CHEMICAL ENGINEERING TRANSACTIONS
VOL. 29, 2012
Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš

ISBN 978-88-95608-20-4; **ISSN** 1974-9791
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
DOI: 10.3303/CET1229034

Reduction of Carbon Footprint of Building Structures

Monika Čuláková[a*], Silvia Vilčeková[b], Eva Krídlová Burdová[b],Jana Katunská[a]

[a] Institute of Architectural Engineering, Civil Engineering Faculty, Technical University of Kosice, Vysokoškolská 4, 042 00 Košice, Slovakia
[b] Institute of Environmental Engineering, Civil Engineering Faculty, Technical University of Kosice, Vysokoškolská 4, 042 00 Košice, Slovakia
monika.culakova@tuke.sk

Degradation of environment is currently at huge risk because of factors related to population growth, resource consumption, industrial activity, etc. This situation is causing serious environmental problems which called for new building developments to bridge the gap between this need for reduction of environmental impacts and ever increasing requirements on living. The developments were generally directed at the reduction of the energy consumption during occupation. But this increase of savings in operational energy is reflected on higher embodied energy and associated emissions from material production. The case study is focused around some issues of environmental performance pertaining to embodied energy, embodied emissions CO_2-eq. and SO_2-eq. from building structures. The optimization of material compositions of structures with passive energy standard are aimed at using materials from biomass in order to create green design. The plant materials serve as a long-term carbon store and use solar energy for production of raw material. The designed passive house from optimized compositions of alternatives achieves low embodied energy (2357.374 MJ per useful area), high negative balance of embodied CO_2-eq. (-356.764 kg CO_2-eq. per useful area) within construction phase of LCA. One of possible ways of reduction of carbon footprint of building is introduced in the paper.

1. Introduction

One of the serious challenges in the earth sciences is to understand the influence of human activities on the biosphere and the global climate system. In the present, considerable attention is devoted to reducing the effect of atmospheric concentration of greenhouse gas (GHG) emissions on climate and to assess environmental impacts of climate change (Denman, et al. 2007). The constructions and occupation of buildings is substantial contributor of CO_2-eq emissions, with almost a quarter of total CO_2-eq attributable to energy consume in buildings (Monahan and Powell 2011). The buildings accounts for more than 40 % of final energy consumption in the European Union, of which residential represent 63% of total energy consumption (Poela, et al. 2007). Consequently, an increase of building energy performance play the key role in reducing overall energy consumption and energy-related CO_2 emissions and can constitute an important instrument in the efforts to alleviate the EU energy import dependency and comply with the Kyoto Protocol to reduce CO_2 emissions (Anisimova, 2011). The energy consumption and associated CO_2 emissions linked with the life cycle of building can be regarded in inter-linked phases which included construction, operation and deconstruction (Monahan and Powell, 2011).
Adalberth presented studies of the total energy use for single-unit dwellings built in Sweden where in, it was demonstrated that 85 % of the total energy consumption was required during the operation phase and energy used in production all the building materials employed in construction with the erection and renovation amounts approximately to 15 % of the total energy consumption (Adalberth, 1997). According

Please cite this article as: Čuláková M., Vilčeková S., Krídlová Burdová E. and Katunská J., (2012), Reduction of carbon footprint of building structures, Chemical Engineering Transactions, 29, 199-204

to several studies, the operational phase has the highest environmental impact, representing about 62-98 % of the life cycle total impacts, while construction phase contributes for a total of 1-20 % and deconstruction phase represents only 0.2-5 % (Rossi, et al. 2012). Improved energy efficiency of buildings assures reduction of operational energy and makes the relative significance of embodied energy higher proportion of the total amount of energy used during the building life cycle. But this increase of embodied energy from material production is more than offset by greater energy reduction during the operation phase of the building, resulting in significant life cycle energy savings (Dodoo, et al., 2010). In spite of the energy used and consequential carbon emitted during the occupation phase of a building equates to the majority of that buildings lifetime carbon footprint, there are significant carbon consequences involved in the initial construction phase. The extraction, production, transportation and built-in of material participate in many environmental impacts, such as embodied energy and embodied CO_2-eq (Mohnan and Powell 2011). The case study of CO_2-eq. emissions in building structures in Hong Kong presented that 82–87% of the total emissions are from the embodied CO_2-eq of conventional materials, 6–8% are from the transportation, and 6–9 % are due to the energy consumption of construction equipment (Yan, et al., 2010).

The results of study of life cycle energy analysis of residential and office buildings showed that occupation (80–90 %) and embodied (10–20 %) phases of energy use are important contributors to building's life cycle energy demand (Ramesh, et al., 2010). The results of study of four typical Belgian residential buildings presented that the embodied energy of buildings with the legal energy performance corresponds to 1/3 - 1/4 of the operational energy consumption during 30 years of occupation. Only for extremely low energy buildings the embodied energy achieved higher value than the operational energy during 30 years (Verbeeck and Hens 2010). The choice of materials can have multiple effects on energy consumption and associated emissions over the different phases of its life cycle, the effects can be contradictory—since properties such as high insulation value may yield relative savings in operational energy together with higher embodied energy. The balance of these factors is especially significant since building’s envelope tend to account for the greatest portion of its embodied energy (Huberman and Pearlmutter, 2008)

The plant materials such as wood reach low embodied energy because mainly use solar energy for production of raw material. The study of the greenhouse gas balances of wood versus concrete building from life cycle perspective showed that the energy used for the production of materials was about 60% – 80 % higher for the concrete than for the wood construction (Bôrjesson and Gustavsson, 2000).

The embodied CO_2-eq emissions from the steel-framed were calculated for 26 % higher than the timber-framed house without regarding the carbon stored. When the carbon (C) stored in the timber for the life of the house is included it makes a 120 % difference. The emissions from the concrete wall-framed were 31 % higher than the timber-framed house without regarding the C stored and are 156 % higher when the stored C is included in the calculation (Lippke, et al., 2010). The carbon that is exported from the forest and remains in materials can be considered an addition to the carbon stored in the forest. The forest carbon stock, which remains stable, the carbon locked in materials continues to increase with every harvest and is growing stock of C that is reduced only by the material volumes that have achieved the end of their useful life. The most of the plant materials in buildings can live of 80 years or more the cumulative C locked in these matters is a significant store of C. By measuring C in the forest, the convention is in units of C but outside the forest, the focus is generally on CO_2 emissions (a loss in stored C) and this is expressed with a molecular weight conversion of 44/12 that of C (1 kg of dry plant mass = 0.5 kg of C = sequestration of 1.8 of CO_2) (Lippke et al., 2010, Berge, 2010). An analyzing of stored C and net emissions from material alternatives based upon life cycle assessment is significant for effective green building standards (Perez-Garcia, et al., 2005).

The case study is aimed at multi-criteria optimization of environmental and energy performance of building structures of dwelling by application of plant materials.

2. Optimization of building structures

2.1 Methodology

Analyze of interaction between the built and the natural environment, Life Cycle Assessment (LCA) presents a comprehensive approach to evaluating the environmental impacts of all materials in building.

(De Benedetto and Klemes, 2008; Estokova, 2011). The environmental impacts are expressed by indicators such as embodied energy (EE), embodied CO_2-eq emissions (ECO_2) and embodied SO_2-eq emissions (ESO_2) within construction stage (system boundary: from Cradle to Gate). The indicators calculated from the inventory data from broadly used IBO database (Waltjen, 2009), only for straw bales are from Wihnan's study (Wihnan, 2007). These indicators of materials of construction alternatives are calculated and compared for particular construction alternatives. The study also evaluates heat transmittance (U) and thermal storage (Q) of alternatives in order to reduce future energy consumption for heating and cooling which are specified according to Slovak standard STN 73 0540. The aim of optimization of material composition of structures is to improve sustainability. The green alternatives are used in designed house and its environmental profile is calculated at the conclusion of study.

2.2 Description of alternatives

The structure alternatives are designed for wood-framed residential building in climatic conditions of Slovak Republic. The particular material compositions for alternatives are mentioned below.

Floor 1A: laminate flooring (10 mm), sound-proofing mat (2 mm), anhydrite screed (3mm), concrete screed (45 mm), separation PE foil, mineral insulation (240 mm), damp proof course – PVC, reinforced concrete slab (150 mm), granulated foam glass (300 mm).

Floor 1B: wood flooring (10 mm), sound-proofing mat (2 mm), anhydrite screed (3 mm), concrete screed (45mm), separation PE foil, wood fibreboard insulation (140 mm), hemp insulation with PE between wood joists KVH (240 mm), OSB (18 mm).

Floor 1C: wood flooring (10 mm), sound-proofing mat (2 mm), OSB with airtight tapes (15 mm), wood fibreboard insulation (100 mm), cross laminated wood panel with cellulose (320 mm).

Floor 1D: wood flooring (10 mm), wood fibreboard insulation (40 mm), OSB with airtight tapes (15 mm), straw bales between wood I-joists (400 mm), OSB (18 mm).

Exterior wall 2A: wood wall cladding - larch (24 mm), ventilation zone (40 mm), diffusive foil, mineral insulation between 2 x wood joists KVH (140+160 mm), vapour barrier- PE foil, installation zone (40 mm), gypsum plasterboard (15 mm).

Exterior wall 2B: silicate plaster (10 mm), mortar with glass-textile grate (5 mm), wood fibreboard insulation (100 mm), hemp insulation between KVH (160 mm), OSB with airtight tapes (15 mm), hemp insulation with PE in installation zone (40 mm), plasterboard (15 mm).

Exterior wall 2C: wood wall cladding - larch (22 mm), ventilation zone (30 mm), OSB (15 mm), cellulose between I-joists (240 mm), diffusive foil, cross laminated wood panel (124 mm), lambswool in installation zone (50 mm), gypsum plasterboard (15 mm).

Exterior wall 2D: loam plaster with hydraulic additive (50 mm), wood-cement fibreboard (16 mm), straw bales between I-joists (450 mm), OSB with airtight tapes (15 mm), lambswool in installation zone (50 mm), wood fibreboard (16 mm), loam plaster on cane mat (20 mm).

Ceiling 3A: OSB (15 mm), mineral insulation between KVH (240 mm), OSB with airtight tapes (15 mm), mineral insulation (60 mm), wood fibreboard (15 mm) , silicate plaster (10 mm).

Ceiling 3B: wood boards (18 mm), hemp insulation between KVH (240 mm), OSB with airtight tapes (15 mm), hemp insulation with PE (60 mm), plasterboard (15 mm).

Ceiling 3C: cork insulation board (30 mm), cross laminated wood panel with cellulose (320 mm).

Ceiling 3D: wood boards (18 mm), straw bales between I-joists (400 mm), OSB with airtight tapes (15 mm), loam plaster on cane mat (20 mm).

Roof 4A: gravel (60 mm), geotextile, damp proof course, OSB (22 mm), wood joists KVH 180x80.

Roof 4B: ceramic roof tiles (20 mm), contralathes, insured damp proof course, wood I-joists.

Roof 4C: vegetation, earth substrate (30 mm), drainage layer – ceramsite (20 mm), geotextile, damp proof course, OSB (22 mm), ventilation zone (60 mm), cross laminated wood panel (116 mm).

Roof 4D: vegetation, earth substrate (40 mm), geotextile, damp proof course, wood boards (22 mm), and wood I-joists.

2.3 Results and multi-criteria analyze

The results of assessment of environmental and thermal-physical indicators in presented in Table 1-4 for all construction alternatives. The alternatives: floor 1D, exterior wall 2D, ceiling 3D and roof 4C are the most effective in term of reduction of carbon footprint. Most of material compositions of constructions achieve higher sustainability thanks to renewable plant materials. The all results are complex compared by using multi-criteria decision analyses. The approximate weights of indicators are calculated by Saathy method and their values are: 16.7 % for embodied energy, for embodied CO_2-eq. and SO_2-eq., 33.1 % for thermal storage, and 16.8 % for heat transmittance. Roof alternatives are only evaluated point of view of environmental aspects because the roof is above unheated space. The weight for heat transmittance (U) is lower than excepted value because all alternatives fulfill U for passive energy standard. The analyses compare the results by methodology Weighted Sum Approach (WSA, the best value is the nearest to 1.0) as seen in table 5-8. This method demonstrates that alternatives D are the most suitable for green design of house. The results of assessment for this house are presented at the conclusion of paper.

Table 1: The results of assessments of floor construction alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2-eq/m^2]	ESO_2 [kg SO_2-eq/m^2]	U [W/(m^2.K)]	Q [kJ/m^2]
Floor 1A	1946.699	129.565	0.696	0.106	531.789
Floor 1B	1046.417	-40.309	0.435	0.105	213.565
Floor 1C	887.854	-71.504	0.394	0.100	156.035
Floor 1D	476.063	-121.210	0.271	0.100	148.260

Table 2: The results of assessments of exterior wall construction alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2-eq/m^2]	ESO_2 [kg SO_2-eq/m^2]	U [W/(m^2.K)]	Q [kJ/m^2]
Exterior wall 2A	1126.288	24.403	0.485	0.136	58.920
Exterior wall 2B	877.405	-21.746	0.333	0.137	109.755
Exterior wall 2C	993.392	-125.068	0.410	0.117	221.940
Exterior wall 2D	307.628	-139.054	0.147	0.090	233.953

Table 3: The results of assessments of ceiling construction alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2-eq/m^2]	ESO_2 [kg SO_2-eq/m^2]	U [W/(m^2.K)]	Q [kJ/m^2]
Ceiling 3A	1483,583	17.906	0.693	0.128	110.886
Ceiling 3B	459,572	-51.442	0.151	0.117	109.755
Ceiling 3C	436,728	-55.993	0.172	0.125	65.760
Ceiling 3D	212,095	-121.654	0.146	0.109	141.760

Table 4: The results of assessment of roof construction alternatives

Alternative	EE [MJ/m^2]	ECO_2 [kg CO_2-eq/m^2]	ESO_2 [kg SO_2-eq/m^2]
Roof 4A	302.579	-29.309	0.129
Roof 4B	402.714	-17.871	0.130
Roof 4C	822.868	-78.842	0.333
Roof 4D	203.914	-22.800	0.061

Table 5: The results of WSA for floor construction alternatives

Floor 1A	Floor 1B	Floor 1C	Floor 1D
0.4990	0.4943	0.3735	0.5010

Table 6: The results of WSA for exterior wall construction alternatives

Exterior wall 2A	Exterior wall 2B	Exterior wall 2C	Exterior wall 2D
0.1680	0.4372	0.6238	0.8320

Table 7: The results of WSA for ceiling construction alternatives

Ceiling 3A	Ceiling 3B	Ceiling 3C	Ceiling 3D
0.3645	0.6453	0.5265	0.8319

Table 8: The results of WSA for roof construction alternatives

Roof 4A	Roof 4B	Roof 4C	Roof 4D
0.5928	0.4751	0.3333	0.6937

3. Green design of house

The most environmental and energy effective alternatives D for floor, exterior wall, ceiling and roof are used in this design of bungalow in Slovak conditions. The interior load-bearing walls consist from loam plasters, wood fibreboards DHF, straw bales between I-joists and partition walls from loam plasters and adobe bricks. These material compositions of structures present innovative approach to Slovak traditional architecture. The concept of passive wood-framed house is illustrated in Figure 1, its built-up area is 177.35 m^2 and useful area is 146.5 m^2 and terrace is 22 m^2. Figure 2 presents environmental impacts of structures of this bungalow. The foundation from concrete strips with thermal insulation from XPS has the most negative impact. Other optimized structures achieve minimal value of environmental indicators considering used amount of building materials.

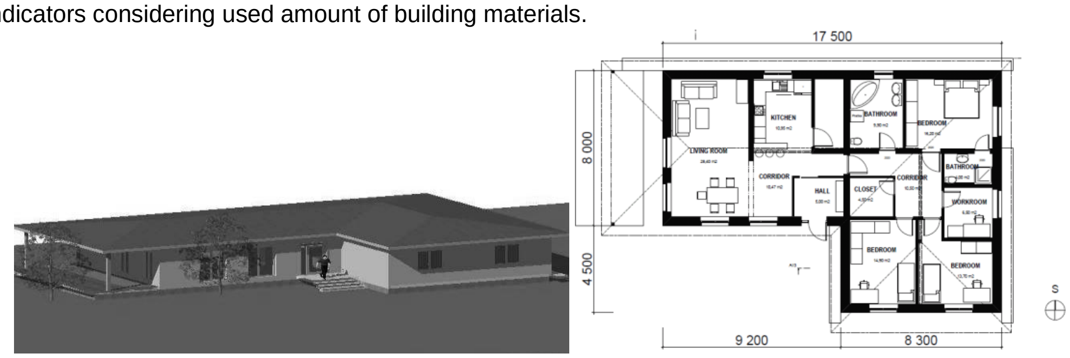

Figure 1: Perspective of bungalow and its scheme of ground-floor plan

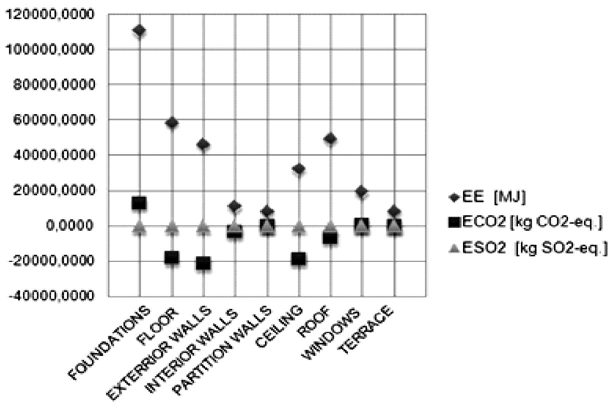

Figure 2: Environmental indicators of particular structures

Table 9: The results of passive house-bungalow

	EE [MJ]	ECO_2 [kg CO_2-eq]	ESO_2 [kg SO_2-eq]
Total values	345,355.229	-52,265.948	206.350
Normalized values per useful area	2357.374	-356.764	1.408

The results of LCA (within boundary: Cradle to Gate) show importance of applied local available, plant materials (Table 9). In spite of the fact increased amount of materials for this design passive bungalow has been showed that structures of this house can assure reduction of energy and energy-related emissions not only in occupation phase but also in construction phase by correct choice and combination of building materials.

Acknowledgements

This work was financially supported by the Slovak Grant KEGA No. 004TUKE-4/2011.

References

Adalberth K., 1997, Energy use during the life cycle of single-unit dwellings: examples, Building and Environment, 32, 321-329.

Anisimova N., 2011, The capability to reduce primary energy demand in EU housing, Energy and Buildings, 43, 2747-2751.

Berge B., 2010, The ecology of building materials, Second edition of book, Elsevier, Oxford, 1-447.

Boerjesson P., Gustavsson L., 2000, Greenhouse gas balances in building construction: Wood versus concrete from lifecycle and forest land-use perspectives, Energy Policy, 28, 575-588.

De Benedetto L., Klemeš J., 2008, LCA as environmental assessment tool in waste to energy and contribution to occupational health and safety, Chemical Engineering Transactions, 13, 343-350.

Denman K. L., Brasseur G., Chidthaisong A., Ciais P., Cox P.M., Dickinson R.E., Hauglustaine D., Heinze C., Holland E., Jacob D., 2007, Coupling between changes in the climate system and biogeochemistry, Climate Change 2007: Contribution of Working Group I to the Fourth Assessment Report of the International Panel on Climate Change, 499-587, Cambridge, United Kingdom.

Dodoo A, Gustavsson L., Sathre R., 2010, Life cycle primary energy implication of retrofitting a wood-framed apartment building to passive house standard, Resources, Conservation and Recycling,54, 1152-1160.

Eštoková A., Porhinčák M., Ružbacký R., 2011, Minimization of CO_2 emissions and primal energy by building materials' environmental evaluation and optimization, Chemical Engineering Transactions, 25, 653-658, DOI:10.3303/CET1125109.

Huberman N., Pearlmutter D., 2008, A life-cycle energy analysis of building materials in the Negev desert, Energy and Buildings, 40, 837-848.

Lippke B., Wilson, J., Meil J., Taylor, A., 2010, Characterizing the importance of carbon stored in wood products, Wood and Fiber Science, 42 (CORRIM Special Issue), 5-14.

Monahan J., Powell J.C., 2011, An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework, Energy and Buildings, 43, 179-188.

Perez-Garcia J., Lippke, B., Comnick, J., 2005, An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood and Fiber Science, 37 140-148.

Poela B., Cruchtena G., Balaras C. A., 2007, Energy performance assessment of existing dwellings, Energy and Buildings, 39, 393-403.

Ramesh T., Prakash R., Shukla K.K., 2010, Life cycle energy analysis of buildings: An overview, Energy and Buildings, 42, 1592–1600.

Rossi B., Marique A. F., Glaumann M., Reiter S.,2012, Life-cycle assessment of residential buildings in three different European locations, basic tool. Building and Environment, 51, 395-401.

Verbeeck G., Hens H., 2010, Life cycle inventory of buildings: A contribution analysis, Building and Environment, 45, 964-967.

Waltjen T., 2009, IBO Passive House components catalog, ecologically rated constructions, Austrian Institute for Building Biology and Building Ecology (in German), Springer, Wien, Austria, 1-337.

Wihnan J., 2007, Humidity in straw bale walls and its effect, Thesis, University of East London School of Computing and Technology. Dagenham, 1-271.

Yan H., Shen O., Fan C.H., Wang Y., Zhang L., 2010, Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong, Building and Environment, 45, 949-955.