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Evaluation of Material Compositions of Internal Bearing Walls from Embodied Energy and Greenhouse Gas Emissions

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***Abstract*—Internal walls as vertical elements of a building which divide space should be fulfill requirements such as strength and stability, fire resistance, thermal as well sound insulation. It can be constructed of different materials such as timber frame, metal frame or masonry. The aim of this paper is evaluation of material compositions of internal wall constructions from energy and environmental aspects using life cycle assessment method. The study assesses environmental indicators such as embodied energy from non-renewable resources, emissions of CO_{2eq} and SO_{2eq} within boundary "Cradle to Gate" of proposed building constructions of walls for nearly zero energy wooden houses. Thermal-physical parameters such as U-value, phase shift of thermal oscillation, relaxation time, etc. are also calculated in order to guarantee the reduction of energy consumption during operation of buildings. All results are compared by using multi-dimensional evaluation approach through mathematical methods. According to multi-criteria decision analysis (MCDA) it can be state that material optimization of building constructions is suitable for ensuring the significant reduction of energy consumption and carbon footprint of building.**

Keywords—embodied energy; greenhouse gas; MCDA; walls

I. INTRODUCTION

The construction industry can play a vital role towards sustainable development. Sustainable construction can be achieved with the application of tools that deal with the assessment of the whole life cycle, site planning and organization, material selection, re-use and recycling of materials, waste and energy minimization [1]. According to study [2] the methods and tools for the quantification of building operational energy requirements are well established and understood, there is much less consensus and understanding on the techniques that can and should be used for quantifying embodied energy. As study [3] state the so-called low carbon buildings based on LCA (Life Cycle Assessment), is point to the buildings that we refer to the least carbon dioxide emissions to the biosphere throughout their life cycle from design, construction, operation, until the destruction as important evaluation criteria. "Low-carbon building" is the advanced reflection of current "green building". LCA as tool to improve sustainability of the construction sector is receiving increasing attention [4]. According to study [5] low-carbon building reduces the use of fossil materials, improves energy efficiency, and reduces the emission of carbon dioxide in its building materials, equipment manufacture, construction, and during the whole life cycle of the building. It has become the mainstream trend in the international architecture. A building uses energy throughout its life i.e. from its construction to its demolition. The demand for energy in buildings in their life cycle is both direct and indirect. Direct energy is used for construction, operation, renovation, and demolition in a building; whereas indirect energy is consumed by a building for the production of material used in its construction and technical installations [6, 7].

Many studies deal with the life cycle assessment of bricks [1, 8], others with assessment of whole buildings. Study [9] is concerned with energy-based life cycle assessment of multi-unit and single-family residential buildings in Canada and study [4] focuses on life cycle assessment of an apartment building.

This study assesses environmental indicators such as embodied energy from non-renewable resources, emissions of CO_{2eq} and SO_{2eq} within boundary "Cradle to Gate" of proposed building constructions of walls for nearly zero energy wooden houses.

II. METHODS OF RESEARCH

Compositions were designed from materials that consist primarily of renewable natural resources and avoid condensation of water vapor inside the structures. There are proposed 40 alternatives of interior bearing wall assemblies (Table 1).

TABLE I. DESCRIPTION OF INTERIOR BEARING WALL ASSEMBLIES

	Bearing system	***Sound insulation (thickness)***
1.	KVH	blown cellulose (140 mm)
2.	KVH	hemp (140 mm)
3.	KVH	fibreboard, 50 kg/m^3 (120 mm)
4.	KVH	cellulosic fibre wood (120 mm)
5.	KVH	hemp with PE (120 mm)
6.	KVH	straw ρ=70 kg/m^3 (200 mm)
7.	KVH	cork insulation (140 mm)
8.	KVH	flax (120 mm)
9.	KVH	fleece (120 mm)
10.	KVH	fleece (120 mm)
11.	I-profile	fibreboard, 50 kg/m^3 (120 mm)
12.	I-profile	blown cellulose (200 mm)
13.	I-profile	hemp with PE (120 mm)
14.	I-profile	flax (120 mm)
15.	I-profile	cork insulation; (200 mm)
16.	I-profile	straw ρ=70 kg/m^3 (200 mm)
17.	I-profile	cellulosic fibre wood (120 mm)
18.	I-profile	fleece (120 mm)
19.	I-profile	fibreboard, 50 kg/m^3 (120 mm)
20.	I-profile	flax (120 mm)
21.	CLT-panel	
22.	CLT-panel	
23.	CLT-panel	blown cellulose (50 mm)
24.	CLT-panel	
25.	CLT-panel	hemp with PE (40 mm)
26.	CLT-panel	fleece (50 mm)
27.	CLT-panel	
28.	wood panel	
29.	wood panel	
30.	wood panel	
31.	wood panel	hemp with PE (50 mm)
32.	wood panel	flax with PE (50 mm)
33.	wood panel	fleece (40 mm)
34.	wood panel	
35.	wood panel	
36.	blockhouse	
37.	blockhouse	
38.	blockhouse	fleece (50 mm)
39.	blockhouse	hemp with PE (40 mm)
40.	blockhouse	flax with PE (40 mm)

CLT - Cross Laminated Timber

KVH – KVH profiles

Environmental indicators of material composition have been calculated using method of Life Cycle Assessment (LCA). The boundary of assessment is in boundary “cradle to gate”. LCA analysis of evaluated alternatives has been in term of the embodied energy from non-renewable resources and CO_2 and SO_2 emissions but also environmental indicator ΔOI3 which describes impact of building material in given structure layer. The input data of these environmental indicators has been extracted from IBO LCA Australian database.

Figures (1-6) and result values presented in Table 2 show that all designed alternatives achieve a negative overall balance of CO_{2eq} emissions. The mentioned reasons are amount of natural plant materials and consideration of system boundaries of LCA from cradle to gate, which regard absorption of emissions during the plant growing. The largest share of that particular assembly is massive wood raw material (wood panel, blockhouse). These wall assemblies are also reported higher levels of surface heat capacity, unlike the other assessed assemblies. The worst results of embodied energy and SO_{2eq} emissions achieved interior bearing wall assemblies from CLT panel. The total value of environmental indicators $OI3_{STR}$ is relatively low, which is because of the lower volume of materials used. Zero values reach all tracks with wood panel, with blockhouse and also wall assemblies 1, 6 and 7 (KVH with blowing cellulose, straw and cork insulation) and interior wall assemblies 16. (I-profile with straw).

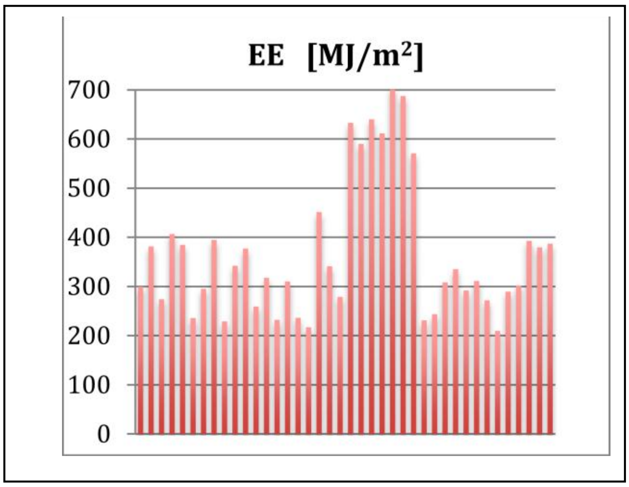

Fig. 1. *Environmental and thermo-technical parameters of evaluation of 40 internal bearing walls assemblies - Embodied energy*

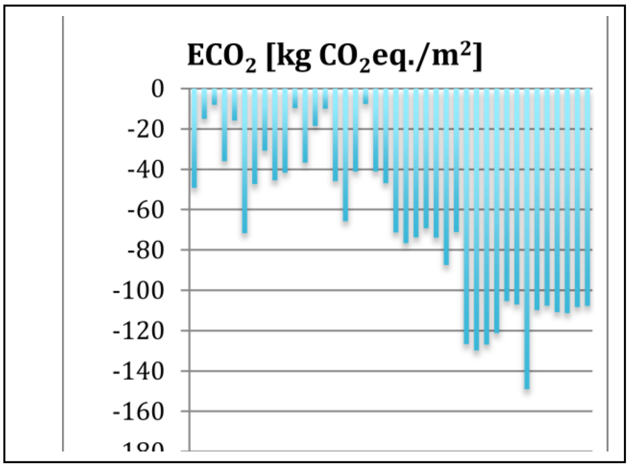

Fig. 2. *Environmental and thermo-technical parameters of evaluation of 40 internal bearing walls assemblies - ECO2*

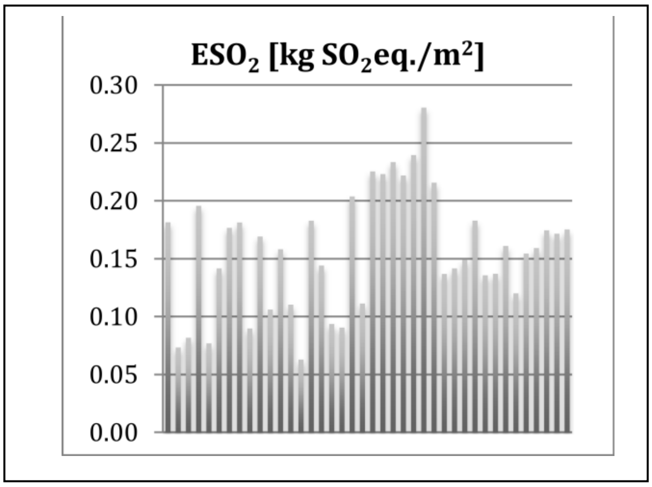

Fig. 3. *Environmental and thermo-technical parameters of evaluation of 40 internal bearing walls assemblies - ESO2*

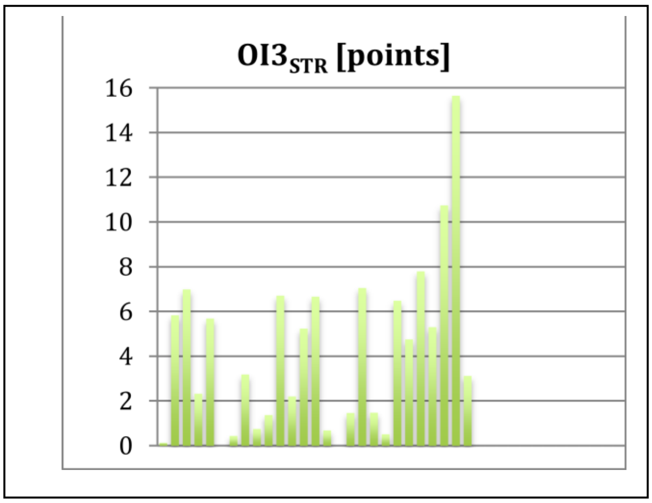

Fig. 4. *Environmental and thermo-technical parameters of evaluation of 40 internal bearing walls assemblies - $OI3_{STR}$*

Table 2 presents the determined values of environmental indicators and thermal physical parameters of designed alternatives of internal bearing walls. Best result is highlighted by the darkest green color. The resulting values of the MCDA for the proposed internal bearing walls are shown in the tables (Tab. 3 and 4). Alternative 34 consisting only of wood panel seems to be the most appropriate in terms of the three most preferred environmental indicators (Tab. 3) and also in the context of a broader amount of the assessed parameters (Tab. 4). The variants of internal wall assemblies are evaluated in order to obtain total score and to indicate the best option. The results are compared through mathematical methods Weighted Sum Approach (WSA) or Simply Additive Weight (SAW) [10], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [11], Ideal Points Analysis (IPA) and Concordance discordance analysis (CDA). Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is developed by Yoon and Hwang [11, 12].

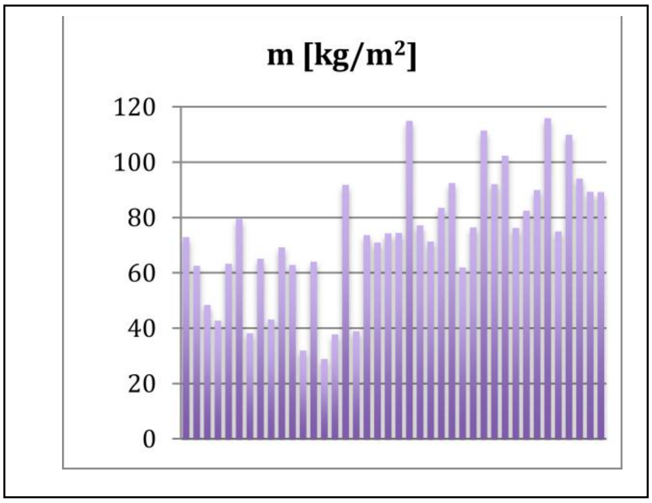

Fig. 5. *Environmental and thermo-technical parameters of evaluation of 40 internal bearing walls assemblies - m*

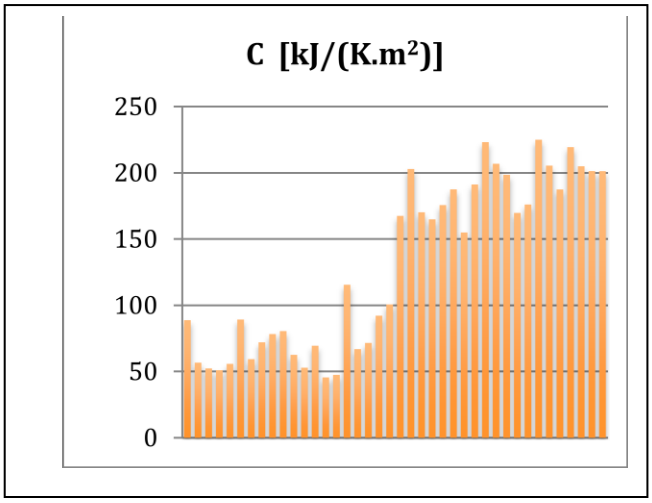

Fig. 6. *Environmental and thermo-technical parameters of evaluation of 40 internal bearing walls assemblies - c*

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 [14] in order to elimination of subjectivity [15].

The alternative 34 achieves the best results of MCDA from environmental evaluation (Table 3). Also the material composition of alternative 34 represents the best solution in terms of value of total score of MCDA according to using mathematical methods as seen in Table 4. Following table (Table 5) shows environmental and thermo-technical results of the best alternative 34.

TABLE II. ENVIRONMENTAL INDICATORS AND THERMAL PHYSICAL PARAMETERS OF INTERIOR BEARING WALL ASSEMBLIES

	thickness [m]	EE [MJ/m^2]	ECO_2 [kg CO2eq./m^2]	ESO_2 [kg SO2eq./m^2]	m [kg/m^2]	C [kJ/(K.m^2)]	$OI3_{STR}$ [points]
1.	0.206	299	-49.2	0.18	72.9	88.7	0
2.	0.180	381	-14.9	0.07	62.6	56.7	6
3.	0.210	273	-8.0	0.08	48.4	52.3	7
4.	0.200	406	-36.0	0.19	42.7	51.0	2
5.	0.200	384	-15.8	0.07	63.3	55.8	6
6.	0.260	235	-71.7	0.14	79.5	89.3	0
7.	0.176	295	-47.3	0.17	38.2	59.3	0
8.	0.210	394	-30.8	0.18	65.1	72.1	3
9.	0.204	228	-45.4	0.09	43.1	78.3	1
10.	0.220	342	-41.7	0.16	69.2	80.5	1
11.	0.240	377	-9.7	0.10	62.9	62.6	7
12.	0.230	259	-36.7	0.15	31.9	52.9	2
13.	0.260	317	-18.5	0.11	64.1	69.4	5
14.	0.250	232	-10.0	0.06	28.9	45.5	7
15.	0.236	310	-45.8	0.18	37.8	47.5	1
16.	0.270	236	-65.7	0.14	91.8	115	0
17.	0.244	217	-41.1	0.09	38.9	66.9	1
18.	0.250	451	-7.6	0.09	73.7	71.5	7
19.	0.266	340	-41.1	0.20	70.9	92.1	1
20.	0.280	278	-46.9	0.11	74.3	100	1
21.	0.134	632	-71.3	0.22	74.5	167	6
22.	0.164	589	-76.6	0.22	115	202	5
23.	0.189	639	-73.7	0.23	77.2	170	8
24.	0.137	611	-69.2	0.22	71.3	164	5
25.	0.179	703	-73.9	0.24	83.5	175	11
26.	0.209	687	-87.4	0.28	92.5	187	16
27.	0.124	570	-71.1	0.21	62	155	3
28.	0.170	231	-126.6	0.13	76.5	191	0
29.	0.195	243	-129.8	0.14	111	223	0
30.	0.183	308	-126.9	0.14	92.1	206	0
31.	0.225	335	-121.2	0.18	102	198	0
32.	0.203	291	-105.3	0.13	76.2	169	0
33.	0.193	311	-107.0	0.13	82.5	176	0
34.	0.200	271	-149.0	0.16	90	225	0
35.	0.180	209	-109.8	0.12	116	205	0
36.	0.150	289	-107.7	0.15	75	187	0
37.	0.175	301	-110.8	0.15	110	219	0
38.	0.213	392	-111.3	0.17	94.1	205	0
39.	0.205	379	-108.3	0.17	89.3	201	0
40.	0.205	386	-107.7	0.17	89.2	201	0
Average		366	-68.2	0.15	73.5	131	3
MAXIMUM		703	-7.6	0.28	116	225	16
MINIMUM		209	-149.0	0.06	28.9	45.5	0
RANGE		494	141.3	0.21	87.05	179	16
MEDIAN		314	-70.2	0.15	74.42	135	1

*data highlighted the darkest green colour present the best results

TABLE III. RESULTS OF MCDA FOR ALTERNATIVES OF INTERNAL BEARING WALL ASSEMBLIES FROM OVERALL – THERMO-PHYSICAL AND ENVIRONMENTAL IMPACT

MCDA	WSA	TOPSIS	IPA	CDA
1.	34. (0.859)	34. (0.852)	34. (0.141)	28. (6.112)
2.	28. (0.851)	29. (0.842)	28. (0.149)	35. (6.257)
3.	29. (0.846)	28. (0.838)	29. (0.154)	34. (7.679)
4.	35. (0.837)	30. (0.796)	35. (0.163)	29. (10.035)
5.	30. (0.778)	35. (0.779)	30. (0.222)	30. (13.639)

TABLE IV. RESULTS OF MCDA FOR ALTERNATIVES OF INTERNAL BEARING WALL ASSEMBLIES FROM ENVIRONMENTAL IMPACTS

MCDA	WSA	TOPSIS	IPA	CDA
1.	34. (0.892)	34. (0.872)	34. (0.108)	34. (7.287)
2.	29. (0.870)	29. (0.856)	29. (0.130)	29. (7.407)
3.	35. (0.823)	30. (0.822)	35. (0.177)	35. (8.335)
4.	28. (0.819)	28. (0.820)	28. (0.181)	28. (9.489)
5.	30. (0.806)	35. (0.799)	30. (0.194)	30. (10.638)

TABLE V. ENVIRONMENTAL AND THERMO-TECHNICAL RESULTS OF THE BEST ALTERNATIVE 34

EE [MJ/m^2]	ECO_2 [kg $CO_{2eq.}$/m^2]	ESO_2 [kg $SO_{2eq.}$/m^2]	m [kg/m^2]	C [kJ/(K.m^2)]
271.8	-149.040	0.161100	90	225

Our previous studies deal with assessment of building material compositions form environmental and energy aspects. Study [16] presents passive house from optimized alternatives of material compositions which achieves low embodied energy (2357.374 MJ per useful area), high negative balance of embodied CO_{2eq} (-356.764 kg $CO_{2eq.}$ per useful area) and low embodied SO_{2eq} (1.408 kg $SO_{2eq.}$ per useful area) within construction phase of LCA. Other study [17] is focused on alternative material solutions for the construction details of foundation, wall and floor to support decisions at the design phase of a project with the reduction of EE by 5–42.89 %, of CO_2 by 22.75–84.76 %, of SO_2 by approximately 2.22–18.54 % in comparison with other alternatives.

III. CONCLUSION

The aim of this paper was analysis and identifying the environmental and thermo-physical quality of material compositions of exterior walls. The environmental impacts were expressed by indicators such as embodied energy (EE) from non-renewable resources, CO_{2eq}. emissions (and $SO_{2eq.}$ emissions within system boundary from Cradle to Gate. The results were compared by using MCDA method. The study shows that in terms of the three most preferred environmental indicators (Tab. 3) and also in the context of a broader amount of the assessed parameters seems to be the most appropriate alternative 34 consisting of wood panel. Determined values of environmental impacts of best alternative were 271.8 MJ/m^2, -149.04 kgCO_{2eq} and 0.1611 kgSO_{2eq} for embodied energy, CO_2 emissions and SO_2 emissions. All designed alternatives achieve a negative overall balance of CO2eq emissions. The mentioned reasons are amount of natural plant materials and consideration of system boundaries from cradle to Gate"), which regard absorption of emissions during the plant growing.

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