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Multi-Criteria Analysis of Material Selection in order to Reduce Environmental Impacts

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In world with limited amount of resources and with serious environmental pollution, it is obvious that more sustainable life style will be more and more important. The case study deals with possible way to sustainable development of dwelling located in Slovak Republic. The paper focuses on evaluation of energy and environmental performance of the building structures. The energy used in the extraction, processing and transportation of materials used in building structures can be significant part of the total energy used over the life cycle of a building, particularly in nearly-zero energy performance buildings. In order to reduce the embodied energy and embodied carbon, this study is aimed at material selection during the design stage of building. Material selection represents systematic and holistic approach to making decisions and can significantly affect the performance and sustainability of the building during its overall lifetime. For the purpose of optimalisation, it uses the method of multi-criteria analysis. The analysis of material compositions of structure alternatives shows that local available materials on plant base improve environmental potential of building because they lock carbon in their mass and consume solar energy for production of raw material source. The results of LCA (within boundary "cradle to gate") demonstrate that in spite of the increased amount of applied materials, the designed nearly zero energy family house with optimised structures achieves approximately 2.6 GJ per floor area and high negative balance of embodied carbon more than -700 kg of CO_2eq per floor area and represents possible way to reduce the carbon footprint.

1. Background of study

Buildings play a key place in our lives and society as a complex system. However, buildings account for a large share of energy and raw material consumption, global carbon emission and so on. It is estimated that buildings in the countries of the European Union consume approximately 50 % of the total energy use and this consumption can result in almost 50 % of the CO_2eq emissions released to the atmosphere over their life cycles (Kapalo, 2012). The residential buildings account for 75 % of the total stock in Europe and belong to the most significant CO_2 emissions sources (Economidou, et al. 2011), at 77 % in the European building sector (Balaras et al. 2007). Several environmental studies demonstrated that for buildings located in temperate or cold regions, the operational energy participates 80 % - 90 % in the life cycle energy consumption and embodied energy of material production accounts for 10 % - 20 %. Embodied energy used for on-site construction of the buildings (including transportation of materials to the site) and its demolition at the end of its lifespan accounted for a minor proportion (1 %) of the life cycle (Ramesh, et al. 2012). However, other LCA approach based on the input-output hybrid analysis demonstrated that the embodied energy can be as significant as the operational energy over the lifespan of the building. On average, the embodied energy represented 77 %, 60 % and 43 % of the life cycle operational energy for the passive house, low-energy house and normal construction (Stephan, et al. 2011).

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The building industry in The UK consumes more than 420 Mt/t of materials, 8 Mt/y of oil and releases 29 Mt/y of CO_2eq. Furthermore, this industry accounts for a large share of waste. It is estimated that amount of waste produced per 100 m^2 of constructed floor area is about 11.68 m^3. This waste is responsible for 1197 MJ of embodied energy per 1 m^2 of floor area and for 75.9 kg embodied CO_2 per 1 m^2 of floor area. Average total value of embodied energy, based on results of 14 UK dwellings, was determined to be 5.3 GJ/m^2 and the average embodied carbon dioxide 403 kg CO_2/m^2 of habitable floor area (Hammond and Jones, 2008). In several studies the calculated the embodied energy reached different values, e.g.: about 2.9 GJ/m^2 (Gustavsson and Joelsson, 2012), 4.4 GJ/m^2 (Rossi, et al. 2012), 3.9 GJ/m^2 (Stephan, et al. 2011), 5.3 GJ/m^2 (Monahan and Powell, 2011), 3.2 GJ/m^2 (Gustavsson, et al. 2010), 4.7 GJ/m^2 (Bribián, et al. 2009), 4.9 GJ/m^2 (Citherlet and Defaux, 2007), 3.6 GJ/m^2 (Sartori and Hestness, 2007), 5.4 GJ/m^2 (Thormark, 2006), 4.1 GJ/m^2 (Vonka, 2006). Considering the results presented in LCA studies of different residential buildings mainly with load-bearing system from bricks, concrete, wood, steel and with conventional insulation materials, located in Europe, it can be concluded that average resultant value of embodied energy is 4.3 GJ/m^2 of floor area. Average value of embodied CO_2eq, based on results of residential buildings from several previously mentioned LCA studies (is 349 kg CO_2eq/m^2 of floor area. However, the relative importance of embodied energy and emissions CO_2eq rise with improvement of energy performance of buildings. The high energy performance buildings have much larger embodied environmental impacts than others. This fact is caused by greater amount of insulation materials of building envelope. Material properties and selection are very important in the design stage of building and can have multiple effects on energy consumption and associated emissions during different phases of its life cycle (,Porhinčák, 2012). The potential of reduction of environmental footprint by using renewable building materials as substitutes for conventional used resource intensive materials is huge. High energy performance buildings from renewable plant materials play significant role in a sustainable future. This case study presents the possibility of optimalisation of material compositions or residential structures through environmental and energy analysis.

2. Case study

2.1 Methods of analyses

Environmental analysis of this case study is based on Life Cycle Assessment (LCA). LCA is a well known tool for analyzing environmental impacts in a wide extent throughout the life cycle of the building (cradle-to-grave) (Benedetto and Klemeš, 2008). It involves the assessment of specific elements of product system to determine its environmental impacts. However it has some limitations in practical building design by reason of highly data-demanding and work-intensive (Benedetto and Klemeš, 2009). This case study evaluates material selection of structures using LCA within system boundary: “cradle to gate”. LCA provides better decision support when optimising environmentally suitable solutions. The input data are mainly extracted from IBO database (Waltjen, 2009) and for straw bales from Wihnan’s study (Wihnan, 2007). The material compositions are compared by calculating of environmental indicators such as embodied energy from non-renewable resources (EE, global impact), embodied CO_2eq emissions (ECO_2, global warming potential, global impact) and embodied SO_2eq emissions (ESO_2, acidification potential, regional impact). This study takes into account impact of locked carbon in plant materials on total balance of ECO_2. Energy analysis is focused on calculation of selected thermal-physical aspects: heat transmittance (U), thermal storage (Q) and surface temperature (θ_{si}) in order to improve the energy performance of building envelope. Process of calculation of the parameters was based according to Slovak standard STN 73 0540 and Svoboda-Teplo 2009 software. Environmental and energy analysis is an integral component of sustainable building practice. Assessing amount of different criteria can help to make better decision to identify the most optimal solution for a given building design in concrete context. The results of material solutions are calculated by using multicriteria decision analysis (MCDA) in order to obtaining clear complex view of material selection. MCDA helps to bridge over several aspects of analysis simultaneously and offers the possibility of weighting the criteria in respect of significance level of a specific building design concept (Frenette, et al. 2008). The process of weighting is based on Saaty method (Korviny, 2009).

2.2 Material solutions of structures

The material solutions of structures are designed for residential buildings located in Slovak Republic. All proposed building structures comply with high energy performance residential building. This case study compares conventional solution for nearly-zero energy houses with alternative solutions from renewable materials. The description of material compositions for structure alternatives of building envelope (from interior to exterior side) is mentioned below.

Conventional floor 1F: wood parquet flooring (14 mm), acoustic wood fibreboard (6 mm), anhydrite screed (5 mm), cement screed (55 mm), PE foil, wood fibreboard insulation (60 mm), insured damp proof course, concrete slab with steel net (200 mm), damp proof course and geotextile, XPS (200 mm), gravel-sand layer (30 mm), separation geotextile, gravel layer (250 mm).

Alternative floor 2F: wood parquet flooring (14 mm), wood fibreboard insulation between lathes (40 mm), vapour barrier, wood boarding (27 mm), flax insulation with PE fibres between wood KVH 80x120 and 80x240 (360 mm), diffusion open foil, wood boarding (27 mm).

Alternative floor 3F: wood parquet flooring (12 mm), EPS impact sound insulation (3 mm), OSB 3 with airtight tapes (2x15 mm), hemp insulation with PE between wood profiles 60x80 (80 mm), vapour barrier, cross laminated timber panel with hemp insulation (340 mm).

Alternative floor 4F: cork flooring (20 mm), adobe bricks (60 mm), vapour barrier, OSB 3 (2x18 mm), straw bales between wood I - joists (400 mm), solid wood panel (212 mm).

Conventional exterior wall 1W: lime plaster (10 mm), honeycomb clay bricks (300 mm), EPS (200 mm) and diffusive open plaster system (lime-cement plaster, mortar with glass-textile grate, 10 mm).

Alternative exterior wall 2W: gypsum fibreboard (2x10mm), flax insulation with polyester fiber in installation zone (60 mm), OSB 3 with airtight tapes (15 mm), flax insulation between wood KVH 80x180 (180 mm), wood fibreboard insulation (50 mm), ventilation zone (40 mm) and wood boarding – larch (22 mm).

Alternative exterior wall 3W: cross laminated timber panel (124 mm), hemp insulation between wooden I-joists with wood-fibre insulation (300 mm), wood fibreboard insulation (40 mm), diffusion open plaster system (10 mm).

Alternative exterior wall 4W: loam plaster (20 mm), solid wood panel - connected with oak pins (200 mm), straw bales between wood I - joists (300 mm), diffusion open wood fibreboard (15 mm), ventilation zone (40 mm) and wood boarding – larch (22 mm).

Conventional roof 1R: lime plaster (10 mm), reinforced concrete (200 mm), XPS (370 mm), damp proof course and geotextile, gravel layer (70 mm).

Alternative roof 2R: gypsum plaster (10 mm), solid wood fibreboard (15 mm), wood fibreboard insulation between 60x60 (60 mm), OSB 3 with airtight tapes (15 mm), flax insulation between wooden KVH 60x180 and 80x220 (340 mm), diffusion open wood fibreboard (15 mm), ventilation zone (60 mm), contra-lathes (50x30) and clay roofing tiles.

Alternative roof 3R: gypsum fibreboard (2x10mm), hemp insulation with polyester fiber between wood profiles 60x80 (80 mm), vapour barrier, cross laminated timber (CLT) panel with hemp insulation with polyester fiber (340 mm), wood-fibreboard (35 mm), ventilation zone (80 mm), OSB (2x15mm), damp proof course and geotextile, gravel layer (70 mm).

Alternative roof 4R: loam plaster (20 mm), solid wood panel - connected with oak pins (212 mm), straw bales between wood I- joists (400 mm), diffusion open wood fibreboard (15 mm), ventilation zone (60 mm), wood boarding (27 mm), damp proof course and geotextile, gravel layer (30 mm), filter-textile and substratum (60 mm).

3. Results of case study

The results of environmental and thermal-physical analysis are presented in Table 1-3 for all structure alternatives of building envelope. Table 1 points out that alternative 4F is the best solution in terms of embodied energy (EE) and embodied CO_2eq (ECO_2). This it is thanks to used massive wood panel and insulation from straw bales. The floor 4F assures higher reduction of EE by 69 % than 1F, 39 % than 3F, 27 % than 2F, and higher elimination of ECO_2 by 138 % than 1F, 76 % than 2F, 74 % than 3F. The conventional solution of floor (1F) is the least suitable solution in terms of all environmental indicators, but this floor achieves the highest value of thermal storage (Q), especially thanks to the influence of ground and application of a layer of heavy material, such as reinforced concrete slab.

Table 1: The results of assessments of material solutions for floor alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2eq/m^2]	ESO_2 [kg SO_2eq/m^2]	weight [kg/m^2]	U [$W/(m^2.K)$]	Q [kJ/m^2]	θ_{si} [˚C]
1F	2,151.320	107.257	0.591	1,087.901	0.142	6,058.97	19.51
2F	912.821	-67.589	0.316	79.296	0.094	118.40	19.18
3F	1,094.326	-71.773	0.375	82.996	0.099	144.00	19.14
4F	665.157	-280.440	0.379	289.235	0.091	483.66	19.21

Table 2 indicates that alternative 4W is the most suitable solution in terms of EE and ECO_2 because it consists from massive wood panel and insulation from straw bales mainly. This wall 4W assures higher reduction of EE by 59 % than 1W and 3W, 40 % than W2 and higher elimination of ECO_2 by 126 % than W1, 80 % than W2, 67 % than W3. The conventional solution is the worst in terms of following indicators: EE and ECO_2. The wall W4 reaches the highest thermal storage and even higher value than conventional 1 W from bricks.

Table 2: The results of assessments of material solutions for exterior wall alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2eq/m^2]	ESO_2 [kg SO_2eq/m^2]	weight [kg/m^2]	U [$W/(m^2.K)$]	Q [kJ/m^2]	θ_{si} [˚C]
1W	1,102.586	65.330	0.245	289.660	0.140	271.22	18.76
2W	751.379	-50.580	0.282	85.780	0.136	82.96	18.83
3W	1,089.940	-81.094	0.378	101.394	0.110	194.22	19.06
4W	450.898	-247.043	0.265	173.495	0.117	319.17	18.97

Table 3 shows that solution 4R is the most suitable in terms of EE, ECO_2 and ESO_2. This roof 4R assures higher reduction of EE by 74 % than 1R, 50 % than 3R, 39 % than R2 and higher elimination of ECO_2 by 146 % than R1, 74 % than R2, 72 % than R3. The conventional solution 1R is the worst solution in terms of environmental performance but this roof achieves the best value of thermal storage (Q), thanks to applied heavy material layer – reinforced concrete.

Table 3: The results of assessments of material solutions for roof alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2eq/m^2]	ESO_2 [kg SO_2eq/m^2]	weight [kg/m^2]	U [$W/(m^2.K)$]	Q [kJ/m^2]	θ_{si} [˚C]
1R	2,597.281	131.515	0.599	527.590	0.099	611.87	19.14
2R	1,084.978	-72.919	0.430	124.960	0.094	95.02	19.19
3R	1,338.284	-80.598	0.446	232.343	0.096	137.14	19.26
4R	665.220	-284.488	0.327	366.800	0.096	350.67	19.24

Table 5: Total results of MDCA methods for floor alternatives

Alternative	WSA	TOPSIS	IPA	CDA
1F	0.3090	0.4602	0.6910	3.7983
2F	0.4652	0.4089	0.5348	3.3541
3F	0.4484	0.3945	0.5516	3.0356
4F	0.7862	0.7056	0.2138	1.1848

All assessment results were analysed using MDCA in order to obtaining clear complex view of material solutions considering the relative importance of each criteria. The process of weighting is based on Saaty method and resultant weights are: 21.9 % for embodied energy as well as for embodied CO_2eq, 12.0 % for embodied SO_2eq, 5.9 % for surface weight, 30.9 % thermal storage, 3.7 % heat transmittance and surface temperature. The weight for U-value is lower than excepted value, because all alternatives fulfil U-value requirement for nearly-zero energy house. The results are calculated through mathematical methods WSA, IPA, TOPSIS and CDA. The best resultant value of method Weighted Sum Approach (WSA) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is marked by the number nearest to 1, and for Ideal Points Analysis (IPA) the optimal solution is number nearest to 0. For Concordance Discordance Analysis (CDA) the best alternative is the one with the lowest number (Korviny, 2009). The resultant score of MDCA for material solutions is presented in Table 5 - 7. Table 5 demonstrates that floor alternative 4F reaches the best total score of MDCA considering all used methods.

Table 6 shows that exterior wall alternative 4W achieves the best total score of MDCA considering all used methods. Table 7 demonstrates that roof 4F achieves the best total score of MDCA considering all used methods. The most suitable solutions 4F, 4W and 4R are illustrated in following Figure 1.

These material solutions are implemented in the building design of nearly-zero energy family house, located in Slovak climatic conditions. The family house is an example of bungalow for up to 2 people and its total floor area is 96 m^2. By application of these high environmental and energy performance material solutions it is possible to design house with minimal ecological footprint through its whole life cycle. Overall results of environmental analysis of this house are following: 2.6 GJ/m^2 of floor area, -706 kg CO$_2$eq/m^2 of floor area, 1.17 kg SO$_2$eq/m^2 of floor area. In comparison to previously average results of case studies (4.3 GJ/m^2 and 349 kg CO$_2$eq/m^2 of floor area), this proposed family house with optimised material compositions of structures assures higher reduction of EE by 40 % and ECO$_2$ by 149 % and represents possible way towards sustainable future.

Table 6: Total results of MDCA methods for exterior wall alternatives

Alternative	WSA	TOPSIS	IPA	CDA
1W	0.3663	0.3489	0.6337	3.4449
2W	0.3585	0.3978	0.6415	4.2400
3W	0.3809	0.3381	0.6191	3.1455
4W	0.9368	0.9354	0.0632	0.5201

Table 7: Total results of MDCA methods for roof alternatives

Alternative	WSA	TOPSIS	IPA	CDA
1R	0.3090	0.7059	0.6910	3.7983
2R	0.4650	0.4087	0.5350	3.3541
3R	0.4495	0.3946	0.5505	3.0356
4R	0.7874	0.7059	0.2126	1.1848

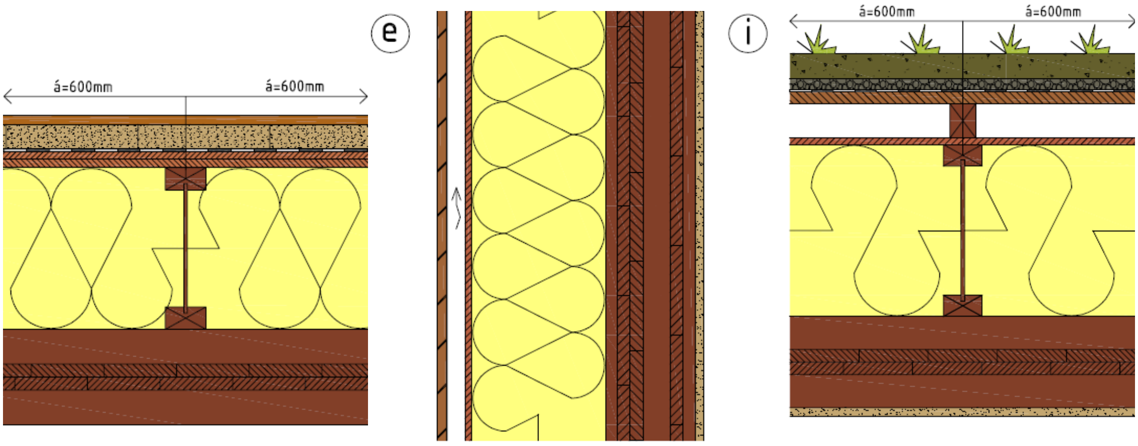

Figure 1: Scheme of material composition of floor structure 4F, exterior wall 4W and roof structure 4F.

4. Conclusions

This case study implements life cycle assessment within “cradle to gate” and demonstrates significance of material selection in the design process of dwelling (especially almost zero energy houses). Improvement of energy performance of building envelope in order to reduction of operational energy consumption in buildings may result in rise of proportion of embodied impacts of building materials on total life cycle environmental impacts. The trade-offs between environmental and thermal-technical criteria and synergies associated with different material compositions of structure alternatives vary and by careful selection of materials it is possible to markedly eliminate total environmental impacts. The materials on plant base such as wood, straw, etc. give greenhouse benefits because they absorb CO$_2$ from atmosphere and lock carbon in their mass. The carbon lock in is very significant factor for reduction of climate changes. The alternatives especially from massive wood panel connected with oak and straw bales are presented as the best solutions for sustainable design of dwellings in Slovak climatic conditions.

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