OPEN ACCESS

2nd World Sustainability Forum
1-30 November 2012

www. wsforum.org

*Article*

# Evaluation of environmental sustainability of material compositions of building structures

**Monika Čuláková [1,*], Silvia Vilčeková[1] and Eva Krídlová Burdová[1]**

[1] Civil Engineering Faculty, Technical University of Kosice / Vyskoskolska 4, 04200 Kosice, Slovakia

E-Mails: monika.culakova@tuke.sk (M.C);silvia.vilcekova@tuke.sk (S.V.)

* Author to whom correspondence, E-mail: monika.culakova@tuke.sk; Tel.: +421-555-602 4262

*Received: / Accepted: / Published:*

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**Abstract:** The paper focuses on evaluation of material compositions of residential building structures in terms of environmental sustainability and influence on energy performance. We calculate the most preferred environmental indicators such as embodied energy from non-renewable resources, Global Warming Potential and Acidification Potential of materials by methodology Life Cycle Assessment within boundary Cradle to Gate. Study of the environmental and energetic effectiveness of designed structures points to importance of suitable choice of materials. By improving the energy performance of building through used higher amount of materials and components is reflected in higher embodied energy and associated emissions. Plant materials compared with other materials prove huge advantage in terms of stored carbon and used clean solar energy. The results of multi-criteria analysis of structure alternatives shows that passive house from traditional nature plant materials with minimal modification require much lower energy used in manufacturing and result in lower emissions from fossil fuel than passive house of other materials. The study would provide a new optimization method for building envelope design in Slovak climatic conditions tends to the lowest environmental impacts of building during construction and occupation phase. Sustainable building is one of the most significant challenges we face. Our responses to environmental issue will influence the quality of life for future generations.

**Keywords:** building materials; environmental aspects; life cycle assessment.

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## 1. Introduction

Buildings are of high environmental relevance; participates 50% in energy consumption of total use energy and associated production of emissions. The operation phase of buildings accounts for 30% of the total energy consumption [1]. Decreasing energy intensity of buildings during the occupation phase present first step to improving the environmental sustainability, it should be pointed out that not only is the occupation phase a source of environmental loads, but the whole life cycle [2]. The buildings influence the energy consumption of future generations and the deconstruction and recycling or disposal will take place about 80–100 years after the construction. The construction sector has significant potential towards more sustainable development [1].

The energy consumed by operation can be readily measured, however the embodied energy contained in the structures is difficult to assess. This energy use is often hidden and can only be fully quantified through a complete LCA. Thormak analyzed energy use in Swedish low energy buildings and found that, for a one-family home with a lifetime of 50 years, embodied energy accounted for some 45% of the whole-life energy requirements [3]. Mithraratne and Vale found that the initial embodied energy of energy efficient residential buildings are often higher than that of conventional buildings, but because the operation energy is much reduced in the energy efficient house compared with the conventional house the overall environmental impact is usually reduced [4]. The analysis of the life cycle inventory of the four dwellings in Belgium demonstrated that reducing the energy consumption of dwellings, the embodied energy increases. However, an increase of the embodied energy with 20–510 $MJ/m^3$ leads to a reduction in energy consumption of 5,5 to even 26 $GJ/m^3$ in 30 years depending on the dwelling and final energy performance level. The sum of both embodied energy and primary energy consumption during usage remains much smaller for extremely low energy dwellings than for average dwellings [5]. Asif et al. evaluated environmental impacts of construction phase of eight materials (timber, concrete, glass, aluminium, slate, ceramics tiles, plaster board, damp course and mortar) for dwelling in Scotland and found that the material used in the house with the highest level of embodied energy was concrete, at 61% [6]. Peuportier compared environmental profiles of three single-family houses in France with a service life of 80 years: a standard construction made of concrete blocks, a solar house made of stones and wood and a well-insulated wooden frame reference house. The results of study showed that the increase of $CO_2$ emissions of the standard concrete blocks house compared to the well-insulated wooden house represents 18% of the total emissions for the wooden house [7].

Researching and evaluating the environmental performance of building materials in structures may help to make better choices in the design phase of building towards environmental sustainability development. This case study compare alternative structures in terms of embodied energy from non-renewable resources, embodied emissions $CO_2$ eq. (Global Warming Potential) and embodied emissions $SO_2$ eq. (Acidification Potential) by methodology Life Cycle Assessment (LCA) within boundary Cradle to Gate (results of environmental assessment are seen in Table 1). LCA is widely known for evaluating the environmental impacts of a product or process over their whole life-cycle, from its origin to its final disposal or recycling and its principles and framework are described in international standards ISO 14040 and ISO 14044 based on four stages: defining the goal and scope, inventory analysis, impact assessment and interpretation [8]. The initial data of environmental aspects are extracted from IBO database [9], only for straw are from Wihnan's study [10].

Furthermore, material compositions of alternatives are compared on the basis of impact on future operational energy consumption (for heating and cooling) by calculated thermal-physical parameters such as heat transmittance (U), thermal storage (Q), surface temperature ($\theta_s$), phase shift of thermal oscillation ($\psi$) and these parameters are specified in Slovak standard STN 73 0540. Calculated relaxation time ($\tau$) describes ability of building structure to stabilize of inner temperature (results of assessment are seen in Table 2). The relaxation time depends on order of material layers and is explained by following equation [11].

$$\tau = \sum_{i=1}^{n} \left( \frac{d_i^{\,2}}{2a_i} + \frac{\lambda_i \cdot d_i}{a_i} \sum_{j=i+1}^{n} \frac{d_j}{\lambda_j} \right)$$

where is:

d - thickness [m],

m - weight per unit area [kg/m$^2$],

$\lambda$ - coefficient of heat conductivity [W/(m.K)],

a - temperature coefficient of conductivity [m$^2$/s)],

## 2. Description of exterior wall alternatives

All material compositions exterior wall alternatives comply with nearly zero energy level and they are described from interior side.

Exterior wall A: plasterboard (15 mm), installation zone (40 mm), vapour barrier, mineral wool insulation between 2 x wood KVH profiles (2 x 160 mm), mortar and silicate plaster (15 mm).

Exterior wall B: gypsum fiberboard (15 mm), flax insulation with PE in installation zone (60 mm), osb 3 with airtight tapes (15 mm), flax insulation between wood I- joists (240 mm), chipboard (15 mm), ventilation zone (30 mm), wood paneling - larch (15 mm).

Exterior wall C: loam plaster on cane mat (20 mm), osb 3 with airtight tapes (15 mm), cork insulation between wood box beams (360 mm), osb (15 mm), ventilation zone (40 mm), wood paneling - larch (22 mm).

Exterior wall D: plasterboard (15 mm), hemp insulation with PE in installation zone (60 mm), diffusion opened foil, cross laminated wood panel CLT (124 mm), diffusion opened foil, ventilation zone (40 mm), wood paneling - larch (22 mm).

Exterior wall E: wood paneling (20 mm), lamb's wool insulation in installation zone (60 mm), osb 3 with airtight tapes (15 mm), cellulose wood fibreboard insulation between wood I-joists (240 mm), diffusion opened foil, ventilation zone (40 mm), wood – half round shape (50 mm).

Exterior wall F: loam plaster on cane mat (20 mm), magnezite wood-fibreboard (16 mm), lamb's wool insulation in installation zone (50 mm), osb 3 with airtight tapes (15 mm), straw bales between wood beams (400 mm), loam plaster (50 mm).

## 2. Results of evaluated alternatives

The results of assessment of environmental indicators (Table 1) and environmental profile of evaluated exterior walls A - F (Fig. 1) presents that alternative F achieves the best values in terms of embodied energy (EE), embodied $CO_2$ eq. ($ECO_2$) and embodied $SO_2$ eq. ($ESO_2$)   However, F has the highest square weight, but it is no problem because almost all used materials are locally available and impact of transport is minimal. The straw, used as thermal insulation, participates 72% in reduction of carbon footprint of structure. The alternative F assures reduction of EE from 50% to 81% and $ESO_2$ from 49% to 80% in comparison with other alternatives. This alternative F is able to elimination of $ECO_2$ about 11% - 160% better than other alternatives.

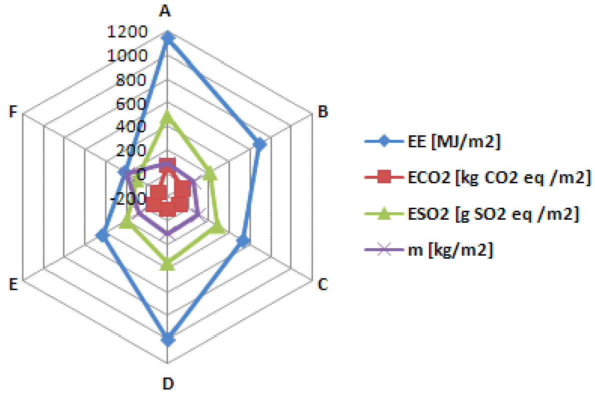


**Figure 1.** Environmental profile of A-F structure alternatives

| Alt. | EE [MJ/m$^2$] | $ECO_2$ [kg $CO_2$ eq /m$^2$] | $ESO_2$ [kg $SO_2$ eq /m$^2$] | m [kg/m$^2$] |
|---|---|---|---|---|
| **A** | 1134.215 | 68.637 | 0.4821 | 80.580 |
| **B** | 685.904 | -53.912 | 0.2101 | 55.080 |
| **C** | 524.980 | -85.694 | 0.2844 | 97.075 |
| **D** | 994.441 | -102.737 | 0.3528 | 104.983 |
| **E** | 435.533 | -69.632 | 0.1934 | 64.605 |
| **F** | 218.043 | -115.913 | 0.0975 | 188.216 |

**Table 1.** Results of environmental indicators of evaluated structures

All evaluated alternatives fulfil U-value for nearly zero energy houses. The annual balance of water vapour is active ($g_c < g_v$) and amount of condensation water ($g_c$) is under 0.5 kg/m$^2$.yr. The material composition of F represents the most suitable alternative in terms of thermal stability; it achieves the best values of thermal storage, phase shift of thermal oscillation and surface temperature and high value of relaxation time. From this perspective, the second most suitable alternative is D (Table 2).

| Alt. | U [W/(m$^2$K)] | Q [kJ] | $\Psi$ [hrs] | $\tau$ [hrs] | $\theta_s$ [°C] | $g_v$ [kg/m$^2$.yr] | $g_c$ [kg/m$^2$.yr] |
|---|---|---|---|---|---|---|---|
| **A** | 0.127 | 70.313 | 14.246 | 70.872 | 18.89 | 0 | 0 |
| **B** | 0.124 | 58.650 | 10.373 | 139.718 | 18.99 | 10.4150 | 0.0026 |
| **C** | 0.106 | 94.026 | 14.748 | 151.339 | 19.14 | 10.3547 | 0.0003 |
| **D** | 0.115 | 192.605 | 19.646 | 331.882 | 19.06 | 0 | 0 |
| **E** | 0.126 | 74.970 | 12.306 | 58.312 | 18.97 | 0 | 0 |
| **F** | 0.102 | 219.035 | 24.007 | 305.619 | 19.17 | 3.8035 | 0.0618 |

**Table 2.** Results of selected parameters of evaluated structures

All resultant values of assessments of structure alternatives are compared by calculating three methods of multi-criteria decision analysis: Weighted Sum Approach (WSA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Ideal Points Analysis (IPA). The best value for method WSA and TOPSIS is the nearest to 1.0; for IPA is nearest to 0.0 [12]. In the case of weights of multi-criteria decision analyze of alternatives for exterior walls are equal; F is the most suitable alternative (Table 3). In the case of weights of evaluated structure alternatives determined according to level of signification and size of differences between resultant values for particular evaluated parameters and their values are: 7.5% for square weight, 12.5% for embodied energy, embodied $CO_2$ eq. and embodied $SO_2$ eq., 5.0% for U-value and surface temperature, 15.0% for thermal storage, phase shift of temperature oscillation, relaxation time; the most suitable alternative is F and order of other alternatives is D, C, E, B and A (Table 4).

| **Alt.** | **WSA** | **IPA** | **TOPSIS** |
|---|---|---|---|
| **A** | 0.1346 | 0.8654 | 0.2345 |
| **B** | 0.4039 | 0.5961 | 0.4573 |
| **C** | 0.5905 | 0.4095 | 0.5873 |
| **D** | 0.6272 | 0.3728 | 0.5510 |
| **E** | 0.4178 | 0.5822 | 0.4742 |
| **F** | 0.8782 | 0.1218 | 0.7321 |

**Table 3.** Results of three methods of multi-criteria analysis in case of similar weights

| **Alt.** | **WSA** | **IPA** | **TOPSIS** |
|---|---|---|---|
| **A** | 0.1210 | 0.8790 | 0.1722 |
| **B** | 0.3761 | 0.6239 | 0.4371 |
| **C** | 0.5221 | 0.4779 | 0.5102 |
| **D** | 0.6557 | 0.3443 | 0.5835 |
| **E** | 0.4053 | 0.5947 | 0.4672 |
| **F** | 0.9106 | 0.0894 | 0.8120 |

**Table 4.** Results of three methods of multi-criteria analysis in case of different weights

## 4. Conclusion

The case study highlights importance of decisions made in the design phase of building in context of selection of materials. The optimization of material composition of structures assures high environmental and energy performance of building from long term point. The nature plant matters are renewable resources, use mainly solar energy for production and bind carbon dioxide from the atmosphere during growth. Therefore, increasing application of these materials in structures contributes to climate protection and presents possible way towards sustainable development. The best alternative with the lowest level of embodied energy (218.043 $MJ/m^2$) and the highest level of elimination emissions of $CO_2$ eq. (-115.913 kg $CO_2$ eq $/m^2$) is alternative F. It is thanks to used straw as thermal insulation which participates approximately 70% in material volume, contributes only 5% for embodied energy and 77% for reduction of embodied $CO_2$ eq. emissions. This material is agricultural waste, renewable and everywhere available. The old traditional houses from straw and loam are possible to see in the East part of Slovakia.

## Acknowledgments

This analysis of building structures was financially supported by the Slovak Grant KEGA No. 004TUKE-4/2011.

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