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Comparative Analysis of Environmental Performance of Building Materials towards Sustainable Construction

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Contemporary the construction sector belongs to major industries with responsibility for the deterioration of environment. Throughout different stages of building life cycle buildings use materials and require adding of energy for various processes. Consumption of tremendous quantity of energy is directly linked with greenhouse gasses emitted to atmosphere causing the effect known as global warming. The key factors to select material basis are technical and economical parameters, however selecting of building materials regarding environmental performance may lead to reduction a negative image of construction sector.
This paper analysis 2 design variants of one conventional Slovak building with alternated materials composition in selected structures. Evaluation was performed in terms of environmental performance of used building materials and included calculation of embodied energy and embodied CO_2 an SO_2 emissions. The result of study found that it is possible to reduce monitored environmental impact by 4.4-10.5 % just by an easy change of several building materials in selected structures.

1. Introduction

Building industry belongs, after food production, to the largest sectors responsible for resources depletion in the world today (Berge, 2009). Construction sector has become the principal consumer of raw materials and according to Dixit et al. (2010) is currently responsible for depletion of 40 % of stone, gravel, and sand; 25 % of wood or 16 % of fresh water. In addition, operation of buildings (heating, cooling, air conditioning, lighting etc.) but also other phases of buildings life cycle require large amount of energy and produce massive quantity of greenhouse gasses (Dodoo et al., 2011). This also results from constantly rising requirements on buildings. The investigation of environmental performance in terms of sustainability has recently become a point of interest of many researchers as summarized by Khasreen et al. (2009). European Commission has also issued strategies aimed at the reduction of negative influence of building sector by introducing the renewable energy resources and increasing their total share or by minimizing the total energy consumed for buildings operation and related greenhouse gasses emissions (EPBD, 2010). However keeping the building life cycle in mind, the minimization of operational needs within the usage phase causes the increase of quantity of building materials used in building structures contributing to increasing of embodied energy and embodied CO_2 emissions (Čuláková et al., 2012).
Results of recent research have proven that generalized optimal design does not exist and precise analysis of single projects is necessary (De Benedetto and Klemeš, 2008). The objective of this case study was to analyze the embodied energy and embodied CO_2 and SO_2 emissions in two building variants of same family house with use of conventional material basis and construction techniques.

2. Material and methods

2.1 Input data: description of building

The building on which the calculation of environmental performance has been illustrated is located in Slovakia, Zlaté Moravce. The family house is suitable for an average Slovak family consisting of 3 - 5 members. The single storey building analyzed in this study consisted of 3 bedrooms, living room with kitchen, bathroom, toilet, boiler room, wardrobe room and larder. Single garage and terrace were also the

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part of the building. Only conventional – commonly available materials were used for construction of building structures of house, which was designed with improved energy performance as low-energy building.
Analysis included comparison of 2 design alternatives of the same house H1 and H2. Alternative H1 represented the original design, while alternative H2 was the alternative of the same project with slightly changed material basis, which was easily performed after the actual design of building H1.
Underwork: Underwork of both buildings consisted of conventionally used concrete foundation on layer of macadam (H1) or gravel (H2). Concrete hollow block were also used as wall footing. Slab in both alternatives were made of reinforced concrete, however in house H2 amount of reinforcement steel was reduced. Damp proof course was designed of bitumen-aluminium sheet. Staircase of entrance was designed of reinforced concrete.
Vertical structures: Both alternatives were designed as masonry buildings, like with a certain exception the majority of Slovak houses is being built. In original house (H1) perforated ceramic bricks were used for load-bearing walls (external walls – 300 mm, internal walls – 250 mm) as well as for partitions (140 mm). Same thickness of load-bearing walls was used in alternative house design (H2), while the material was changed to aerated concrete. Partition made of aerated concrete of house H2 were 150 mm thick. Capping as well as pillars used in both alternatives were designed of reinforced concrete.
Horizontal structures: Material used for construction of bond beams and girders was reinforced concrete. For single storey houses like evaluated one wood ceiling are the most preferred choice of material, which was used in both design variants. Technically dried wood was used in building H1, while air dried wood was designed in building H2.
Roof: Generally, the material of slant roof is without certain exceptions wood - technically dried wood in house H1 and air dried wood in house H2. OSB was also used as shuttering and vapour barrier. In original design (H1) ceramic roof tiles were designed, however in alternative building concrete tiles were used.
Thermal insulation: Polystyrene and mineral insulation representing the conventional insulating materials were used. Polystyrene XPS was used for insulation of foundation strips, EPS was used in floors on the ground, rock wool was applied on facade (insulation of walls - ETICS), and another type of rock wool was used for insulation of ceiling. Due to use of aerated concrete in external walls of alternative design (H2), which has better insulation ability comparing to ceramic brick used in original building, the thickness of facade insulation could be decreased from 160 m to 140 mm. In addition to resource conservation also area of indoor space increased slightly.
Surfaces: Interior plastering consisted of lime-cement plasters in H1 and gypsum plaster in H2. Exterior plasters were designed of silicate plaster. Ceramic tiles, as well as wood parquets were used as floor surfaces and were placed on concrete layer. Gypsum plasterboard was used in the lower ceiling.
Doors and windows: Triple glazed windows and external doors in plastic frames were used in both houses. In alternative H2, 10 changes in material composition were performed comparing the original H1. Size characterization of both alternatives of evaluated building H1 (original) and H2 (optimized) is presented in Table 1.

Table 1: Size description of analyzed alternatives

	H1	H2	Balance	Gain	Note
Build-up area (m^2)	183.99	183.99	0	0.00 %	House, garage, roofed terrace, entrance
Useful area (m^2)	140.41	141.14	0.73	0.52 %	Area of rooms including garage
Living area (m^2)	75.56	76.00	0.44	0.58 %	Habitable rooms area
Floor area (m^2)	176.18	176.18	0	0.00 %	Area determined by external walls
Total cubature (m^3)	855.30	855.30	0	0.00 %	Total cubature of house
Heated area (m^2)	152.58	152.58	0	0.00 %	Area of heated rooms
Heated cubature (m^3)	518.77	518.77	0	0.00 %	Volume of heated rooms

2.2 Methodology of assessment

Evaluation was aimed at calculation of environmental performance of building materials used for building structures of 2 alternatives of the same building H1 and H2 including comparison of the selected environmental parameters: weight m_i (kg) and volume V_i (m^3) of used materials, primary energy *PEI* (MJ), global warming potential *GWP* (kg CO_2eq) and acidification potential *AP* (kg SO_2eq). Selected parameters

were calculated for whole buildings as well as for particular structures (8 structures as mentioned in description of house) and for used material groups (12 groups) by using LCA data of evaluated materials. Input LCA data of building materials were used according to specific environmental database (Waltjen et al., 2008) within cradle to gate boundaries (Pieragostini et al., 2012).
Normalization to specific area and cubature was also performed in order to provide more precise environmental profile comparable with other houses from similar studies.

3. Results

Overall environmental profile of both buildings alternatives in terms of used building materials of as well as environmental performance of building materials according to structures (underwork, vertical load bearing structures, partition structures, ceiling, roof, thermal insulation, surfaces, doors & windows) and according to material groups were calculated.

3.1 Overall environmental profile

Environmental profile of both alternatives of the same house is presented in Table 2. The comparison of values of the calculated environmental indicators is illustrated.

Table 2: Overall environmental profile of H1 and H2

	Volume (m^3)	Weight (kg)	PEI (MJ)	GWP (kg CO_2eq)	AP (kg SO_2eq)
Original (H1)	315.3	343,492.0	780,051.9	36,488.2	252.26
Alternative (H2)	311.4	329,713.9	698,423.3	34,873.7	226.61
Change	1.2 %	4.0 %	10.5 %	4.4 %	10.2 %

As presented in Table 2, the total calculated reduction of used materials in alternative building H2 reached 1.2 % of building material volume and 4.0 % of material weight. Overall reduction of environmental impact indicators was achieved by 4.4 -10.5 %.

3.2 Normalized environmental performance

In order to provide values comparable with different houses of the different size and configuration a normalization of results to specific area and cubature was calculated. The calculated values were related to useful area (UA), floor area (FA) and total cubature (C) (Table 3).

Table 3: Normalized environmental profile

Normalization to UA	Volume m^3/ m^2	Weight kg/ m^2	PEI MJ/ m^2	GWP kg CO_2eq/ m^2	AP kg SO_2/ m^2
H1	1.94	2,114.58	4,802.09	224.63	1.55
H2	1.91	2,020.68	4,280.34	213.73	1.39
Change	1.7 %	4.4 %	10.9 %	4.9 %	10.6 %
Normalization to FA					
H1	1.79	1,949.67	4,427.59	207.11	1.43
H2	1.77	1,871.46	3,964.26	197.94	1.29
Change	1.2 %	4.0 %	10.5 %	4.4 %	10.2 %
Normalization to C	m^3/ m^3	kg/ m^3	MJ/ m^3	kg CO_2eq/ m^3	kg SO_2/ m^3
H1	0.37	401.60	912.02	42.66	0.29
H2	0.36	385.50	816.58	40.77	0.26
Change	1.2 %	4.0 %	10.5 %	4.4 %	10.2 %

Analyzing the normalized results as presented in Table 3 and comparing to overall results in Table 2, even higher reduction of all investigated indicators was reached when comparing overall results and values normalized to useful area. This was caused not only due to change of used materials in house H2, but also as a result of increased indoor floor area.

3.3 Environmental profile of materials in building structures

Environmental profiles of original (H1) as well as alternative (H2) materials used in particular building structures are presented in Table 4. The changes in values of environmental parameters are also illustrated.

Table 4: Environmental profile of H1 and H2 materials in structures

		Volume m^3	Weight kg	PEI MJ	GWP kg CO_2eq	AP kg SO_2eq
H1	Underwork-ballast - macadam	41.30	66,080.0	7,268.8	462.6	7.93
H2	Underwork-ballast - gravel	41.30	74,340.0	5,947.2	297.4	3.72
	Balance	0.0 %	+12.5 %	-18.2 %	-35.7 %	-53.1 %
H1	Underwork-slab - reinf. concrete	29.51	72,098.8	123,298.9	10,222.9	35.73
H2	Underwork-slab - reinf. concr. (less steel)	29.51	71,620.8	107,870.3	9,602.9	31.89
	Balance	0.0 %	-0.7 %	-12.5 %	-6.1 %	-10.7 %
H1	Bearing walls - perforated ceramic brick	53.63	42,900.0	106,821.0	7,550.4	23.60
H2	Bearing walls - aerated concrete block	53.68	24,153.8	83,088.9	7,994.9	19.32
	Balance	+0.1 %	-43.7 %	-22.2 %	+5.9 %	-18.1 %
H1	Partition walls - perforated ceramic brick	7.84	6,272.0	15,617.3	1,103.9	3.45
H2	Partition walls - aerated concrete block	8.40	3,780.0	13,003.2	1,251.2	3.02
	Balance	+7.1 %	-39.7 %	-16.7 %	+13.3 %	-12.3 %
H1	Capping-partitions - reinforced concrete	0.31	759.1	1,349.3	109.6	0.39
H2	Capping-partitions - reinforced concrete	0.33	806.3	1,378.8	114.3	0.40
	Balance	+6.1 %	+5.9 %	+2.2 %	+4.3 %	+2.8 %
H1	Ceiling - technically-dried wood	4.53	2,265.0	6,160.8	-3,252.5	4.67
H2	Ceiling - air-dried wood	4.53	2,446.2	4,623.3	-3,446.7	3.03
	Balance	0.0 %	+8.0 %	-25.0 %	-6.0 %	-35.0 %
H1	Roof-framework - technically-dried wood	8.83	4,415.0	12,008.8	-6,339.9	9.09
H2	Roof-framework - air-dried wood	8.83	4,768.2	9,011.9	-6,718.4	5.91
	Balance	0.0 %	+8.0 %	-25.0 %	-6.0 %	-35.0 %
H1	Roof-weatherproofing - ceramic roof tiles	5.04	9,079.2	41,401.2	1,815.8	6.36
H2	Roof-weatherproofing - concrete roof tiles	4.85	11,640.0	20,835.6	2,304.7	5.47
	Balance	-3.8 %	+28.2 %	-49.7 %	+26.9 %	-13.9 %
H1	Facade thermal insulation - rock wool	26.62	3,993.6	93,050.9	6,549.5	41.93
H2	Facade thermal insulation - rock wool	23.30	3,494.4	81,419.5	5,730.8	36.69
	Balance	-12.5 %	-12.5 %	-12.5 %	-12.5 %	-12.5 %
H1	Indoor plaster - lime-cement plaster	3.20	5,760.0	8,985.6	881.3	3.23
H2	Indoor plaster - gypsum plaster	2.15	2,795.0	7,155.2	357.8	1.26
	Balance	-32.8 %	-51.5 %	-20.4 %	-59.4 %	-61.0 %

In the underwork, the use of gravel instead of macadam and application of slab with lower steel content caused reduction of PEI, GWP and AP values. Alternation of ceramics with aerated concrete in wall structures contributed to reduction of weight, PEI and AP. In addition, the use of aerated concrete requires less thermal insulation and keeps insulation ability on same level. The use of less amount of same thermal insulation not only reduced environmental impact, but also led to increase of area of indoor rooms. The use of different type of wood in ceiling and roof also led to reduction of environmental burdens. Application of concrete instead of ceramic roof tiles contributed to reduction of embodied energy and SO_2 emissions. Gypsum plaster used in house alternative H2 instead of lime-cement plaster in house H1 contributed to reduction of weight and moreover reduction in PEI, GWP an AP were achieved. Comparison of environmental profile of materials used in particular building structures for both alternatives H1 and H2 is presented in Figure 1.

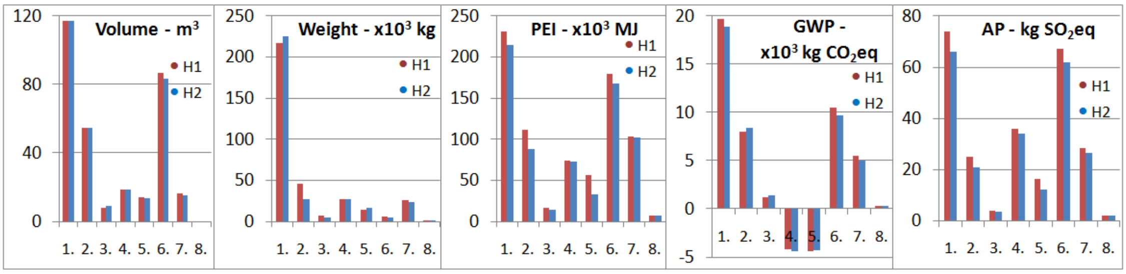

Figure 1: Environmental profile of building structures (1-underwork, 2-vertical load bearing structures, 3-partition structures, 4-ceiling, 5-roof, 6-thermal insulation, 7-surfaces, 8-doors & windows)

According to Figure 1, materials of underwork of both buildings were those with the highest volume (116.8 m^3). Due to use of bulky materials (concrete, gravel or macadam), also weight reached the highest value in the underwork (217,376 – 225,158 kg), what is responsible for the most negative environmental impact with PEI ranging from 214,269 to 231,019 MJ, GWP ranging from 18,902 to 19,687 kg CO_2eq and calculated AP ranging from 65.9 to 73.9 kg SO_2eq. Thermal insulation materials were also used in large extent and reached the second place in terms of volume (83.5 – 86.9 m^3). The bulk density of thermal insulation (mineral insulation, polystyrene) is relatively low therefore also the weight reached relatively low measure (5,272 - 5,771 kg). However, environmental profile of thermal insulation is relatively negative and calculated PEI, GWP and AP values reached relatively high values (167,993 - 179,624 MJ, 9,675 - 10,494 kg CO_2eq and 61.8-67.0 kg SO_2eq).

3.4 Environmental profile of used materials according to material groups

Building materials environmental performance was also analyzed on groups of materials upon their manner (e.g. concrete materials, wood materials, sheets, etc.). Ratio of amount of used material group of original building (H1) and their contribution to investigated indicators is presented in Figure 2.

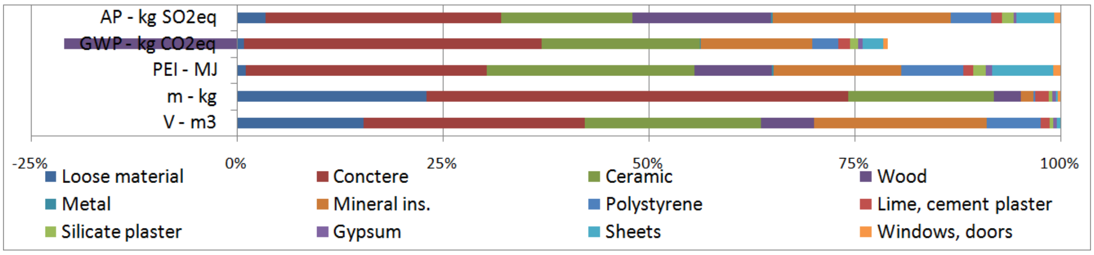

Figure 2: Contribution of material to environmental indicators of house alternative H1

As presented in Figure 2, material with the highest volume (26.8 %) and weight (51.3 %) was concrete. Also other indicators reached the highest lever for concrete: PEI 29.3 %, GWP 31.6 % and AP 28.6 %. Ceramic was material with the second largest volume percentage (21.5 %) and with substantial environmental impact. The use of large quantity of mineral insulation in house H1 was also responsible for relatively large embodied energy as well as CO_2 and SO_2 emissions. Contribution of wood product to global warming reached the negative level (-21 %), which is a positive fact in terms of carbon storage.

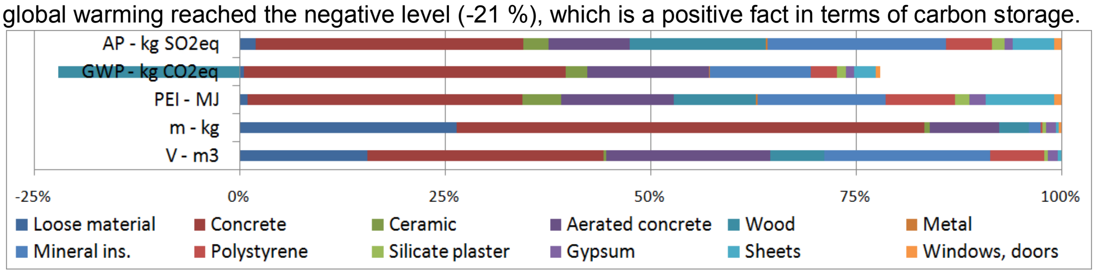

Figure 3: Contribution of materials to environmental indicators of house alternative H2

The volume and weight percentage of materials used in house H2 and their contribution to particular environmental indicators is presented in Figure 3. As illustrated in Figure 3, concrete was the material with largest volume percentage (28.7 %), the calculated weight percentage reached even 56.8 %. Therefore, environmental impact of concrete structures reached the largest scale in concrete materials (PEI = 33.5 %, GWP = 39.1 % and AP = 32.6 %). Relatively large volume percentage was calculated for aerated concrete and mineral insulation with 19.9 % and 20.2 % respectively. For these materials the calculated embodied energy ranged from 13.8 to 15.6 % MJ, embodied CO_2 ranged from 12.3 to 14.8 % and AP was in range from 9.9 to 21.7 %. Contribution of wood materials to global warming reached -22.1 %.

4. Conclusions

The design of buildings is a complicated process which requires cooperation of specialists from several branches including architecture, civil engineering as well as non-technical sectors. Selection of building materials is an important stage in the design process, because this is the key factor to influence also future behaviour, including environmental performance. It is rather important to analyze the environmental performance in the early project phase to make sure that all necessary decisions and changes of the design can be taken relatively quickly and easily rather than more complicatedly in further stages.

Analysis of 2 alternatives of one building with slightly changed material basis of selected structures presented that even relatively easy changes in material composition may lead to reduction of environmental impacts. In addition, also other advantages can be achieved, e.g. increase of useful floor area what is another benefit of optimization. The results of evaluation have proven that to reduce the negative impact of construction sector further investigation in the branch of environmental engineering is necessary.

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