CHEMICAL ENGINEERING TRANSACTIONS

VOL. 52, 2016

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Peng-Yen Liew, Jun-Yow Yong, Jiří Jaromír Klemeš, Hon Loong Lam

ISBN 978-88-95608-42-6; **ISSN** 2283-9216

DOI: 10.3303/CET1652210

Comparison of Material Compositions of Roofs in term of Environmental and Energy Performance

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In world with limited amount of energy sources and with serious environmental pollution, interest in comparing the environmental embodied impacts of buildings using different structure systems and alternative building materials will be increased. The selection of building materials used in the constructions (floors, walls, roofs, windows, doors, etc.) belongs to one of the most important roles in the phase of building design. This decision has impact on the performance of building with respect to criteria of sustainability. The energy used in extraction, processing and transportation of materials used in building constructions can be significant part of the total energy used over the life cycle of building, particularly in nearly-zero energy buildings. The environmental impacts are expressed by indicators such as embodied energy (EE) from non-renewable resources, embodied $CO_{2.eq}$ emissions (GWP, Global Warming Potential) and embodied SO_{2eq} emissions (AP, Acidification Potential) within system boundary from Cradle to Gate. The aim of analysis is to identify the environmental quality of material compositions for designed variants of roof constructions. The final values of assessments are compared by using methods of multi-criteria decision analysis.

1. Introduction

Directives in the European Union are ensuring that buildings in this region are moving towards nearly zero energy buildings (nZEB) (Goggins et al., 2016). The construction industry in general and buildings in particular are key drivers of natural resource consumption and emissions into the environment, aside from their effects on the economy and society. Considering these effects that occur throughout a building's whole life cycle, including but not limited to production of construction materials, demolition of building and waste disposal, various assessment methods and tools are being developed to account for the different aspects of sustainability (Ceniter, 2014). Construction has been accused of causing environmental problems ranging from excessive consumption of global resources both in terms of construction and building operation to the pollution of the surrounding environment, and research on green building design and using building materials to minimize environmental impact is already underway. However, relying on the design of a project to achieve the goal of sustainable development, or to minimize impacts through appropriate management on site, is not sufficient to handle the current problem. The aim for sustainability assessment goes even further than at the design stage of a project to consider its importance at an early stage, before any detailed design or even before a commitment is made to go ahead with a development. However, little or no concern has been given to the importance of selecting more environmentally friendly designs during the project appraisal stage; the stage when environmental matters are best incorporated (Ding, 2008). During the last few decades there has been an increasing interest in environmental assessments of the built environment. As a result, we can find several qualitative and quantitative assessment tools (Forsber et al., 2004). In the life cycle of a building, various natural resources are consumed, including energy resources, water, land, and minerals. Many kinds of pollutants are also released back into the global or regional environment. These environmental inputs and outputs result in global warming, acidification, air pollution etc., which inflict damage on human health, primary production, natural resources and biodiversity. The building sector, constituting 30–40 % of the society's total

Please cite this article as: Kridlova Burdova E., Vilcekova S., Vojtus J., Sedlakova A., 2016, Comparison of material compositions of roofs in term of environmental and energy performance, Chemical Engineering Transactions, 52, 1255-1260 DOI:10.3303/CET1652210

energy demand and approximately 44 % of the total material use as well as roughly 1/3 of the total CO_2 emissions (Erlandsson et al., 2003), has been identified as one of the main factors in greenhouse gas emissions. There is no doubt that reducing the environmental burden of the construction industry is essential to sustainable development (Li, 2006). In recent years, the desire to quantify the environmental impact of human activities has increased more and more in order to help mitigate climate change. Various environmental certification systems are being established such as the Environmental Product Declaration (EPD) and thanks to this trend, the quantifiable impact, such as carbon footprint or energy demand can, for instance, be seen on a product's label and in advertisements in daily life. This raises our awareness about environmental problems and leads competition in industry. Life cycle assessment (LCA) is an internationally recognized and ISO standardized accounting tool to quantify the environmental impacts of a product, a process or a service throughout its life cycle, by identifying, quantifying and evaluating all the resources consumed and all the emissions and wastes released in an analysis known as a "from cradle to grave" (Iannone et al., 2014). LCA studies the potential environmental impacts throughout a product’s or system’s life (i.e. from cradle to grave), from raw material acquisition through production. In the life cycle impact assessment (LCIA) stage, an assessment is made of the potential human, ecological, and depletion effects of energy, water, and material usage; and the environmental releases identified in the inventory. The impact assessment is where the potential effects on the chosen environmental issues are assessed (Adams et al., 2014). LCA supports industry and policymakers in making reasonable decisions concerning products, processes and policy strategies. Since LCA is a data-intensive method, the availability of adequate and reliable data is a fundamental issue for the assessment (Peeredoom, 1999). According to study (Frischknecht et al., 2006) the ideally complete LCA database not only includes all datasets, but at the same time should include the links in between them according to economic interrelations. This would result in a huge number of interlinked datasets and an even larger number of links (inputs and outputs). Takano et al. (2014) investigates numerical and methodological differences in existing databases related to building LCAs. They state that the databases show similar trends in the assessment results and the same order of magnitude differences between the reference buildings are shown by all the databases. In study (Rocha et al., 2014) the LCA is used for the evaluation and comparison of main environmental life cycle impacts and energy balance of ethanol. In another study (Iannone et al., 2014) the LCA was carried out to compare the environmental impacts and the energy efficiency of four kinds of wines.

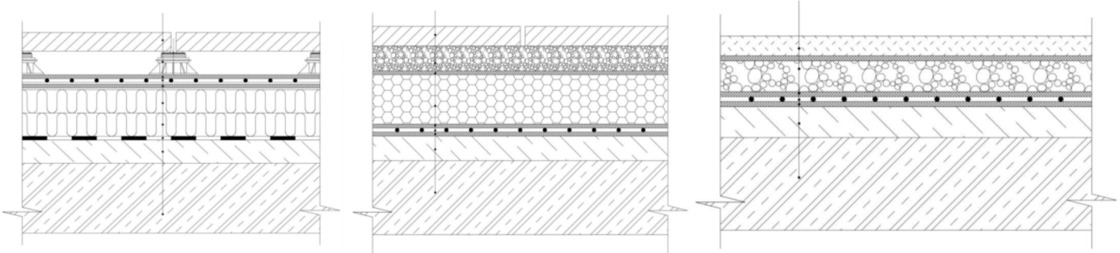
The aim of many papers is to analyse how to improve energy efficiency of buildings. Study of Hannoudi et al. (2015) investigated façade system for existing office buildings in Copenhagen. Another study (Lupíšek et al., 2015) is focused on design strategy for low embodied carbon and low embodied energy buildings. Study of Sedláková et al. (2014) is focused on evaluation of structures design concept of lower structure from embodied energy and emissions. Comparison of environmental and energy performance of exterior walls is presented in another study (Vilčeková et al., 2015a). Salcido et. al. (2016) compares alternative materials used in reticulated dome construction from embodied energy and environmental impact. Castell et al. (2013) analyse the environmental impact of alveolar brick construction systems with and without phase change materials. Buildings are major consumers of energy. Types of energy used during a building’s life cycle comprise embodied energy, operational and maintenance energy, demolition and disposal energy. Embodied energy (EE) represents the total energy consumption for a building construction, i.e., sum of embodied energy of building materials, transportation energy of materials and building construction energy. Praseeda et al. (2016) points out that EE of building materials represents major contribution to embodied energy in buildings. The construction industry has significant environmental, social and economic impacts on the society. As a result, the last decades have witnessed the rapid growth of the green building sector in order to mitigate the negative impacts associated with construction related activities. Similar to conventional building projects, green building projects have a variety of objectives that may not necessary be compatible. These include upfront cost vs. ongoing savings; and energy savings vs. building users' health and wellbeing (Shi, 2016). Zhang et al. (2015) proposes a detailed carbon emission inventory for buildings and divides the life-cycle of a typical building into three stages based on material and energy flow: the materialization stage, the operation stage, and the disposal stage. This study provides a standard method for life-cycle carbon assessment of buildings, which will be critical for future low-carbon development. As study (Gardezi et al., 2016) states the housing sector holds a very pivotal role in providing basic living needs and this role becomes more crucial with an increase in population and rapid urbanization in any country.

Comparison of material compositions of variants of roof constructions is the main goal of this paper. Presented alternatives of roof constructions are analysed from environmental quality and energy aspects. Methods of multi-criteria decision analysis are used for investigation.

2. Materials and methods

Three variants of roof constructions were designed to optimally economical and structurally accurate detail. These variants were designed to meet the recommended value of heat transfer coefficient U = 0.10W/m.K. Evaluated roof constructions are illustrated in Figure 1. Variant 1 consists of reinforced concrete slab, gravity layer, vapour barrier, thermal insulation from EPS, separating layer, waterproofing from PVC and ceramic paving. Roof 2 consists of reinforced concrete slab, gravity layer, separating layer, waterproofing, from PVC, thermal insulation from XPS, gravel and ceramic paving. And finally Roof 3 consists of reinforced concrete slab, gravity layer, separating layer, thermal insulation from XPS, separating layers, gravel and vegetation layer.

Firstly, the variants are evaluated in terms of energy performance. Thermo-physical parameters are calculated for Slovak climatic conditions (STN EN 730540): θ_e- outdoor air temperature (-13 °C); θ_i- indoor air temperature (20 °C); Rh- relative air humidity outdoors (84 %) and Rh- relative air humidity indoors (50 %).



(a) Variant 1 (b) Variant 2 (c) Variant 3

Figure 1: Roof constructions

Table 1: Compositions of roofs and thermo-physical parameters

No.	Assemblies	Thickness d[m]	Thermal coefficient λ [W/(mK)]	Specific heat capacity C [J/kg.K]	Density ρ [kg/m^3]	μ [-]
1	Reinforced concrete slab	180	1.58	1,020	2,400	29
	Gravity layer - perlite	50	0.13	1,150	450	11
	Vapour barrier - bitumen	1.5	0.21	1,470	1,140	300,000
	Thermal insulation - EPS	350	0.037	1,270	20	70
	Separating layer - geotextile	1.5				
	Waterproofing - PVC	1.5	0.16	960	1,400	16,700
	Paving mat	25				
	Ceramic paving	30				
2	Reinforced concrete slab	180	1.58	1,020	2,400	29
	Gravity layer - perlite	50	0.13	1,150	450	11
	Separating layer - geotextile	1.5				
	Waterproofing - PVC	1.5	0.16	960	1,400	16,700
	Thermal insulation layer - XPS	350	0.034	2,060	30	100
	Fine gravel	50	0.65	800	1,650	15
	Ceramic paving	30	1.01	840	2,000	200
3	Reinforced concrete slab	180	1.580	1,020	2,400	29
	Gravity layer - perlite	50	0.13	1,150	450	11
	Separating layer - geotextile	1.5				
	Vapour barrier - bitumen	1.5	0.16	960	1,400	16,700
	Separating layer - geotextile	1.5				
	Thermal insulation - XPS	350	0.034	2,060	30	100
	Separating layer - geotextile	1.5				
	Gravel	50	0.65	800	1,650	15
	Separating layer - geotextile	1.5				
	Vegetation layer	100	2.3	920	2,000	2

Material compositions of roof assemblies are evaluated from environmental and thermo-physical indicators. Environmental indicators are calculated by LCA method. The results of assessment are compared through mathematical method such as Concordance Discordance Analysis (CDA), Ideal Point's Analysis (IPA), Weighted

Sum Approach (WSA) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Vilcekova et al., 2015a).

3. Results and discussion

Thermal-physical parameters for evaluated alternatives are presented in Table 2.

Table 2: Thermal-physical parameters of roof constructions

Variant	d [mm]	U [W/m^2.K]	R [m^2.K/W]	θsi [°C]	$f_{Rsi,p}$ [-]	v [1]	Ψ [h]
1	641	0.099	9.98	19.20	0.976	732.9	13.10
2	663	0.091	10.91	19.26	0.978	1,727.9	19.60
3	737.5	0.090	10.92	19.26	0.978	2,274.9	21.30

The results of environmental indicators evaluation for total values per square meter are illustrated in Figure 2. Environmental profiles of roof constructions show that variant3 achieved the lowest value of embodied energy (620.279 MJ.m^2) and variant 2 achieved highest value of embodied energy (1,589.89 MJ.m^2). The best variant from CO$_2$ emissions is variant 1 with value of 76.97 kgCO$_{2eq}$.m^{2}and the worst is variant 2 with value of 124.54 kgCO$_{2eq}$.m^2. The best variant in term of SO$_2$ emissions is variant 3 (0.3352 kgSO$_{2eq}$.m^2) and the highest value of SO$_2$ emissions achieved variant 1 (0.5294 kgSO2eq.m^2).
Figure 2 illustrates EE and CO$_2$ emissions and Figure 3 the SO$_2$ emissions and ΔOI3$_{STR}$. The ΔOI3$_{STR}$ indicator describes the impact of building material in the given structure layer. The ΔOI3 indicator for one building material layer indicates by how many OI3 points that layer of building materials raises the OI3$_{CON}$ of a construction. In other words, if we eliminate one layer from a structure the OI3$_{CON}$ of the construction will sink by ΔOI3 points.

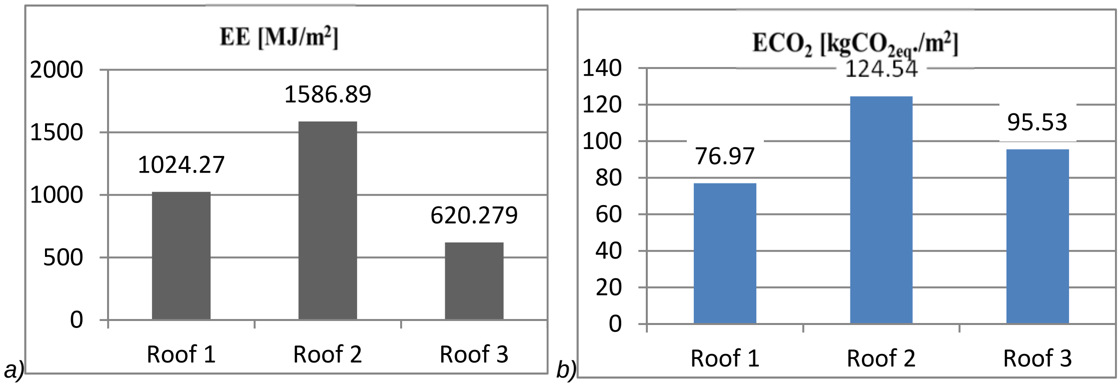


Figure 2: (a) Embodied energy; (b) CO$_2$ emissions of roof structures

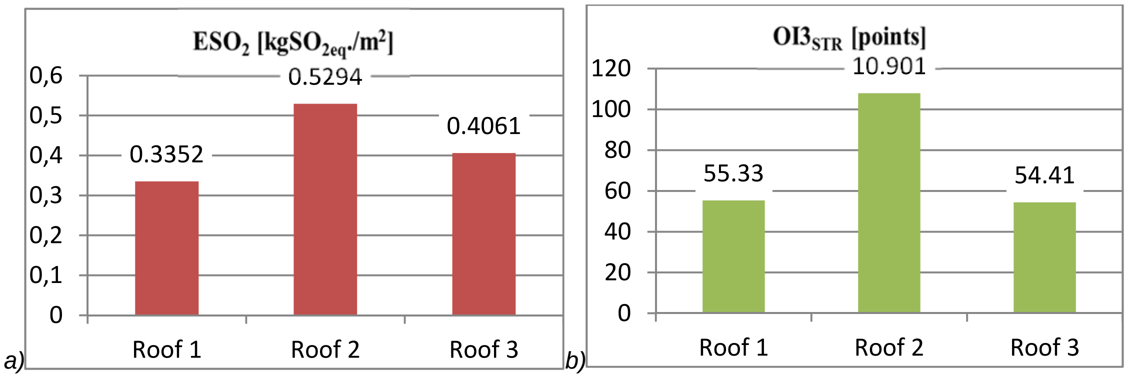


Figure 3: (a) SO$_2$ emissions; (b) OI3$_{CON}$ of roof constructions

The percentage weights of environmental indicators are determined according to their impacts on the environment, i.e. global impacts of EE and ECO$_2$ and regional impact of ESO$_2$. In Table 3 is shown significance weights of environmental indicators determined by Saaty method. Variant 3 (Table 4) is appeared to be the most environmentally suitable. Determined values of environmental impacts for variant 3 are 620.279 MJ.m^2, 95.53 kgCO$_{2eq}$ and 0.4061 kgSO$_{2eq}$ for embodied energy, CO$_2$ emissions and SO$_2$ emissions, respectively.

Table 3: Weights of relative significance for environmental indicators

Indicators	EE	ECO2	ESO2
Weights [%]	40	40	20

Table 4: Results of MCDA for environmental evaluation

Order	Variant	CDA	Variant	IPA	Variant	WSA	Variant	TOPSIS
1	Roof 1	0.8179	Roof 1	0.1672	Roof 1	0.8328	Roof 1	0.7489
2	Roof 3	0.9902	Roof 3	0.2291	Roof 3	0.7709	Roof 3	0.7399
3	Roof 2	4	Roof 2	1	Roof 2	0	Roof 2	0

In Table 5 is shown significance weights of overall indicators (environmental and thermo-physical indicators) determined by Saaty method. Variant 3 (Table 6) is appeared to be the most suitable from environmental and thermo-physical indicators.

Table 5: Weights of relative significance for determined indicators

Indicators	EE	ECO2	ESO2	d [mm]	U [W/m^2.K]	θsi [°C]
Weights [%]	20	20	10	10	20	20

Table 6: Results of MCDA for overall evaluation

Order	Variant	CDA	Variant	IPA	Variant	WSA	Variant	TOPSIS
1	Roof 3	2.0248	Roof 3	0.2647	Roof 3	0.7353	Roof 3	0.6368
2	Roof 1	2.8929	Roof 1	0.4318	Roof 1	0.5682	Roof 1	0,6203
3	Roof 2	3.3214	Roof 2	0.5524	Roof 2	0.4476	Roof 2	0.3708

4. Conclusions

The goal of this paper was to assess the alternative material solutions for roof assemblies to support decisions made at the design phase of the project. Solutions were aimed at reducing the embodied environmental impacts and improving energy performance. In this study cradle-to-gate life cycle analysis was used and focused on environmental indicators such as embodied energy and emissions of CO$_{2eq.}$ and SO$_{2eq}$. The selection and combination of materials influences the amount of energy consumption and associated production of emissions during the building operation phase. Methods of multi-criteria decision analysis (CDA, IPA, WSA, TOPSIS) were used for the interpretation of results of assessments. Variant 3 of roof construction designed from vegetation layer and thermal insulation of XPS with graphite is evaluated as the best solution. Study (Vilcekova et al., 2015b) presents as the best solution also an extensive green roof, which is consisted of clay plaster, a massive wood panel, straw bales between I-profiles, DHF boards, wooden formwork, waterproofing, a drainage layer, and substrate. This variant was determined to be the best material composition for both assessments (*i.e.*, environmental evaluation and evaluation based on environmental and thermal-physical parameters).

Acknowledgments

This study was financially supported by Grant Agency of Slovak Republic to support of projects No. 1/0307/16.

References

Adams P.W.R., McManus M.C., 2014, Small-scale biomass gasification CHP utilisation in industry: Energy and environmental evaluation, Sustainable Energy Technologies and Assessment, 6, 129-140, DOI: 10.1016/j.seta.2014.02.002.

Castell A., Menoufi K., de Gracia A., Rincón L., Boer D., Cabeza L.F., 2013, Life Cycle Assessment of alveolar brick construction system incorporating phase change materials (PCMs), Applied Energy, 101, 600-608, DOI: 10.1016/j.apenergy.2012.06.066.

Cetiner I., 2014, An environmental and economic sustainability assessment method for the retrofitting of residential buildings. Energy and Buildings, 74, 132-140, DOI:10.1016/j.enbuild.2014.01.020.

Ding G.K.C., 2008, Sustainable construction: the role of the environmental assessment tool. Journal of Environmental Management, 8(1), 451-464, DOI:10.1016/j.jenvman.2006.12.025.

Gardezi S.S.S., Shafiq, N. Zawawi N.A.W.A., Khamidi M.F., Farhan S.A., 2016. A multivariable regression tool for embodied carbon footprint prediction in housing habitat. Habitat International, 53, 292-300, DOI: 10.1016/j.habitatint.2015.11.005.

Erlandsson M., Borg M., 2003, Generic LCA-methodology applicable for building, construction and operation services-today practice and development needs. Build and Environment 38(7), 919–38, DOI: 10.1016/S0360-1323(03)00031-3.

Environmental Product Declaration (EPDs). <www.environdec.com/en/What-is-an-EPD/>, Accessed 25 September 2016.

Forsberg A., Malmborgc Von F. 2004, Tools for environmental assessment of the built environment. Building and Environment, 39, 223 – 228, DOI: 10.1016/j.buildenv.2003.09.004.

Frischknecht R. 2006, Notions on the design and use of an ideal regional or global LCA database. The International Journal of Life Cycle Assessment, 11(1), 40–48, DOI: 10.1065/lca2006.04.010.

Goggines J., Moran P., Armstrong A., Hajdukiewicz M., 2016, Life cycle environmental and economic performance of nearly zero energy buildings (NZEB) in Ireland, Energy and Buildings, 116, 622-637, DOI: 10.1016/j.enbuild.2016.01.016.

Hannoundi L.A., Christensen J.E., Lauring M., 2015, Façade system for existing office buildings in Copenhagen, Energy Procedia, 78, 937-942, DOI: 10.1016/j.egypro.2015.11.023.

Iannone R., Miranda S., Riemma S., de Marco I., 2014, Life Cycle Assessment of Red and White Wines Production in Southern Italy, Chemical Engineering Transactions, 39, 595-600, DOI: 10.3303/CET1439100.

International Standards Organisation (ISO). 2006. Environmental management – life cycle assessment – principles and framework, 2nd ed. Geneva: EN ISO 14040, ISO.

Li Z., 2006, A new life cycle impact assessment approach for buildings. Building and Environment, 41, 1414–1422, DOI:10.1016/j.buildenv.2005.05.034.

Lupíšek A., Vaculíková M., Mančík Š., Hodková J., Ružička J., 2015, Desing strategies for low embodied carbon and low embodied energy buildings: principles and examples, Energy Procedia, 83, 147-156, DOI: 10.1016/j.egypro.2015.12.205.

OI3-indicator: Guidelines to calculating the OI3 indicators for buildings. 2011. <www.ibo.at/documents/OI3_Berechnungsleitfaden_V3.pdf>, Accessed 3 October 2014.

Peeredoom E.C., Kleijn R., Lemkowitz S., Lundie S., 1999, Influence of inventory data sets on life-cycle assessment results: a case study on PVC. Journal of Industrial Ecology, 2(3), 109–147, DOI: 10.1162/jiec.1998.2.3.109.

Praseeda K.I., Venkatarama B.V., Mani M., 2016, Embodied and operational energy of urban residential buildings in India, Energy and Buildings, 110, 211-219, DOI: 10.1016/j.enbuild.2015.09.072.

Rocha M.H., Capaz R.S., Lora E.E.S., Nogueira L.A.H., Leme M.M.V., Renó M.L.G., del Olmo O.A., 2014, Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis, Renewable and Sustainbale Energy Reviews, 37, 435-459, DOI: 10.1016/j.rser.2014.05.036.

Salcido J.C., Raheen A.A., Ravi S., 2016, Comparison of embodied energy and environmental impact of alternative materials used in reticulated dome construction, Building and Environment, 96, 22-34, DOI: 10.1016/j.buildenv.2015.11.010.

Sedláková A., Vilčeková S., Krídlová Burdová E., 2014, Evaluation of structures design concept of lower structure from embodied energy and emissions, Chemical Engineering Transactions, 39, 139-144. DOI: 10.3303/CET1439024.

Shi Q., Yan Y., Zuo J., Yu., 2016, Objective conflicts in green buildings projects: A critical analysis, Building and Environment, 96, 107-117, DOI:10.1016/j.buildenv.2015.11.016.

Takano A, Winter S., Hughes M., Linkosalmi L., 2014, Comparison of life cycle assessment databases: A case study on building assessment. Building and Environment, 79, 20-30, doi:10.1016/j.buildenv.2014.04.025.

Vilčeková S., Sedláková A., Krídlová Burdová E., Vojtuš J., 2015a , Comparison of Environmental and Energy Performance of Exterior Walls, Energy Procedia, 78, 231-236, DOI: 10.1016/j.egypro.2015.11.617.

Vilčeková S., Čuláková M., Krídlová Burdová E., Katunská J., 2015b, Energy and Environmental Evaluation of Non-Transparent Constructions of Building Envelope for Wooden Houses, 8(10), 11047-11075, DOI: 10.3390/en81011047.

Zhang X., Wang F., 2015, Life-cycle assessment and control measures for carbon emissions of typical buildings in China, Building and Environment, 86, 89-97, DOI: 10.1016/j.buildenv.2015.01.003.