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QUANTIFICATION OF SOLAR INFRARED RADIATION IMPACT ON OPAQUE SURFACES OF RESIDENTIAL BUILDINGS ENVELOPE AS HEAT GAIN FACTOR FOR OPTIMIZED ENERGY BALANCE MODEL

BY

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Abstract. The authors clarifie key aspects regarding the capacity of building envelope opaque surfaces to capture and store solar energy and new opportunities emerging in determining the optimal net thermal energy demand for heating residential buildings following the freshest information provided in the updated international norm EN ISO 13790:2008. These ones aims to identify key indicators thoroughly edifying for their intended purpose and shaping usage through case studies developed using numerical simulations based on the relationship between exterior walls parameters and specific climatic data for 5 major locations.

Key words: optimization; infrared solar radiation; solar heating; buildings envelope; heat balance; black walls; emissivity.

1. Introduction

All latest updated European Directives enforce the Member States to promote the implementation of new measures, instruments and calculation methodology to improve the buildings energy performances. This study aims to

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demonstrate the global benefits of good insulated building envelopes. Energy benefits related to the economic issues are critical and the final users see supplementary insulation as an additional useless extra cost for the dwelling at the purchase phase, with small attention to the future managing costs. In a first step, the study consists in demonstrating the further significant economic advantages that come out from an optimized high-performance building envelope and heating system.

The net solar heat gains that an opaque surface without transparent insulation can accumulate during the heating season can be only a small portion of the total solar heat gains which are partially compensated by radiation losses from the building to clear skies. However, for grey to dark, poorly insulated surfaces, or large areas facing the sky, the solar heat gains accumulated through opaque elements can become extremely important for total energy balance, especially close to the middle spring or beginning of autumn.

Thermal energy balance of the new low energy buildings suppose that technical design and details follow the next principles:

a) solar energy is a dominant part of the balance;

b) significant contribution to the balance of internal gains and heat recovery;

c) reduced impact of conventional heating.

Many studies had been conducted following the functions of the building shell that appears in indirect passive systems where absorption and accumulation of the transmitted solar energy are mandatory. Total amount of the useful solar gains from well designed indirect system (windows) is very close to the gains attainable from large indirect system (collecting and accumulating wall) due to surface amount ratio gap. A wall that transmits, absorbs and accumulates solar energy becomes for a building a real solar thermal collector. In the whole building scale heating demand reduction, due to this passive solar system, may reach 14% (Kisilewicz, 2009) and can increase in transient seasons climate conditions of Romania.

1.1. Optimization Problem

Mathematical optimization (or mathematical programming) implies a set of operations to facilitate the selection of a best element (with regard to some criteria or restrictions) from some set of available alternatives. Basically, an optimization problem consists of maximizing or minimizing a real function by systematically choosing input values from within an allowed set and computing the value of the objective function.

A thermal energy balance optimization problem can be represented in the following way:

Given: a function f: $A \rightarrow Q_{H,\text{net}}$ from indicators set A to the net thermal energy demand.

Searched: all indicators x in A set such that $f(x)$ provides a minimization, consequence that is restricted in the set of values provided by $Q_{H,\text{net}}$.

Optimization problem can be expressed under:

a) minimum and maximum values of objective function;

b) optimal input arguments.

In this problems class, the techniques are designed primarily for optimization in dynamic contexts, involving that

a) Calculus of variations seeks to optimize an objective defined over many points by evaluating how the objective function changes if there are small changes in the choice path.

b) Dynamic programming to study the case in which the optimization strategy is based on splitting the problem into smaller sub-problems.

The boundary conditions that implies in this process are revealed in Fig. 1.

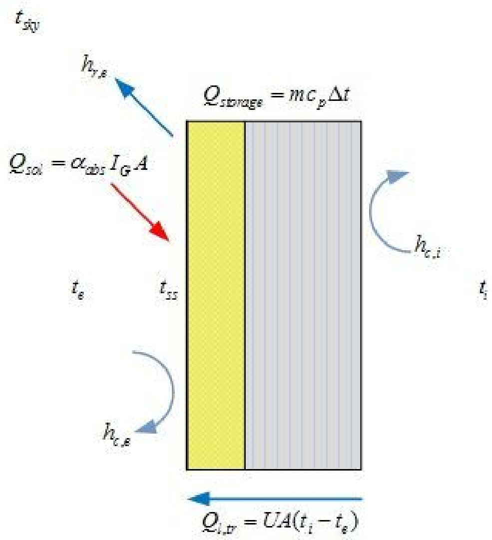


Fig. 1 – Boundary conditions in thermal energy balance evaluation of a building envelope opaque surfaces (see terms explaination in section 2.3.).

2. Review of Existing Methodologies for Solar Heat Gain Quantification

In this chapter, some of the most important calculation methodologies existing in Romania and new European norms will be presented, synthesizing most relevant informations regarding this aspect.

2.1. NP048 Romanian Normative Calculation Methodology

Considering that for steady state conduction heat transfer calculation it is used the monthly medium exterior air temperature which is measured at meteorological station in non-convective and no direct sunlight conditions, Romanian NP048 norm introduces the $t_{E_{Pe_j}}$ equivalent temperature to quantify the impact of solar heat load on exterior opaque walls surfaces namely

$$t_{E_{Pe_j}} = \frac{\alpha_{\mathrm{abs}_j}}{\alpha_e}\left[c_{s_j} I_{T_j} + (1 - c_{s_j}) I_{\mathrm{dif}_j}\right] + t_e, \ [^{\mathrm{o}}\mathrm{C}], \tag{1}$$

where: $t_{E_{Pe_j}}$ is the exterior equivalent temperatures for the exterior wall surface with j orientation; t_e – medium temperature of exterior air for the considered period, [$^{\mathrm{o}}$C]; $\alpha_{\mathrm{abs},j}$ – solar radiation absorption coefficient of the exterior wall surface with j orientation; α_e – superficial convection heat transfer coefficient for the external surface of the opaque walls derived from McAdams relation (Duffie & Beckman, 1974) for the medium wind speed (in Romania) 3 m/s: α_e = 17.0 W/m².K; $I_{T,j}$ – direct solar radiation intensity on the plan of the opaque element with the orientation j, [W/m²]; $I_{\mathrm{dif},j}$ – diffuse solar radiation intensity on the plan of the opaque element with the orientation j, [W/m²]; $c_{s,j}$ – sunlight factor of the surface orientation j, $0 \le c_{sj} \le 1$ (depending on shadow factor).

For estimative calculations are recommended $c_{s,j}$ = 0.55 – vertical surfaces and 0.70 – horizontal surfaces. (NP 048:2000).

Comparing to the latest EN ISO 13790 international standard the NP048 deficiencies may concern the following aspects:

a) Radiation heat loss is not accurate quantified as the α_e term is expressed globally in a fixed value (Duffie & Beckman, 1974, admits that superficial convection heat transfer quantify both convective and radiation heat loss).

b) Global radiation is splitted in two components $I_{T,j}$ and $I_{\mathrm{dif},j}$, corrected by a constant, $c_{s,j}$, that may not correspond with the results obtained utilizing international standards which use global irradiation in the algorithm.

c) Further constants applied to the entire calculation algorithm.

2.2. MC 001-4-2009 Calculation Methodology

Current regulation that applies in Romania – MC 001-4-2009 methodology – is inspired from the SR EN ISO 13790 up to 2005 version that do not propose any evaluation on this topic other than for glazed surfaces. However, in MC 001-4-2009 appears a formula for opaque elements solar heat gaining but the relevant term to explain the different results compared with updated EN ISO 13790:2008 version presented in next section, is the F_{sky} correction factor with the $I_{s,c}$ term as a denominator in eq. (3).

Effective collecting area of an element opaque envelope (wall, terrace), $A_{s,p}$, [m^2], is evaluated with

$$A_{s,p} = F_{\text{sky}} \alpha_{s,c} R_{se} U_c A_c,\ [\text{m}^2], \quad (2)$$

where: $\alpha_{s,c}$ is the dimensionless solar absorption coefficient for solar radiation of the opaque element; A_c – total area considered for the calculation of the wall, [m^2]; R_{se} – opaque element thermal resistance determined according Mc 001-PI, [m^2.K/W]; U_c – thermal transmittance of the opaque surface determined in accordance with Mc001-PI, [W/m^2.K]; F_{sky} – correction factor which takes account the heat exchange by radiation of the vault wall heavenly [m^2.K/W], calculated with

$$F_{\text{sky}} = \frac{1 - \varphi_{\text{sky}} t}{\alpha_{s,c} I_{s,c}}, \quad (3)$$

where: φ_{sky} is the uniform heat flux due to radiation heat transfer through the sky, [W/m^2]; $I_{s,c}$ – integrated total solar radiation (solar energy) on the opaque element surface, [MJ/m^2]; t – time interval, [Ms];

2.3. EN ISO 13790:2008 Standard Calculation Methodology

EN ISO 13790:2008 states the subclause that establishes the heat flow by solar gains, based on the effective collecting areas of the relevant building elements and corrections for solar shading by external obstacles. It also provides a correction for the thermal radiation to the sky. The collecting areas to be taken into consideration are: the glazing (including any integrated or add-on solar shading provision), the external opaque elements, the internal walls and floors of sunspaces, and walls behind a transparent covering or transparent insulation.

The heat flow by solar gains through building element k, $\Phi_{\text{sol},k}$, is given by eq.

$$\Phi_{\text{sol},k} = F_{\text{sh,ob},k} A_{\text{sol},k} I_{\text{sol},k} - F_{r,k} \Phi_{r,k},\ [\text{W}], \quad (4)$$

where: $F_{\text{sh,ob},k}$ – shading reduction factor for external obstacles for the solar effective collecting area of surface k; $A_{\text{sol},k}$ – effective collecting area of surface k with a given orientation and tilt angle, in the considered zone or space, determined in accordance with eq. (5), [m^2]; $I_{\text{sol},k}$ – solar irradiance, the mean energy of the solar irradiation over the time step, considered per square metre of collecting area of surface k, with a given orientation and tilt angle, [W/m^2]; $F_{r,k}$ – form factor between the building element and the sky with value as $F_r = 1$ for an unshaded horizontal roof and $F_r = 0.5$ for an unshaded vertical wall; $\Phi_{r,k}$ – extra heat flow due to thermal radiation to the sky from building element k, [W].

The effective solar collecting area of an opaque part of the building envelope, A_{sol}, expressed in m^2, is given by eq.

$$A_{sol} = \alpha_{s,c} R_{se} U_c A_c, \tag{5}$$

where: $\alpha_{s,c}$ is the dimensionless absorption coefficient for solar radiation of the opaque part, obtained from appropriate national sources – in Romanian context can be useful consulting NP048:2000 for different materials, texture and colour of the opaque element.

An optimum value for solar absorption coefficient had been established around a value of 0.45…0.65 taking into account the energy balance between heating and cooling needs (Yao *et al*., 2011).

R_{se} is the external surface heat resistance of the opaque part, determined in accordance with ISO 6946 [m^2.K/W], as revealed in Table 1.

Table 1
Correspondence between Wind Speed and R_{se}
(EN ISO 6946:2007)

Wind speed, [m/s]	R_{se}, [m^2.K/W]
1	0.08
2	0.06
3	0.05
4	0.04
5	0.04
7	0.03
10	0.02

However, for detailed simulation the convection heat transfer coefficient h_c (or α_c), between the surface and surrounding air, has two components (Hagentoft ,2001) that quantify the wind speed v, [m/s], impact over a building envelope:

a) Windward side element:

$$\alpha_c = 5 + 4.5v - 0.14v^2, \text{ [W/m}^2\text{.K]}. \tag{6}$$

Leeward (as defined on http://www.weca.org/nws-terms.html) side element – as the side of an object that is facing away from the direction that the wind is blowing:

$$\alpha_c = 5 + 1.5v, \text{ [W/m}^2\text{.K]}, \tag{7}$$

where: U_c is the thermal transmittance of the opaque part, determined in accordance with ISO 6946, [W/m^2.K]; A_c – projected area of the opaque part, [m^2].

The extra heat flow due to thermal radiation to the sky for a specific building envelope element, Φ_r, [W], is given by eq.:

$$\Phi_{r,k} = R_{se} U_{c,k} A_{c,k} h_r \Delta\theta_{er}, \text{ [W]}, \tag{8}$$

where: h_r is the external radiative heat transfer coefficient, [W/m^2.K]; $\Delta\theta_{er}$ – average difference between the external air temperature, t_e , and the apparent sky temperature, t_{sky}, is calculated using eq.

$$\Delta\theta_{er} = \frac{t_e - t_{sky}}{2}, \text{ [}^{o}\text{C]}. \tag{9}$$

The external radiative heat transfer coefficient, h_r , may be estimated using eq.

$$h_r = 4\varepsilon\sigma\left(\theta_{ss} + 273\right)^3, \text{ [W/m}^2\text{.K]}, \tag{10}$$

where: ε is the emissivity for thermal radiation of the external surface with informative values presented in Table 2.

Table 2

Emissivity of the most Common Construction Materials[1]

Material	ε
Concrete	0.94
Brick	0.75…0.80
Limestone	0.95
Plater	0.90…0.96
Glass	0.90…0.96
Wood	0.80…0.90
Roofing felt	0.93
Gypsum	0.80…0.90
Paints (all colours)	0.90…0.96
Clay	0.95
Brickearth	0.93

[1]Total emissivity, ε, for common building materials adapted from http://www.omega.com/temperature/z/pdf/z088-089.pdf

Hagentoft (2001) states that for emissivity quantification, "*in building physics applications following approximation is often use, which means that the absorptivity is approximately equal to the emissivity of a material*":

$$\varepsilon = \alpha_{s,c}\,, \tag{11}$$

where: σ is the Stefan-Boltzmann constant: σ = 5.67 × 10^{-8} W/(m^2.K^4); θ_{ss} – arithmetic average of the surface temperature and the sky temperature, [^{o}C], which is calculated with eq.

$$\theta_{ss} = \frac{t_s + t_{\text{sky}}}{2}\,. \tag{12}$$

As an approximation, $h_r = 5\varepsilon$, [W/(m^2.K)], which corresponds to an average temperature of 10°C.

Also, it is stated that "*when the sky temperature is not available from climatic data, the average difference, $\Delta\theta_{\text{er}}$, between the external air temperature and the sky temperature should be taken as 9 K in sub-polar areas, 13 K in the tropics and 11 K in intermediate zones*". To improve the results the authors consider relevant the following aspects regarding radiative heat transfer, as Hagentoft, (2001), states that „*t_{sky} depends on the surrounding surfaces and the atmosphere that has a long wave radiation exchange with the outer surface. A flat roof has only a radiation exchange with the sky.*" and „*for a totally clouded sky t_{sky} is equal to the exterior air temperature, t_e*". In these conditions we should have the following quantification formulas:

$$t_{\text{sky}} = 1.2t_e - 14\,,\ [^o\text{C}],\ \textit{horizontal surface, clear sky conditions}; \tag{13}$$

$$t_{\text{sky}} = 1.1t_e - 5\,,\ [^o\text{C}],\ \textit{vertical surface, clear sky}; \tag{14}$$

$$t_{\text{sky}} = t_e\,,\ [^o\text{C}],\ \textit{cloudy sky}\,. \tag{15}$$

As a particularly case that needs a more detailed approach should be mentioned the hypothesis of a snow covered roof that may reduce the radiative transfer due to new snow covered surface temperature and its insulating effect impact to the film temperature of the roof surface and the minimum emissivity level of a white surface.

All these indicators helps modeling an optimized case for net thermal energy demand, expressed for each square meter of opaque surface, which is calculated using 2 most relevant from the total of 5 default values for dynamic parameters for internal heat capacity of the building according to eq.

$$Q_{H,\text{net}} = Q_{H,ht} - \eta_{H,gn} Q_{H,gn}\,, \tag{16}$$

where: $Q_{H,\text{net}}$ is the net thermal energy need for continuous heating, [kWh]; $Q_{H,ht}$ – total heat transfer for the heating mode, [kW.h]; $Q_{H,gn}$ – the total heat gains for the heating mode [kW.h]; $\eta_{H,gn}$ – the dimensionless gain utilization factor according to EN ISO 13790:2008.

3. Numerical Modeling Case Studies

3.1. Initial Assumptions

It had been chosen 5 different locations, 4 major cities in Romania (Iaşi, Bucharest, Constanța and Miercurea Ciuc) affected by 4 major different climate zones and Copenhagen, Denmark.

Assumptions that were made are

a) interior temperature set to 21^{o}C;

b) time interval considered in evaluation corresponds to each entire month number of hours obtained by multiplying number of days by 24;

c) wind speed monthly average speed not taken into account dynamically as convection heat transfer coefficient, α_c, is considered to be 8 W/m^2.K;

d) external radiative heat transfer coefficient was approximated using $h_r = 5\varepsilon$, [W/(m^2.K)] eq.;

e) exterior air daily average temperature corresponding to each month of the year was specifically selected for each climate zone;

f) average daily solar radiation was considered over 2 tilted surfaces (0º – roof case and 90º – vertical exterior wall case) oriented to 4 major directions;

g) area of exterior wall opaque surface to heated surface ratio: 1 m^2/1 m^2;

h) variable *R*-value starting from 0.5 m^2.K/W to 10 m^2.K/W (corresponding to *U*-value: 2…0.1 W/(m^2.K)).

3.2. Climate Data

The first option to collect input climate data was the METEONORM 5 database, which is actually outdated for Romania due the fact that the values correspond to 1995 year's level. As an alternative, it had been chosen the European Comission http://re.jrc.ec.europa.eu database to extract external air monthly averaged temperatures (t_e) and global solar radiation parameters were collected using the Solar Radiation Data (SoDa) Online Tool http://www.soda-is.com, setting up 0.5 as an average value for albedo and expressed as daily value. SoDa tool collects data from HelioClim-3 Database of Solar Irradiance v2 (derived from satellite data) managed by MINES ParisTech - Armines (France) and has updated values until 2005 year's level.

Five different climate parameters databases have been constructed following the Table 3 samples.

Table 3
Climate Parameters for Iaşi (Climate Zone III – t_c = –18°C)

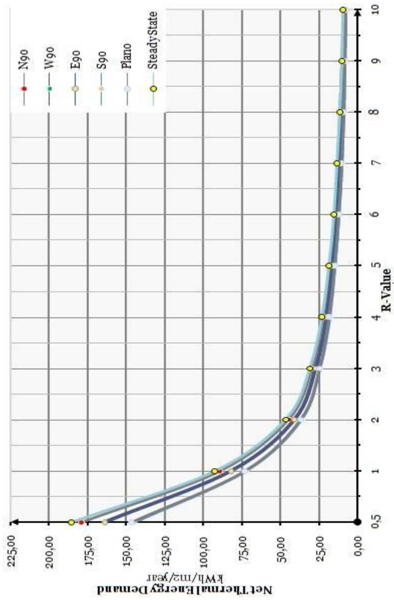
Month	No. of days	t_e, [°C]	North 90° W.h/m²	West 90° W.h/m²	East 90° W.h/m²	South 90° W.h/m²	Horizontally 0° W.h/m²
January	31	–2.40	22.50	32.30	32.20	67.90	46.20
February	28	0.20	31.00	37.30	37.40	51.10	55.60
March	31	4.20	56.80	111.70	110.60	189.30	157.30
April	30	11.00	74.50	132.00	133.60	182.20	200.40
May	31	16.70	93.00	168.50	163.60	180.40	257.50
June	30	20.20	101.50	166.60	169.00	164.40	261.10
July	30	22.20	97.13	163.89	169.47	174.63	258.85
August	31	21.40	80.50	145.50	140.60	172.30	214.80
September	30	16.00	61.90	120.10	122.40	192.80	177.70
October	31	10.90	42.10	73.50	74.10	145.10	108.00
November	30	4.80	26.00	37.40	34.60	69.40	52.40
December	31	–0.90	18.50	24.90	25.30	48.40	35.60

3.3. Parametric Case Studies Results

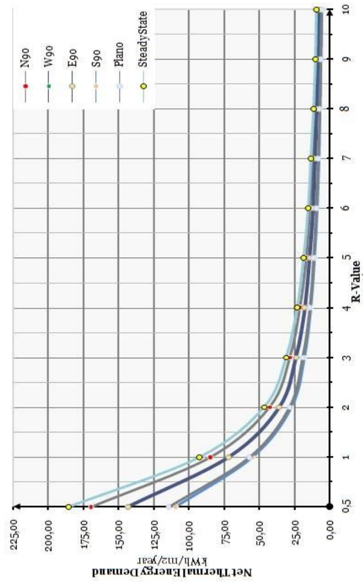
To allow numerical simulations and avoid errors or zero results in no internal gains situation, a small conditional correction had been made for $\gamma_H < 0$ (dimensionless heat-balance ratio for the heating mode according to EN ISO 13790:2008) and $Q_{H,gn} < 0$ case. The results can be consulted in Table 3 and it is mandatory to be noticed that for winter months there is a supplementary heat loss compared to the heat loss obtained applying only the steady state process as in $Q_{H,ht}$ formula existing in EN ISO 13790:2008.

Table 4
Particulary Case for Vertical North Oriented Opaque Wall Surface with ε = 0.8 and Very Heavy Thermal Mass – location: Iaşi

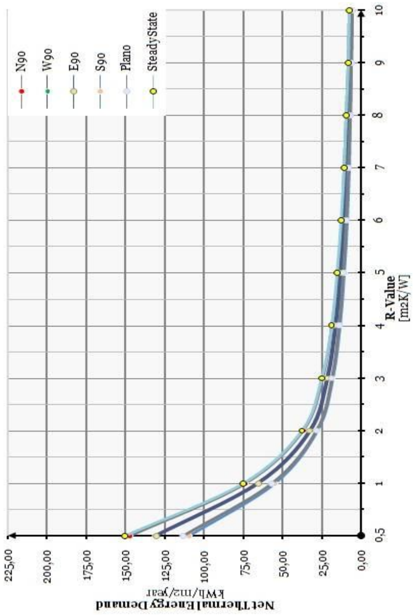
Month	$Q_{H,ht,\mathrm{N90}}$ kWh/m²/month	$Q_{H,gn,\mathrm{N90}}$ kWh/m²/month	$\eta_{H,gn}$	$Q_{H,\mathrm{net}}$ kWh/m²/month
January	17.41	–1.02	1.0000000000	18.42888
February	13.98	–0.26	1.0000000000	14.23968
March	12.50	1.78	0.9999998079	10.72106
April	7.20	3.24	0.9989581414	3.96338
May	3.20	4.94	0.6403436901	0.03818
June	0.58	5.52	0.1044386404	0.00000
July	–0.86	5.27	–0.1638598088	0.00000
August	–0.30	4.18	–0.0711743772	0.00000
September	3.60	2.51	0.9812767449	1.13425
October	7.51	0.93	0.9999999322	6.58072
November	11.66	–0.48	1.0000000000	12.13920
December	16.29	–1.26	1.0000000000	17.55468



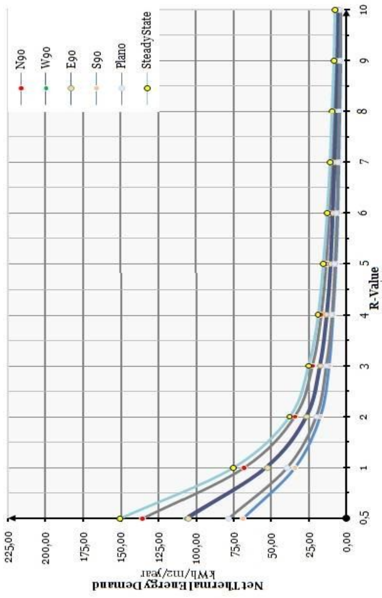
Iaşi ε = 0.3



Iaşi ε = 0.8

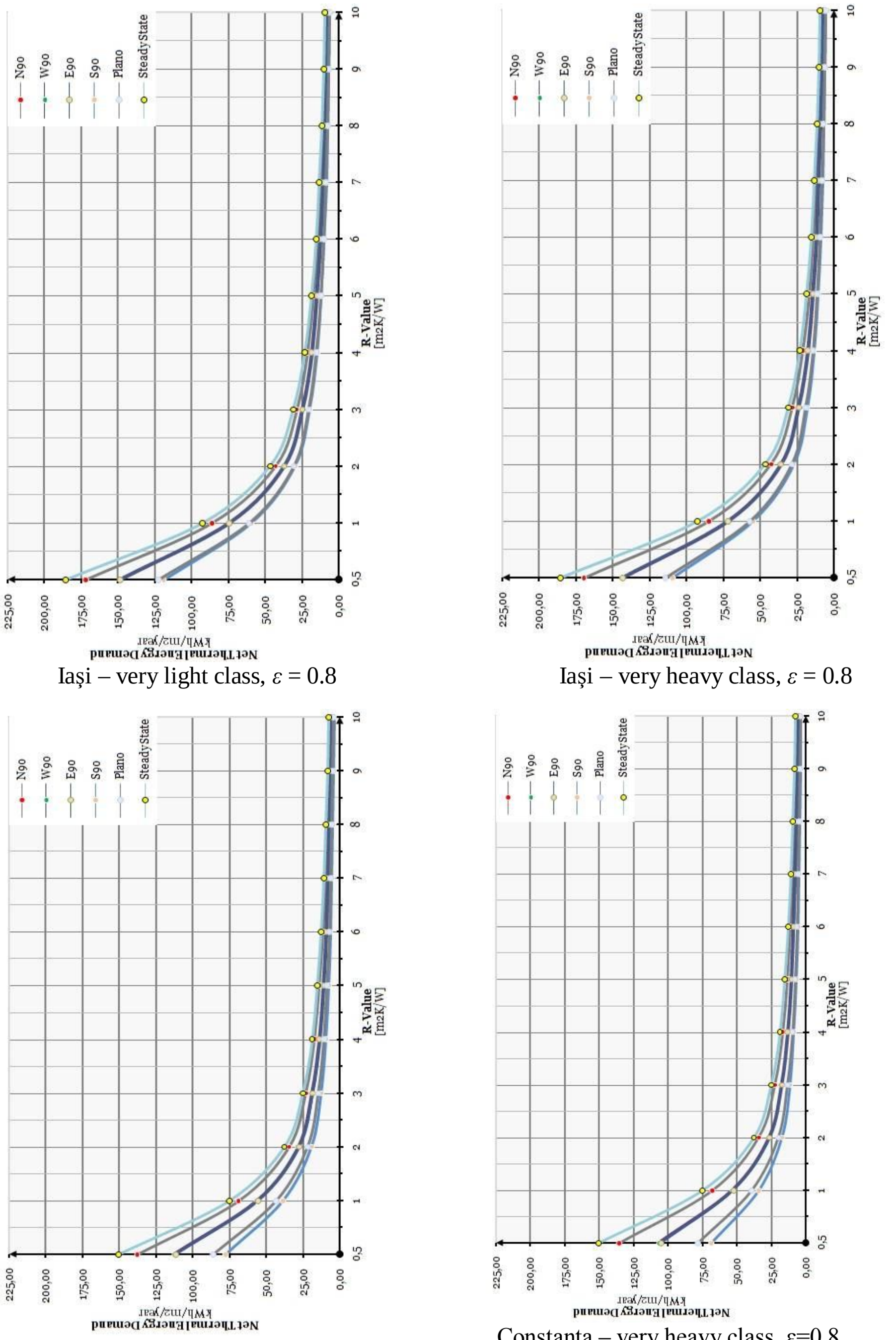


Constanța ε = 0.3



Constanța ε = 0.8

Fig. 1 – Emissivity value relevance in heat balance evaluation to find the optimized net thermal energy demand value.



Iaşi – very light class, ε = 0.8

Iaşi – very heavy class, ε = 0.8

Constanța – very light class, ε=0,8

Constanța – very heavy class, ε=0,8

Fig. 2 – Thermal mass class relevance in heat balance evaluation to find the optimized net thermal energy demand value.

A parametric study have emerged concerning net thermal energy demand expressed per square meter of opaque building envelope surface with ratio 1 to the heated space surface and the results are presented in Fig. 1 for different small or high common emissivity (ε) options and Fig. 2 for different thermal mass of walls construction system.

To have a relevant comparison for the case studies in different climates the parameters were set to emissivity ε = 0.8 (corresponding to a dark color concrete structure having a heavy thermal mass), with form factor for horizontal (0º) $F_{r,k}$ =1 and vertical wall (90º)case $F_{r,k}$ = 0.5, oriented to North,West,East and South directions, with no internal heat gains. The results are shown in Fig. 3 diagram.

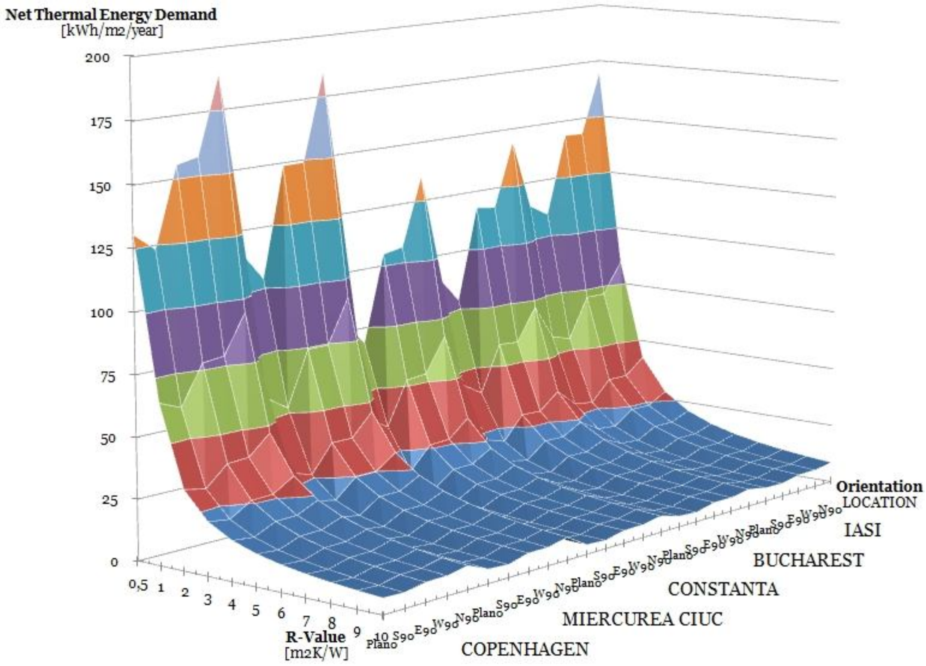


Fig. 3 – 3-D diagram showing annual net thermal energy demand for various R-values in different locations and orientations

It can be observed a decreased net thermal energy demand to compensate heat losses in a super insulated environment according to each location. However, for poor insulated walls a dark coloured surface oriented to South – South West – South East may compensate any accelerated heat loss in cool and sunny days conditions of spring and autumns but needs green roof or tilted panel for Sun exposure protection against hot summer days.

4. Conclusions

As before only solar heat gain through glazed elements was taking into account, in this paper were proposed defining elements in terms of an improved model for determining optimal energy demand for space heating in residential buildings in accordance with the latest details provided in new concepts of low-energy building techniques, as first major step approaching passive solar building design in order to achieve further autonomous building or net-zero energy building (NZEB) perspectives.

For light or very light walls construction systems with surfaces with bright colours and low absorptivity materials, the solar radiation impact will not be so relevant but all these mentioned aspects lead to the conclusion that it has to be considered at least when designing new buildings because solar influence really matters in the economy of energy saving politics.

The ratio of heating/cooling energy demand imply another discussion but actually affects only the quantified balance value in a manner that it is increasing for a low insulation and decreasing for better or super insulation cases.

All these aspects lead to an optimized approach in heat gaining/losses balance calculations and that can be justified economically through comparison between the heating system and collecting wall based on combined energy use and investment costs criterion application that request rationally designed relationship between passive and direct systems.

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CUANTIFICAREA IMPACTULUI RADIAŢIEI SOLARE ÎN SPECTRUL INFRAROŞU ASUPRA SUPRAFEŢELOR OPACE ALE ANVELOPEI CLĂDIRILOR DE LOCUIT CA FACTOR APORT DE CĂLDURĂ CU SCOPUL DE A OPTIMIZA BILANŢUL ENERGETIC

(Rezumat)

Se clarifică principalele aspecte legate de capacitatea suprafeţelor opace ale anvelopei clădirilor de locuit de a capta şi stoca energia solară şi se conturează noile oportunităţi în privinţa determinării optime a necesarului net de energie termică pentru încălzirea clădirilor de locuit folosind informaţiile cele mai recente prevăzute în varianta actualizată a normativului internaţional EN ISO 13790:2008. Se propune identificarea minuţioasă a principalilor indicatori edificatori pentru scopul propus şi modelarea comportării acestora prin intermediul unor studii de caz formulate în baza unor simulări numerice funcţie de parametrii pereţilor exteriori şi de datele climatice specifice de calcul.