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Evaluation of environmental sustainability of material compositions of building structures

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Abstract: 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. The paper focuses on evaluation of material compositions of residential building structures in terms of environmental sustainability and influence on energy performance. The most preferred environmental indicators such as embodied energy from non-renewable resources, Global Warming Potential and Acidification Potential of materials by LCA within boundary Cradle to Gate were calculated. Study of the environmental and energy effectiveness of designed structures points to importance of suitable choice of materials. By improving the energy performance of building through higher amount of materials and components used is reflected in higher embodied energy and associated emissions. Plant materials prove huge advantage in terms of stored carbon and used clean solar energy comparing to other materials. The results of multi-criteria analysis of structure alternatives show that passive house from traditional nature plant materials with minimal modification requires much lower energy used in manufacturing process and results in lower emissions from fossil fuels than passive house of conventional materials. The case study develops a new optimization method for design of building envelope in Slovak climatic conditions tending to the lowest environmental impacts of building during construction and use stage.

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

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1. Introduction

Buildings have high negative environmental impact; participate in total energy consumption and associated production of emissions by 50%. Operation of buildings consumes more than 30% of the total energy [1]. Reduction of energy consumption and environmental impacts of buildings has recently become a priority in policies in European countries. These policies are being integrated in energy strategies and building regulations at different scales especially through direct and indirect actions which are aimed at reducing of energy requirements during the use stage. This is the first important step for improving of environmental sustainability of buildings. However, it should be pointed out that besides the use stage also the other phases of life cycle are the source of environmental concerns. The overall environmental burdens of buildings extend beyond the operation phase as they also include the embodied energy and embodied emissions related to extraction of raw materials, transportation, production and demolition at the end-of-life. Furthermore, each phase can influence one or more of the others. For instance, the selection of building materials and components can improve the energy performance of buildings but might also lead to increase of embodied energy and transport-related impacts [2].

The analysis of life cycle of four typical residential buildings in Belgium showed the relative small importance of the embodied energy of buildings comparing to energy consumption during the use stage. The total embodied energy corresponded to 25-30% of the primary energy consumption during 30 years of use of the building for common residential buildings that comply with the legal energy performance level. Only extremely energy performance buildings might have a total embodied energy higher than the energy consumed during 30 years of occupation [3]. Swedish study analyzed the total energy balance of energy efficient apartment housing and found that embodied energy accounted for 45% of the total energy needs during lifetime of 50 years [4].

Scottish study evaluated environmental impacts of construction phase of eight materials (timber, concrete, glass, aluminium, slate, ceramics tiles, plaster board, damp course and mortar) of dwelling and found that concrete was the material with the highest share of embodied energy (61%) [5]. In the French study of three single-family houses within life span of 80 years, environmental profiles were compared. The results showed that the increase of CO_2 emissions of the standard concrete house represented 18% of the total emissions comparing to the well-insulated wood framed house. Wood framed structures allow CO_2 storage throughout the life of a building [6].

Evaluating of the environmental performance of building materials in structures may result in better decisions in the building design towards environmental sustainability. This case study assesses material compositions of structures using Life Cycle Assessment (LCA). The LCA is widely known method for evaluating the environmental impacts of a product or process over their whole life-cycle, from their origin to the final disposal. The principles and framework of LCA are specified in ISO 14040 and ISO 14044 based on four stages: defining the goal and scope, inventory analysis, impact assessment and interpretation [7].

The designed structure alternatives are analyzed in terms of embodied energy from non-renewable resources, emissions of embodied CO_2eq (Global Warming Potential) and embodied emissions of SO_2eq (Acidification Potential) within Cradle to Gate system boundary. The initial data for calculation of environmental indicators are extracted from IBO database [8] (data for straw are from Wihnan’s study [9]).

The case study also evaluates material compositions in terms of their impact on future energy consumption (for heating and cooling) by calculating of thermal-physical parameters such as heat transmittance (U), thermal storage (Q), surface temperature (θ_s), phase shift of thermal oscillation (ψ) and relaxation time (τ). All parameters (except for relaxation time) are specified in Slovak national standard STN 73 0540 [10]. The relaxation time expresses the ability of building structure to stabilize the inner temperature during stationary cooling (after turning the heating off) (Table 2). The relaxation time depends on the order of material layers and is explained by equation (1) [11].

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

where is:
d - thickness [m],
λ - coefficient of heat conductivity [W/(m.K)],
a - temperature coefficient of conductivity [m^2/s)].

2. Description of exterior wall alternatives

All material compositions of exterior wall alternatives comply with nearly zero energy level and are described from interior to exterior:

- Exterior wall A: plasterboard (15 mm), installation zone (40 mm), vapor barrier, mineral wool insulation (between 2 x wood KVH profiles (2 x 160 mm)), adhesive mortar with glass textile mash and silicate plaster (15 mm).
- Exterior wall B: gypsum fiberboard (15 mm), flax insulation with PE fibers in installation zone (60 mm), OSB3 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), OSB3 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 fibers in installation zone (60 mm), diffusion-open foil, cross laminated wood panel CLT (124 mm), diffusion-open 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), OSB3 with airtight tapes (15 mm), cellulose wood fiberboard insulation between wood I-joists (240 mm), diffusion-open foil, ventilation zone (40 mm), wood log – half round shape (50 mm).
- Exterior wall F: loam plaster on cane mat (20 mm), magnesite wood-fiberboard (16 mm), lamb’s wool insulation in installation zone (50 mm), OSB3 with airtight tapes (15 mm), straw bales between wood beams (400 mm), loam plaster (50 mm).

2. Results of evaluation

The results of assessment of environmental indicators (Table 1) and environmental profile of evaluated exterior walls A - F (Fig. 1) demonstrate that alternative F achieves the best values in terms of embodied energy (EE), embodied CO_2eq (ECO_2) and embodied SO_2eq (ESO_2). The wall F reaches the highest value of weight (per 1 square meter), but this is not an issue because the majority of all used materials are locally available and impact of transport is minimal. This alternative assures the reduction of EE from 50% to 81% and reduction of ESO_2 from 49% to 80% comparing to other alternatives. This alternative is able to eliminate ECO_2 by 11% - 160% comparing to other alternatives.

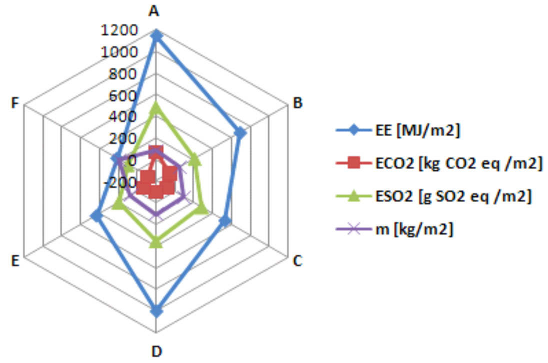

Figure 1. Environmental profile of structure alternatives A-F

Alt.	**EE [MJ/m^2]**	**ECO_2 [kg CO_2eq/m^2]**	**ESO_2 [kg SO_2eq/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 A-F

All evaluated alternatives fulfil the requirements on U-value for nearly zero energy houses ($U \leq 0.15$ W/(m^{2}K)). The annual balance of water vapour is active ($g_c < g_v$) and amount of condensed water (g_c) is under 0.5 kg/m^2.yr. The material composition F represents the most suitable alternative in terms of thermal stabilisation; it reaches the best values of thermal storage, phase shift of thermal oscillation and surface temperature, and relatively high value of relaxation time. From this perspective, the second most suitable alternative is wall D (Table 2).

Alt.	**U [W/(m^{2}K)]**	**Q [kJ]**	**Ψ [hrs]**	**τ [hrs]**	**θ_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 A-F

All resultant values of assessments of structure alternatives are compared through 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 number nearest to 1.0; while for IPA the best value is the nearest to 0.0 [12]. In the case of equal weights of multi-criteria decision analysis of alternatives, the most suitable alternative is the wall F (Table 3). In the second case the weights were determined according to level of signification and size of differences between resultant values for particular evaluated parameters. The weights are: 7.5% for square weight, 12.5% for embodied energy, embodied CO_2eq and embodied SO_2eq, 5.0% for U-value and surface temperature, 15.0% for thermal storage, phase shift of temperature oscillation, relaxation time. The most suitable alternative for this case is F. The order of other alternatives is D, C, E, B, 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 equal 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 the importance of decisions made in the design phase of buildings in the context of selection of materials. The optimization of material composition of structures assures high environmental and energy performance of buildings from long term point. The nature plant materials are renewable resources, use solar energy and absorb carbon dioxide from the atmosphere during their 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 of emissions of CO_2eq (-115.913 kg CO_2eq/m^2) is alternative F. It is thanks to the use of straw as thermal insulation which participates in material volume by 70%, contributes to embodied energy by only 5% and are responsible for 77% reduction of embodied CO_2eq emissions. This material is agricultural waste, renewable and broadly available. The old traditional houses from straw and loam can be still seen in the eastern part of Slovakia.

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