis of indoor comfort there are taken into account objective factors defined by the indoor climate conditions (air temperature, operative temperature and relative humidity) and subjective factors, such as the metabolic rate, the thermal protection of clothing and the nature of activity, which together with objective factors define thermal comfort indices PMV and PPD. In addition, it is considered the final energy consumption for heating and cooling the indoor environment.

Operative temperature, calculated by using eq. (5), enters a correction to the indoor air temperature, in order to obtain perceived values at the superficial level of indoor elements. Considering the adaptability of occupants by controlling indoor climate factors, it has been proposed an adaptive model (Brager and de Dear, 2001), that considers the measure to which the comfort level is achieved, comfort defined by the optimal operative temperature, with eq. (6). Figures 2-4 include minimum, mean and maximum values for the differences between operative temperature and optimal operative temperature, calculated with eq. (7) or (8) according to SR EN 15251:2007, in order to expose thermal deviations of the indoor environment in regard to the ideal climate conditions.

$$\theta_o = \frac{\theta_{mr} + \theta_a \cdot \sqrt{10v}}{1 + \sqrt{10v}} \tag{5}$$

Where: $\boldsymbol{\theta_a}$ represents the air temperature, [°C]; $\boldsymbol{\theta_{mr}}$ – mean radiant temperature, [°C]; $\boldsymbol{v}$ – air velocity [m/s].

$$\theta_{o.op.} = 17{,}8 + 0{,}31 \cdot \theta_{rm} \tag{6}$$

Where: $\boldsymbol{\theta_{o.op}}$ represents the optimal operative temperature, or the temperature of optimal comfort, [°C]; $\boldsymbol{\theta_{rm}}$ – running mean external temperature, or exponentially weighted running mean of the daily mean external air temperature, [°C].

$$\theta_{rm} = (1-\alpha) \cdot (\theta_{ed-1} + \alpha \cdot \theta_{ed-2} + \\ + \alpha^2 \cdot \theta_{ed-3} + \ldots) \tag{7}$$

$$\theta_{rm} = (1-\alpha) \cdot \theta_{ed-1} + \alpha \cdot \theta_{rm-1} \tag{8}$$

Where: $\boldsymbol{\theta_{rm-1}}$ represents the running mean external temperature for the previous day, [°C]; $\boldsymbol{\theta_{ed-1}}$ – daily mean external temperature for the previous day, [°C]; $\boldsymbol{\alpha}$ – constant value between 0 and 1; recommended to use 0,8.

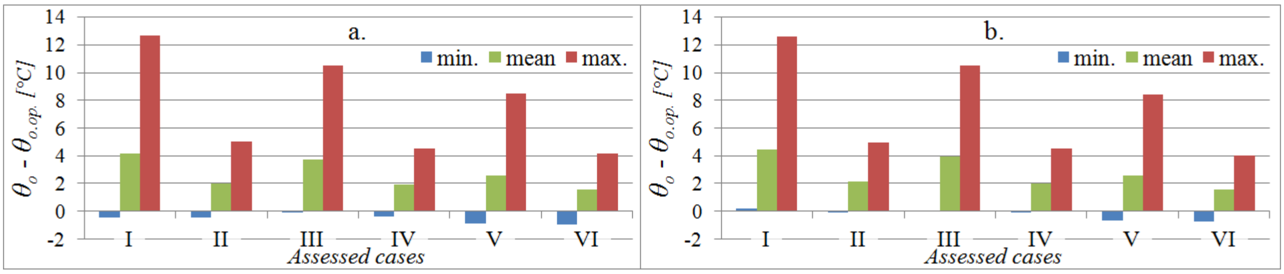

Fig.2. Differences between operative and optimal operative temperatures; a. SW bedroom; b. NW bedroom

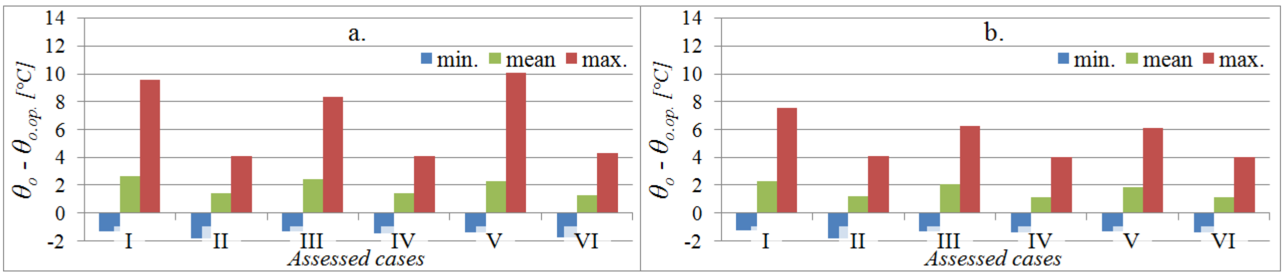

Fig.3. Differences between operative and optimal operative temperatures; a. Living room; b. Hall

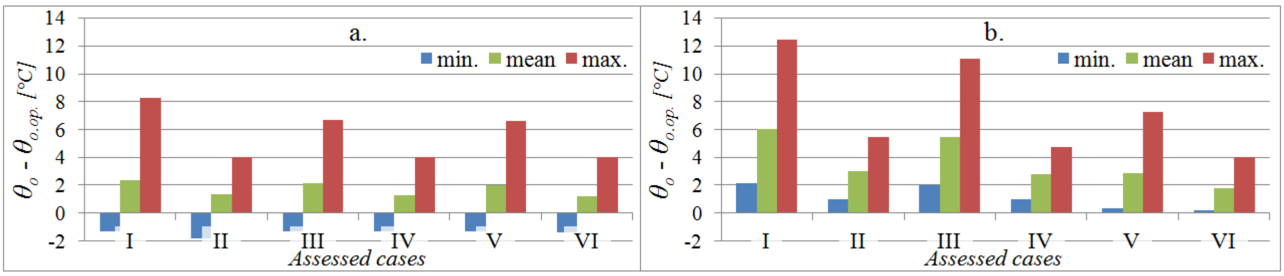

Fig.4. Differences between operative and optimal operative temperatures; a. Kitchen; b. Bathroom

Among the rooms with long occupancy it is determined that the bedrooms present the most unstable conditions of thermal comfort, as shown by the high values of mean deviations, correlated with the largest variation ranges. Further characterization by thermal comfort indices will be shown for the bedroom with SW exposure, this option being reasoned also by the intention to investigate the influence of the three types of exterior walls in the area with the highest exposure to outdoor climate conditions. If negative deviations are not conclusive for the comparison between thermal performances of the three envelope variants, due to the heating system, yet the scenarios without cooling system demonstrate the effectiveness of materials with a higher coefficient of heat assimilation. Therefore, the brick masonry contributes significantly to environmental thermal stability, the rammed earth with straw bales having a notable impact on attenuation only over the major variations in temperature.

Also as an objective indicator, the final energy consumption for heating and cooling the dwelling is determined for cases II, IV and VI, wherein inhabited environments are conditioned by maintaining indoor air temperature between 20÷25°C (Fig.5). The high energy performance of straw bales wall is due to the level of thermal insulation, being close to the rammed earth with straw wall, but it is slightly decreased by the lower capacity to absorb heat.

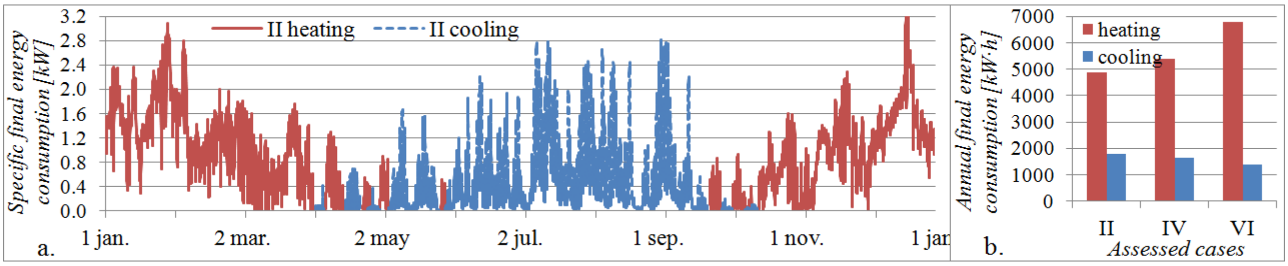

Fig.5. Final energy consumption for heating and cooling; a. Specific consumption; b. Annual consumption

A more relevant picture on the quality of the inhabited environment, in terms of human perception, is shown in Figures 6-8 through PMV index, which lays out anticipation for the mean vote given by a large group of persons, on a seven-point scale of thermal sensation (Table 4). At the basis of this judgment there are evaluation elements of the human body heat balance. This evaluation operates with the hypothesis that the loss of heat to the environment is compensated by the internal heat production in the body. Considering metabolic and physiological particularities of individuals, there are expected different occurrences in the way that the human thermoregulatory system will attempt to modify skin temperature and sweat secretion. Therefore, certain degrees of uncertainty have been regarded through the subjectiveness of a vote.

For the cases without cooling system, periods of discomfort are recorded only in the hot season, with very short intervals for the variant of building with brick walls, but with significant intervals for variants with natural materials. For the cases with cooling in summer, there is no recording of discomfort.

Table 4. Seven-point thermal sensation scale (SR EN ISO 7730:2006)

PMV [-]	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The PPD index reflects the state of comfort in a less nuanced manner, classifying it in thermal satisfaction, which corresponds to thermal sensations of slightly warm, neutral and slightly cool, and thermal dissatisfaction, which corresponds to thermal sensations of hot, warm, cool and cold.

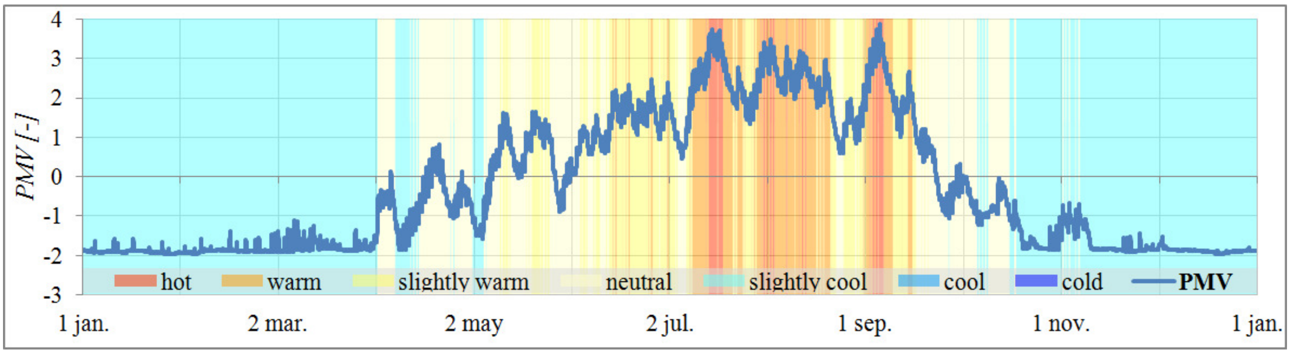

Fig.6. Predicted mean vote for SW bedroom – Case I

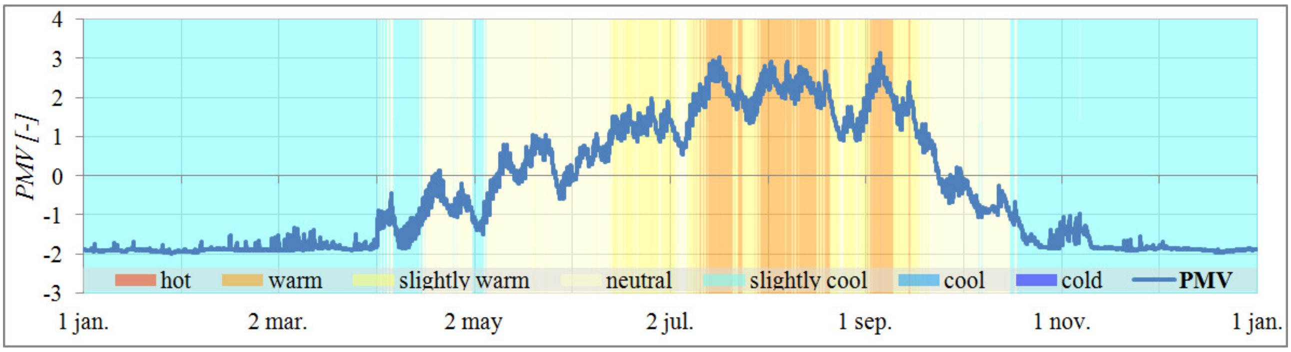

Fig.7. Predicted mean vote for SW bedroom – Case III

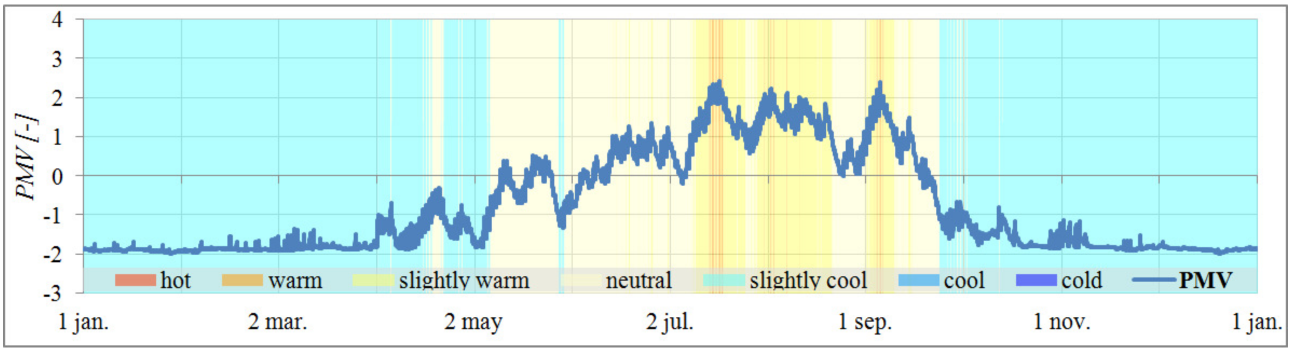

Fig.8. Predicted mean vote for SW bedroom – Case V

Evaluation of thermal comfort conditions by applying standard SR EN 15251:2007 reveals an incidence of 13.8% for thermal dissatisfaction for case I (Fig.9), which corresponds to hot and warm sensations, close as order of magnitude with thermal dissatisfaction incidence within case III (Fig.10). Therefore, it results in 50 days of discomfort for case I, 39 days for case III, respectively 4 days for case V (Fig.11). The transposing of graphs from Figures 6-8, into expressing the incidence of thermal sensations and thermal satisfaction, is completed with representing the incidence of thermal environment categories from Table 5.

Table 5. Categories of thermal environment (SR EN 15251:2007)

Category	Thermal state of the body as a whole	
	PPD [%]	PMV [-]
I	< 6	-0,2 < PMV < +0,2
II	< 10	-0,5 < PMV < +0,5
III	< 15	-0,7 < PMV < +0,7
IV	> 15	PMV < -0,7 or PMV > +0,7

These categories are given rather as recommendations expected to be met in different situations, but without an imperative character. Thus, as explained in the standard, the first category should answer to a high level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons. Second and third categories are corresponding to expectations for new buildings, respectively existing buildings, while the last category should only be accepted for a limited part of the year. Without a cooling system it is very difficult to achieve the conditions for categories I-III, which are represented for cases I, III and V over 47, 51 and 62 days. Even for cooling in summer scenarios, the three categories are represented for cases II, IV and VI only for 158, 149 and 131 days.

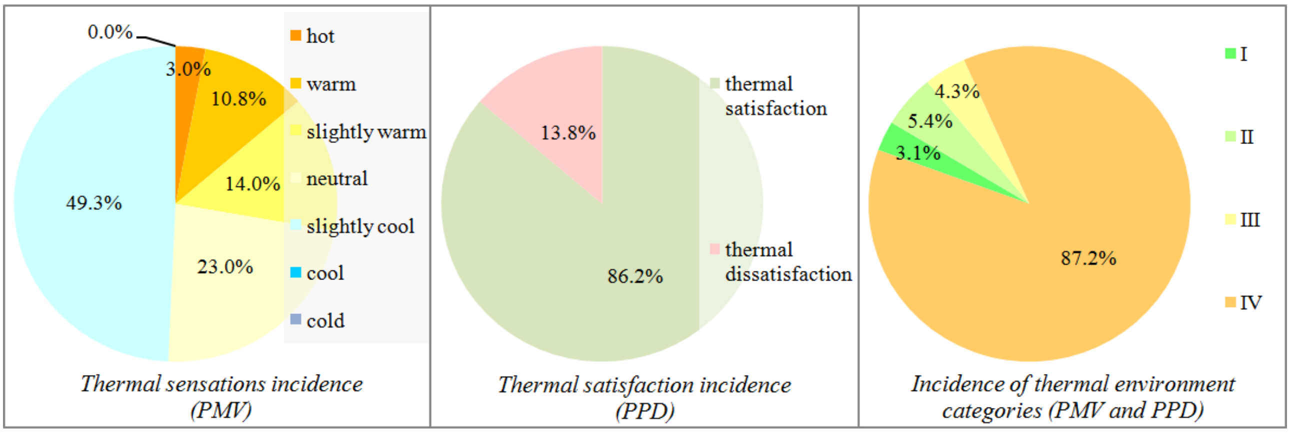

Fig.9. Thermal classification of the indoor environment for the SW bedroom – Case I

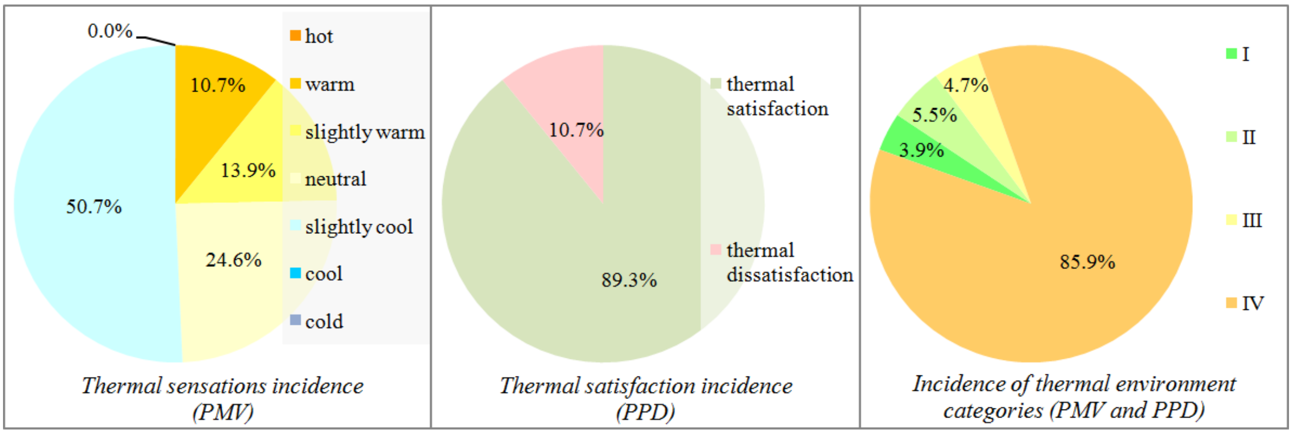

Fig.10. Thermal classification of the indoor environment for the SW bedroom – Case III

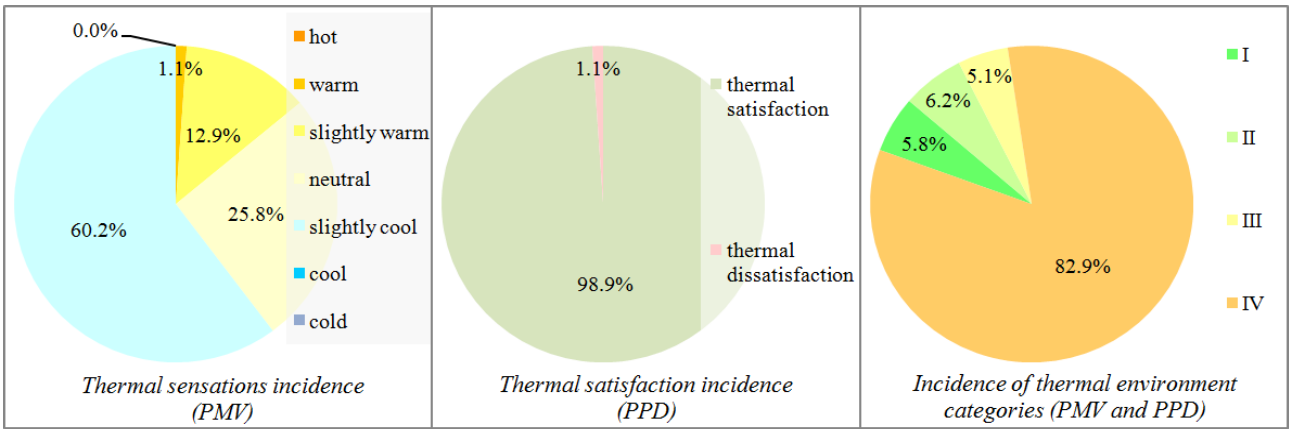

Fig.11. Thermal classification of the indoor environment for the SW bedroom – Case V

For buildings without air cooling system, SR EN 15251:2007 indicates four categories of the indoor environment for the hot season, considering an adaptive model, which requires for the occupants to have access to windows that can be opened, and also to be able to adapt their clothing to environmental conditions. In defining the boundaries of the 4 categories, the operating temperature is determined by the running mean external temperature.

5. CONCLUSIONS

The construction sector is currently experiencing trends of extending the current practices, from the application of classical materials, products and structures, to the development of innovative products, subjected to optimization processes, as a first direction, and as a second direction, to the reintroduction of traditional materials and techniques. In this context, there is a risk for the user perception to be detrimentally influenced by the term "natural", specific to the materials used in traditional techniques, and thus to be determined a popular advertising of agreeable concepts, without any analysis necessary to verify their compliance.

The results of this study reveal a potential high vulnerability of thermal comfort for the environment of dwellings made with natural materials and, without concluding towards penalizing those solutions, it is demonstrated the need for further research in order to benefit from advanced engineering expertise in optimization of such archetypal elements.

From the comparative analysis of the three envelope variants, the hygrothermal control of indoor environment parameters in narrower ranges results as the easiest way to improve thermal comfort in buildings made from natural materials, for a high thermal stability.

As an effect of the study presented in this paper, the following proposed research steps are aiming to numerical analyses of thermal and humidity fields, for details specific to envelope elements made of natural materials, with a view to defining a plan for monitoring the hygrothermal behaviour of a building by in situ measurements.

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