International Journal of Sustainable Materials, Processes & Eco-Efficient – IJSMPE
Volume 1 : Issue 2
Publication Date : 25 June 2014

Assessment of Performance of Building Structures in Compliance with Sustainable Concept

[Monika Čuláková, Silvia Vilčeková, Jiři Hejhálek]

***Abstract*—The building sector is known to be dominant consumer of energy resources, contributor to greenhouse gas emissions and other environmental impacts. Over the last decade, the development towards sustainability has become important issue in building design decisions. Life cycle assessment (LCA) belongs to broadly used methodology which helps to make decisions in sustainable building design. In this paper, environmental building material performance of wall assemblies for exterior wall is evaluated through LCA (construction phase). The relative contribution of embodied impacts of building materials has been recognized as being significant, especially for high energy effective residential buildings. The exterior walls of houses were by far the most significant contribution of embodied impacts associated with the construction phase. The case study assesses environmental indicators such as embodied energy from non-renewable resources, embodied emissions of CO_2-eq. and SO_2-eq. (within boundary from cradle to gate) of wall assemblies of newly designed nearly zero houses. The material compositions of walls are also calculated in terms of selected thermal-physical aspects in order to assure reduction of future energy consumption during operation. All results are compared by using multi-dimensional evaluation approach through four mathematical methods. The multi-criteria decision analysis (MCDA) demonstrates that this way of material optimization of exterior walls it is possible to ensure markedly reduction of energy consumption and carbon footprint of building. The second variant from massive wood panel and other materials on wood base is able to absorb more than 300 kg of equivalent CO_2 emissions per square meter of structure and to improve overall energy balance of structure in despite of this wall achieves the highest value of embodied energy in comparison with other variants.**

***Keywords*—building materials, wall assemblies, life cycle assessment, environemntal and energy assessment**

Monika Čuláková
Civil Engineering Faculty, Technical University of Košice
Slovakia

Silvia Vilčeková
Civil Engineering Faculty, Technical University of Košice
Slovakia

Jiři Hejhálek
Vega s.r.o
Czech Republic

Acknowledgment: The research was financially supported by the Slovak Grants No. 1/0405/13 and No. 004TUKE-4/2011.

I. Introduction

The Human being, as other living creatures, grows and depends on the conditions of the surrounding environment. Therefore, preserving environment and minimizing negative environmental impacts is a matter of survival [1]. The interaction between the society and the environment is a complex web of positive and negative feedback flows. By simplification of relationship between the natural and the social systems, we have on one side, the flows of natural resources to the system, and on the other side, the flows of wastes back to the environment. The damage of the environment depends on its ability of regeneration and its assimilation capacity [2]. Pollutants for which the environment has little or no absorptive capacity create interdependency between the present and the future, the intensity of damage imposed on the future depends on current actions. The present generation creates a burden for future generations by using up depletable resources and production of pollutants [2, 3]. The buildings are associated with large environmental impacts over a long duration. They consume enormous amount of energy and other resources, they contribute to carbon emissions at each stage of building project from design and construction through operation and final demolition [3, 4]. The existing building stock accounts for over 40% of final energy consumption in the European Union member states and are responsible for more than one third of final greenhouse gas emissions. The analysis shown that the residential stock is the biggest segment with an EU floor space of 75% of the building stock and 64% of the residential building floor area is associated with single family houses and 36% with apartments. The residential buildings consume approximately 63% of total energy consumption in the buildings sector [5, 6]. The identification of the building sector as one of the key consumers of energy led to the creating of some rules that are targeted at improvement in the energy performance of buildings towards to near zero energy performance buildings, through the reduction of energy consumption during the occupation phase [7]. This energy consumption of building is considered as the energy that is used to maintain the occupants' comfort inside building (operational energy for heating, cooling, lighting, etc.). When taking entire building life cycle perspective into account, total used energy includes operational and embodied energy [8]. The energy needed for operations can be reduced considerably by improving the insulation of the building envelope, technical solutions, etc. By decreasing energy demand for operation it is necessary to pay more attention to the energy use for the material production, which is the embodied energy [9].

The analysis residential buildings in Hong Kong indicated that the embodied energy could account for up to 40% of the life-cycle energy used in residential buildings [10]. Environmental analysis of life-cycle impacts of single-family house demonstrated that exterior walls were by far the most significant construction component with 35% of embodied energy and 43% of embodied emissions of CO_2-eq associated with the construction phase [11]. The embodied environmental impacts such as embodied energy aren't considered in current requirements for new building. These embodied impacts of building materials and components achieve high values mainly in the case of extremely energy performance dwelling. Appropriate selection of building materials for design process plays significant role during the life cycle of building and can affect the sustainability of building project [3].

The high energy intensity components are often subject to a wide range of replacements [12]. Comparative study of beams at the new airport outside Oslo demonstrated that the total energy consumption in the manufacturing of steel beams is two to three times higher, and the use of fossil fuels 6 – 12 times higher, than in the manufacturing of glulam beams [13].The substitution of some building materials was shown that the embodied energy can be decreased by approximately 17% [14]. The environmental assessment of three different structural materials for the same house (timber, concrete and light steel framing) presented that the timber solution achieved a better score for all the evaluated environmental aspects. The timber buildings take greater advantage in the low energy processes required to its manufacture, than on the carbon storage itself, considering the whole life-cycle [15]. Comparative study of greenhouse gas emissions for residential building in Sweden concluded that the timber solution decreases carbon emissions from 2 to 3 times against to concrete solution, considering that wood waste and logging residues are use to replace fossil fuels [16].

The aim of this case study is implementation of environmental evaluation and sustainable principles in material selection decision making. The analysis investigates the role of different building materials compositions of exterior wall in terms of the embodied energy and the equivalent emissions of CO_2 and SO_2 in near zero energy residential timber buildings.

II. Evaluation of Wall Assemblies

A. *Methodology*

Environmental quality of material selection is calculated by the Life Cycle Assessment method. LCA is broadly used decision-making tool which is interpreted in ISO 14040 – 44. This paper focuses on "cradle-to-cradle" life-cycle assessment of material compositions for exterior wall variants of timber dwelling. The input dates for calculation of environmental indicators such as embodied energy from non-renewable resources (EE), embodied CO_2-eq emissions (ECO_2- potential of global warming) and embodied SO_2-eq emissions (ESO_2-potential of acidification) are extracted mainly from IBO-database [17], take account of impact of locked carbon in plant materials on total balance of ECO_2.

For purpose of reduction of future operational energy demand, these wall assemblies of variants are compared through selected thermal-physical aspects such as U-value (U), surface thermal capacity (C), relaxation time (τ) and surface temperature (θ_{si}). The most of aspects are calculated by using software Svoboda - Heat 2009 and according to STN 730540 [19]. The mathematical calculation of the relaxation time is explained by following equation (1), where: d - thickness, λ - coefficient of thermal conductivity and a - temperature coefficient of conductivity [18].

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

This parameter expresses the ability of exterior wall to stabilize the inner temperature during stationary cooling (after turning the heating off) and its resultant value depends on the order of material layers [18].

B. *Description of Material Compositions*

All variants of wall assemblies are designed for nearly zero energy performance residential buildings for conditions of Slovak republic (-15°C and 84% of humidity for exterior). The material compositions of each variant consist from timber load-bearing and are described from interior to exterior.

1. variant: plasterboard (2 x 12.5 mm), flax insulation with PE fibres (50 mm) in installation zone, OSB 3 board with airtight tapes (18 mm), flax insulation (300 mm) between wood I - profiles, diffusive opened foil, ventilation zone (40 mm), wood panelling- larch (22 mm).
2. variant: gypsum fibreboard (12.5 mm), wood fibreboard insulation (60 mm) in installation zone, diffusive opened foil, wood massive panel connected with oak pins (364 mm), wood fibreboard insulation (140 mm), reinforced mortar with glass-textile grate and external diffusive plaster (10 mm).
3. variant: fireproof plasterboard (12.5 mm), hemp insulation with PE fibres (60 mm) in installation zone, cross laminated wood panel -glued (124 mm), hemp insulation (240 mm) between wood KVH-profiles, diffusive opened foil, ventilation zone (40 mm), wood panelling- larch (22 mm).
4. variant: wood panelling (20 mm), lamb's wool (80 mm) in installation zone, OSB3 board with airtight tapes (18 mm), lamb's wool (240 mm) between wood KVH-profiles, diffusive opened wood-fibreboard DHF (15), ventilation zone (40 mm), wood panelling in shape of half-round log (50 mm).

International Journal of Sustainable Materials, Processes & Eco-Efficient – IJSMPE
Volume 1 : Issue 2
Publication Date : 25 June 2014

C. *Results of Evaluations*

The resultant values of the evaluated environmental indicators are calculated per square meter of structure and are presented in following Table 1 and in graphical form in Fig. 1. The environmental evaluation results and environmental profiles of variants of wall assemblies show that variant 4 achieves the lowest values of EE, variant 1 the lowest values of ESO_2 and surface weight (m), and the variant 2 is the best solution in terms of ECO_2. Exterior wall 4 can assure the highest reduction of EE by approximately 17% - 52% in comparison with other variants. The material composition of variant 2 can assure by 56% - 86% higher elimination of CO_2 emissions in comparison with other variants.

TABLE I. RESULS OF ENVIRONMENTAL EVALUATION

Variant	Environmental Assessment			
	EE *[MJ/m²]*	*ECO₂* *[kgCO₂eq/m²]*	*ESO₂* *[g SO₂eq/m²]*	*m* *[kg/m²]*
1	655.727	-38.673	220.846	65.62
2	1114.071	-276.809	555.593	227.02
3	1005.243	-121.133	335.773	118.98
4	539.484	-109.104	268.124	97.82

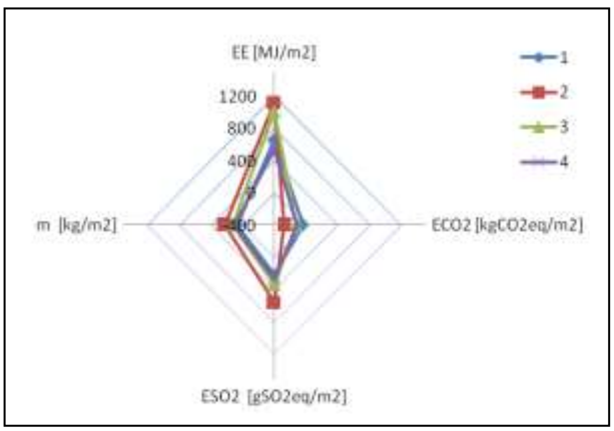

Figure 1. Environmental profiles of wall assemblies 1 - 4.

The wall variant 1 achieves low value of embodied energy, the lowest value of embodied emissions SO_2 and surface weight but it represents the worst solution in terms of thermal stability of house. The best solution in terms of thermal stability of house is wall assembly 2.

The wall 2 reaches the best values in terms of thermal capacity, relaxation time (as seen in Table 2). It is shown that although the total value of embodied energy and equivalent SO_2 emissions for wall assembly 2 are greater than wall assemblies 1, 3 and 4, the alternative 2 has higher potential for reduction in future operational energy demand. It is known that the operational energy has the biggest share of the total life cycle energy balance of building.

All evaluated wall assemblies comply U-value for nearly zero energy performance residential buildings ($U \leq 0.15$ $W/(m^2K)$).

TABLE II. RESULS OF ENVIRONMENTAL EVALUATION

Variant	Assessment of Energy Performance			
	U *[W/(m²K)]*	*C* *[kJ/(K.m²)]*	*τ* *[hrs]*	*Θ_{si}* *[˚C]*
1	0.108	-38.673	220.846	65.62
2	0.114	-276.809	555.593	227.02
3	0.120	-121.133	335.773	118.98
4	0.110	-109.104	268.124	97.82

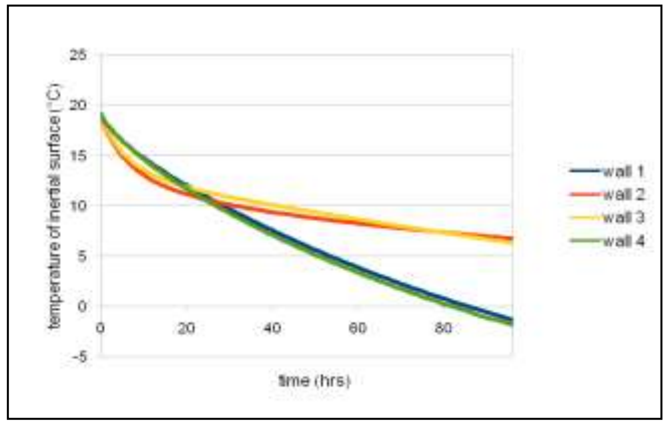

Figure 2. Temperature decrease of inertial surface of wall assemblies after turning the heating off.

The Fig. 2 illustrates temperature decrease of inertial wall surface after turning the heating off which are defined by values of relaxation time for constant external air temperature -15 °C and internal air temperature 20°C. The curve of cooling point out that wall alternative 2 assures the lowest fall of temperature, it is positive impact on thermal stability during winter.

The following multi-criteria decision analysis facilitates identification of the best option from comprehensive view (environmental and energy performance).

D. *Multicriteria Decision Analysis*

Multi-criteria decision analysis (MCDA) is now widely accepted and popular as a non-monetary assessment method to aid decision-making when dealing with environmental issues in building projects. It has multi-dimensional approach in evaluation of complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi interests and perspectives [20]. The wall assemblies are evaluated in order to obtain total score from assessment results and to indicate the best option. The results are compared through mathematical methods Weighted Sum Approach (WSA), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Ideal Points Analysis (IPA) and Concordance discordance analysis (CDA). The best value of total score for methods WSA and TOPSIS is the number nearest to 1.0, for IPA is the number nearest to 0.0 and for CDA is the lowest number. The weighting of assessed aspects is calculated by using Saaty's method in order to elimination of subjectivity [21]. The values of weights are also determined on the basis of level of signification and size of differences between results and resultant weights are 14% for embodied energy and embodied emissions CO_2; 8% for embodied emissions SO_2; 5% for surface weight; 2.5% for U-value; 27% for thermal capacity and relaxation time; 2.5% for surface temperature. The wall assembly 1 achieves the worst results of MCDA. The material composition of alternative 2 represents the best solution in terms of value of total score of MCDA according to using mathematical methods as seen in Table 3. It is the fact that the relaxation time (τ) and surface thermal capacity (C) have the highest share in weighting and the wall 2 reaches by 52% - 82% better value of τ than other alternatives and by 64% - 88% better value of parameter C than others. Furthermore, wall assembly 2 provides the highest reduction of carbon footprint.

TABLE III. RESULS OF MULTI-CRITERIA ANALYSIS

Variant	Results of Assessment Methods of MDCA			
	WSA	*TOPSIS*	*IPA*	*CDA*
1	0.2917	0.2566	0.7083	3.7682
2	0.7078	0.7140	0.2922	1.9867
3	0.3311	0.3218	0.6689	2.8318
4	0.3910	0.3397	0.6090	2.8964

III. Conclusions

The overall environmental and energy performance of building structures is important in achieving more sustainable solution. The careful choice of building materials play significant role in increasing the sustainability of buildings and represent the easiest way for designers to begin incorporating environmental criteria in building project. This comparative analysis of material compositions of exterior wall demonstrates that it is possible to improve total environmental and energy potential by using local available renewable materials on plant base. The wall assembly 2 from massive wood panel and other materials on wood base is able to absorb enormous amount of CO_2 emissions and to improve overall energy balance of structure in despite of this wall achieves the highest value of embodied energy in comparison with other alternatives but it represents the highest potential in reduction of future operational energy consumption.

References

[1] S. Neiva, R. Mateus, and L. Bragança, "Environmental LCA database for conventional Portuguese building Technologies", Proc. of the 1st International Conference on Building Sustainability Assessment, Porto, Portugal, May 2012, pp. 613–620.

[2] R. R. Cordero, P. Roth., and L. Da Silva, "Economic growth or environmental protection? The false dilemma of the Latin-American countries", Environ. Sci. Policy, vol. 8, 2005, pp. 392–398.

[3] O. P Akadiri, "ICT Development of a multi-criteria approach for the selection of sustainable materials for building projects", PhD Thesis, February 2011, pp. 437.

[4] S. C. M. Hui., "Low energy building design in high density urban cities", Renew. Energy, vol. 24, 2001, pp. 627–640.

[5] C. A. Balaras, A.G. Gaglia, E. Georgopoulou, S. Mirasgedis, Y. Sarafidis, D. P. Lalas, "European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings", Build. Environ., vol. 42, 2007, pp. 1298–1314.

[6] M. Economidou, "Europe's buildings under the microscope", Buildings Performance Institute Europe (BPIE), 2011, available on http://www.europeanclimate.org/documents/LR_%20CbC_study.pdf

[7] M. Paleari, M. Lavagna, and A. Campioli, "Life cycle assessment of a zero energy residential building", Proc. of the 1st International Conference on Building Sustainability Assessment, Porto, Portugal, May 2012, pp. 641–650.

[8] A. Dimoudia and C. Tompa, "Energy and environmental indicators related to construction of office buildings", Resour. Conserv. Recy., vol. 53, 2008, pp.86–95.

[9] N. Huberman and D. Pearlmutter, "A life cycle energy analysis of building materials in the Negev desert", Energy Build., vol. 40, 2008, pp. 837–848.

[10] T. Y. Chen, J. Burnett, and C. K. Chau, "Analysis of embodied energy use in the residential building of Hong Kong", Energy, vol. 26, 2001, pp. 323–340.

[11] H. Monteiro and F. Freire, "Environmental Life-Cycle Impacts of a Single-family house in Portugal", Gazi University Journal of Science, vol. 24, 2011, pp. 527–534.

[12] C. Scheuer., G. A. Keoleian., and P. Reppe, "Life cycle energy and environmental performance of a new university building", Energy Build., vol. 35, 2003, pp.1049–1064.

[13] A. Petersen and B. Solberg, "Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction", Environ. Sci. Policy, vol. 5, 2002, pp.169–182.

[14] C. Thormark, "The effect of material choice on the total energy need and recycling potential of a building", Build. Environ., vol. 41, 2006, pp. 1019–1026.

[15] A. C. Coelho, J. M. Branco, and H. Gervásio, "Life-cycle assessment of a single-family timber house", Proc. of the 1st International Conference on Building Sustainability Assessment, Porto, Portugal, May 2012, pp. 533–542.

[16] P. Borjesson and L. Gustavsson, "Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives", Energy Policy, vol. 28, 2000, pp. 575–588.

[17] T. Waltjen, "Passivhaus-Bauteilkatalog, Ökologisch bewertete Konstruktionen", Springer, Wien, Austria, 2009, pp.347.

[18] J. Hejhálek, "Thermal storage and inertia of wood houses", Architecture and Interior, vol. 2, 2001, pp. 56.

[19] STN 73 0540, Thermal protection of buildings. Thermal performance of buildings and components, 2013.

[20] J. J. Wang., Y.Y. Jing., CH. F. Zhang, J. H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making", Renew. Sust. Energ. Rev., vol. 13, 2009, pp. 2263–2278.

[21] P. Korviny, "Theoretical basis of multi-criteria decision", PhD Thesis, Technical University of Ostrava, Czech Republic, 2009, pp. 31.

„When we build, let us think that we build forever. Let it not be for present delight nor for present use alone; let it be such work as our descendants will thank us for."
John Ruskin, The Seven Lamps of Architecture, 1849