Environmental impact analysis of five family houses in Eastern Slovakia through a life cycle assessment

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Abstract

This study performs a life cycle assessment (LCA) of five new family houses in Eastern Slovakia to compare them in terms of the materials and technologies used. The main goal of the analysis is to investigate and highlight the expectable reduction rate of environmental impact resulting from using green materials and technologies. Their environmental impact is determined by using eToolLCD software. The life cycle impact assessment (LCIA) categories of global warming, ozone depletion, acidification, eutrophication and photochemical ozone creation potential are determined within the cradle-to-grave boundary. The examined family houses are built of conventional materials such as aerated concrete blocks, expanded polystyrene (EPS) for thermal insulation and roofing mineral wool, as well as natural materials such as clay, straw, wood, cellulose and vegetation for the roofs. Family houses built of natural materials are characterized by negative emissions of CO_{2eq} in the product phase. Results show that especially the product phase contributes greatly to all environmental impact categories for houses built of conventional materials, such as aerated concrete blocks, mineral wool for thermal insulation, reinforcement concrete and ceramic or concrete tiles.

Key words: Life cycle assessment (LCA), Global warming potential (GWP), Family house, Green materials, Green technologies

1 Introduction

The construction industry has a significant impact on the consumption of natural resources and energy globally, as well as on greenhouse gas emissions. By applying the life cycle assessment (LCA) methodology in this sector, it is possible to assess and minimize environmental impacts and improve sustainability indicators [1,2]. This method evaluates environmental impact categories related to the production, transport and installation of building materials, as well as building use and end of building life, including recycling or landfill disposal [3]. Weißenberger et al. [4] pointed to the increasing interest of the scientific community in the evaluation of buildings using LCA in recent years. LCA analyses have been performed for residential buildings, both multifamily [5,6] and single-family houses [7-10], as

well as non-residential buildings such as schools [11,12] and office buildings [13-15]. Research in this area has produced interesting results, which are gradually being applied in the design phase. For example, Dahlstrøm et al. [7] conducted LCAs of single-family residences built of conventional materials as well residences built according to the Passive House Standard. An interesting result was that a standard building envelope with an air-to-water heat pump system reduced the environmental impact by approximately 20%, a level comparable with that of a passive house with only electric heating. Comparisons of greenhouse gas emissions have shown that the reduction in a passive design is almost 30%. Lavagna et al. [5] found that single-family houses are responsible for the highest proportion of environmental impact of housing in Europe, and that the same type of building has different impacts in different locations (climatic zones) mainly due to differences in space heating needs. Space heating and electricity use were found to contribute most to the overall impact. Sharma et al. [16] observed that the operational phase required the highest amount of energy (80–85%) and contributed to more than 50% of the overall greenhouse gas emissions. Similarly, Asdrubali et al. [17] performed LCAs of a multi-storey office building, a multi-family residential building and a detached house in Italy and showed that the operational phase had the greatest contribution to the total impact, ranging from 77% (detached house) to 85% (office building), while the impact of the construction phase ranged from 14% (office building) to 21% (detached house). Petroche et al. [18] also found that the operational phase of residential buildings is responsible for the greatest burden in all impact categories except ozone layer depletion, which represents a substantial burden only during the construction phase. On the other hand, an LCA of a two-storey residential building in Canada found that not only the operational but also the construction phase had a significant environmental impact, with the roof and walls accounting for most of the burden [1]. An LCA of a residential building in Turin (demolished by controlled blasting) revealed that waste recycling was sustainable from an energy and environmental point of view, with a recycling potential of 29% in terms of life cycle energy and 18% in terms of greenhouse emissions, compared to the environmental burdens related with the conventional materials embodied in the building shell [19]. In addition to LCA studies on entire buildings, other LCA analyses have focused on specific construction systems, material options or green technologies [20-26]. Kylili et al. [27] performed an LCA of a passive house in the sub-tropical climatic zone and found that concrete was the greatest contributor in all impact categories except abiotic depletion of elements, with the wall systems, floors and foundations significantly contributing to the house's environmental performance. Studies using parametric analysis discovered that utilising insulating materials in the wall systems can have a positive effect in a building's energy efficiency without substantially affecting its total embodied energy. A comparative environmental assessment of reinforced concrete and wood housing constructions confirmed that the steel-reinforced concrete construction had a higher environmental impact compared to the wooden construction [26,28]. This study [28] also revealed that using solar energy for the operation phase reduced the total life cycle carbon emissions by 73%. Asif et al. [29], who studied eight construction materials for a dwelling in Scotland, found concrete to be the material with the highest level of embodied energy, followed by timber and ceramic tiles. As can be seen from the studies cited above, the LCA method is a widely used tool worldwide. However, very few similar studies have been conducted in Slovakia. The aim of this research, therefore, was to investigate the environmental impact of five family houses from East Slovakia, which use combination of conventional and green materials and

technologies. The first two of selected houses are not typical for Slovak region due to their architecture and as well as from chosen materials point of view. However, they scored best in terms of environmental impact.

The main contribution of this study is that it highlights the feasibility of reducing the environmental impact of building construction through using green materials and technologies as a means of mitigating climate change.

2 Aims, scope and methodology

Managing the environmental impact of building construction and operation is a key factor in mitigating the damage caused to the biosphere directly and indirectly. Life cycle assessment (LCA) is the leading industry standard for clearly identifying optimum strategies to reduce buildings' environmental impact. LCA addresses the environmental aspects and potential impact throughout a product's life cycle from raw material acquisition to production, use, end-of-life treatment, recycling and final disposal.

The aim of our analysis was to assess the environmental impact of the global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP), expressed as kilograms of $\text{CO}_{2\text{eq}}$, CFC11_{eq} , $\text{SO}_{2\text{eq}}$, $\text{PO}_4^{3-}_{\text{eq}}$ and $\text{C}_2\text{H}_{4\text{eq}}$, respectively, within the cradle-to-grave boundary. The "kg substance s_{eq} " ("kilogram equivalent of a reference substance s ") expresses the amount of a reference substance s that equals the impact of the considered pollutant within midpoint category studies. For example, the global warming potential of fossil-based methane on a 100-year scale is 27.75 times higher than CO_2 , and thus its characterization factor (CF) is 27.75 kg $\text{CO}_{2\text{eq}}$ [30].

The aim of comparison on environmental impacts is:

- To find out, which phase of family house's life cycle causes the greatest environmental damage.
- To determine, which of the building materials are the biggest contributors to these damages.
- To support a development of technologies and production processes of environmentally friendly products or materials.

The eToolLCD software was used to model the houses' environmental impact, in accordance with EN ISO 14040, EN ISO 14044 and EN 15978. This software is compliant with the CML-IA methodology v4.5 [31]. The software uses third-party background processes aggregated as midpoint indicators, which are stored in a library of software and are coupled with algorithms and user inputs to output the environmental impact assessment. The selected life cycle impact assessment (LCIA) methodology is widely used.

The assessment of the selected houses included all the upstream and downstream processes involved in providing the structures' primary function from the product stage to the construction, use, maintenance, refurbishment, operation and disposal phases. The inventory encompasses all phases from the extraction of raw materials or energy to the release of substances back to the environment or to the point where inventory items exit the system boundary. The functional unit is 1 m² of the total floor area. The estimated design life adopted for the LCA study period is 60 years, which is on par with Building Research Establishment

Environmental Assessment Method (BREEAM) certification system. The system boundary, shown in Fig. 1, follows EN 15978 guidelines.

Figure 1: System boundary diagram.

3 Inventory analysis: design and technical equipment of the assessed houses

The design was modeled using the available eToolLCD elements, templates and products with Environmental Product Declaration (EPD). The eToolLCD library templates are customizable, and users may submit templates for validation. The template validation process is undertaken by experienced LCA practitioners and involves checking the user inputs and ensuring that the assumptions are adequately referenced.

The selected family houses, presented in Figs. 4–6, are located in villages near the towns of Košice, Bardejov and Gelnica in Eastern Slovakia. The project location is shown in Figs. 2–3.

Figure 2: Location of the project – Locality view: (a) Family house 1, (b) Family house 2.

Figure 3: Location of the project – Locality view: (c) Family house 3, (d) Family house 4, (e) Family house 5.

Houses 1 and 2 are located near forest lands with habitats of European importance. Veľký Folkmár is located in the northeast of the Slovenské rudohorie, Jedlinka in the western part of the Low Beskids. Family houses 3, 4 and 5 are situated in flat areas near fertile fields. Unlike the first two houses, they have quick access to the busy metropolis of the East, which also has a major impact on the owners' lifestyle.

Family house 1 is located in the village of Veľký Folkmár and family house 2 in the village of Jedlinka, both in Bardejov district. Their fully built areas are 78 m^2 and 120 m^2 , respectively. Their energy demands for space heating are 76.96 kWh/m^2 per year and 20.7 kWh/m^2 per year, respectively, and for water heating $4,000 \text{ kWh}$ per year and $3,580 \text{ kWh}$ per year, respectively.

Figure 4: View of evaluated family houses: (a) Family house 1; (b) Family house 2.

Figure 5: View of evaluated family houses: (c) Family house 3; (d) Family house 4.

Family houses 3 and 4 are located in Rozhanovce in the Košice district. Their fully built areas are 154 m² and 122 m², respectively. Their energy demands for space heating are 35.16 kWh/m² per year and 26.85 kWh/m² per year, respectively, and for water heating 1,500 kWh per year and 1,384 kWh per year, respectively.

Table 1 provides basic information about the houses, the building materials and their heating, ventilation and air conditioning (HVAC) systems that were evaluated in this study.

Table 1: Description of the family houses

Family house	External walls	Roofs	Floors	Heating
1	clay poured into the shell, timber cladding, clay plaster	extensive vegetation, mineral wool, rafter framework-saddle roof	wood, ceramic tiles, EPS	gas boiler
2	wooden framed structure, straw insulation, clay plaster, timber cladding	extensive vegetation, mineral wool, rafter framework-saddle roof	wood, ceramic tiles, EPS	gas boiler
3	wooden framed structure, wooden insulation, timber cladding, plasterboard	extensive vegetation, cellulose, reinforced concrete	wood, ceramic tiles, EPS	air-to-water heat pump
4	aerated concrete blocks, wooden fibre slabs, silicate plaster	ceramic tiles, cellulose fibres, rafter framework-saddle roof	wood, ceramic tiles, EPS	air-to-water heat pump
5	aerated concrete blocks, wooden fibre slabs, silicate plaster	concrete tiles, cellulose, rafter framework-hip roof	wood, ceramic tiles, EPS	gas boiler

4 Results and discussion

The life cycle impact assessment (LCIA) results for each house are shown in Tables 2–6. The colored cells in the tables indicate the rate of each impact category in each life cycle phase (red: over 50%; violet: 41–50%; orange: 31–40%; green: 21–30%; yellow: 10–20%).

The highest contributors to environmental impact are the three phases of the product stage (A1–A3), the integrated operational energy (B6) of the use stage and, to a great extent, the refurbishment phase (B5). Family houses built of natural materials, where wood

predominates, are characterized by negative CO_{2eq} emissions in the product stage. Trees absorb carbon dioxide from the atmosphere during photosynthesis and store carbon as their building material. This process – known as terrestrial sequestration – reduces the amount of CO₂ in the atmosphere. Carbon remains bound in the wood even after the plant's death. By burning or decomposition the wood, it returns naturally to the atmosphere. Product phases A1–A3 greatly contribute to the GWP for houses built of conventional materials, such as aerated concrete blocks, reinforced concrete, mineral wool for thermal insulation and ceramic or concrete tiles.

In the integrated operational energy phase, CO_{2eq} values are lower for single-family homes with gas boiler space and water heating. House 4 has a CO_{2eq} value of 1,000 kg due to the usage of solar collectors, which lower electricity energy consumption significantly for at least 5 months per year.

In the cases of ODP and POCP, house 3 has the highest impact in the product and refurbishment phases. It seems that the materials used in the bearing structure (pre-treated weatherboarding timber clad with plasterboard) contribute the most to this result.

In terms of AP and EP, houses 3 and 4 have the highest impact. This appears to be due to their use of heat pumps, as opposed to gas boilers, used in houses 1, 2 and 5.

Table 2: Environmental impact indicators for each phase – House 1

Impact	Materials and construction			Use stage					End of life stage	Total
	A1–A3	A4	A5	B1	B2	B5	B6	B7	C4	
GWP [kg CO _{2eq}]	270	43	30	-1.2	0.037	20	990	26	22	1400
ODP [kgCFC11 _{eq}]	0.12E ⁻⁴	0.28E ⁻⁵	0.19E ⁻⁵	0	0.19E ⁻⁸	0.38E ⁻⁵	0.16E ⁻⁵	0.13E ⁻⁵	0.48E ⁻⁸	0.24E ⁻⁴
AP [kg SO _{2eq}]	1.5	0.11	0.2	0	0.17E ⁻³	0.52	0.28	0.13	0.04	2.8
EP [kg (PO ₄) ³⁻ _{eq}]	0.41	0.022	0.056	0	0.4E ⁻⁴	0.12	0.068	0.03	0.19	0.91
POCP [kg C ₂ H _{4eq}]	0.26	0.019	0.039	0	0.98E ⁻⁵	0.05	0.037	0.74E ⁻²	0.24E ⁻²	0.42

Table 3: Environmental impact indicators for each phase – House 2

Impact	Materials and construction			Use stage					End of life stage	Total
	A1–A3	A4	A5	B1	B2	B5	B6	B7	C4	
GWP [kg CO _{2eq}]	-110	29	11	0	0.14	20	360	12	12	330
ODP [kgCFC11 _{eq}]	0.12E ⁻⁴	0.19E ⁻⁵	0.63E ⁻⁶	0	0.7E ⁻⁸	0.5E ⁻⁵	0.6E ⁻⁶	0.61E ⁻⁶	0.78E ⁻⁸	0.21E ⁻⁴
AP [kg SO _{2eq}]	1.4	0.068	0.073	0	0.64E ⁻³	0.54	0.1	0.06	0.072	2.3
EP [kg (PO ₄) ³⁻ _{eq}]	0.39	0.015	0.045	0	0.15E ⁻³	0.13	0.025	0.014	0.58	1.2
POCP [kg C ₂ H _{4eq}]	0.21	0.013	0.012	0	0.36E ⁻⁴	0.07	0.014	0.0035	0.52E ⁻²	0.33

Table 4: Environmental impact indicators for each phase – House 3

Impact	Materials and construction			Use stage					End of life stage	Total
	A1–A3	A4	A5	B1	B2	B5	B6	B7	C4	
GWP [kg CO _{2eq}]	-150	22	5.9	0	0.065	-230	1400	34	29	1100
ODP [kgCFC11 _{eq}]	0.13E ⁻³	0.7E ⁻⁵	0.28E ⁻⁶	0	0.33E ⁻⁸	0.6E ⁻³	0.69E ⁻⁴	0.17E ⁻⁵	0.11E ⁻⁷	0.8E ⁻³
AP [kg SO _{2eq}]	1.6	0.053	0.042	0	0.31E ⁻³	1.4	6.4	0.17	0.13	9.7
EP [kg (PO ₄) ³⁻ _{eq}]	0.33	0.012	0.027	0	0.69E ⁻⁴	0.57	1.4	0.039	0.38	2.8
POCP [kg C ₂ H _{4eq}]	1.4	0.96E ⁻²	0.57E ⁻²	0	0.17E ⁻⁴	1.4	0.36	0.98E ⁻²	0.66E ⁻²	3.2

Table 5: Environmental impact indicators for each phase – House 4

Impact	Materials and construction			Use stage					End of life stage	Total
	A1–A3	A4	A5	B1	B2	B5	B6	B7	C4	
GWP [kg CO _{2eq}]	520	59	25	-12	0.033	92	1000	24	22	1700
ODP [kgCFC11 _{eq}]	0.23E-4	0.39E-5	0.16E-5	0	0.17E-8	0.31E-4	0.52E-4	0.12E-5	0.61E-8	0.11E-3
AP [kg SO _{2eq}]	2	0.14	0.18	0	0.15E-3	0.51	4.8	0.12	0.053	7.7
EP [kg (PO ₄) ³⁻ _{eq}]	0.46	0.03	0.045	0	0.35E-4	0.17	1.1	0.027	0.087	1.9
POCP [kg C ₂ H _{4eq}]	0.28	0.031	0.034	0	0.87E-5	0.053	0.27	0.68E-2	0.23E-2	0.67

Table 6: Environmental impact indicators for each phase – House 5

Impact	Materials and construction			Use stage					End of life stage	Total
	A1–A3	A4	A5	B1	B2	B5	B6	B7	C4	
GWP [kg CO _{2eq}]	240	48	7.8	-1.3	0.089	88	1000	24	36	1400
ODP [kgCFC11 _{eq}]	0.23E-4	0.31E-5	0.41E-6	0	0.45E-8	0.35E-4	0.16E-5	0.12E-5	0.29E-8	0.64E-4
AP [kg SO _{2eq}]	1.6	0.12	0.043	0	0.42E-3	0.54	0.29	0.12	0.66E-3	2.7
EP [kg (PO ₄) ³⁻ _{eq}]	0.31	0.025	0.014	0	0.94E-4	0.17	0.069	0.028	0.09	0.7
POCP [kg C ₂ H _{4eq}]	0.24	0.021	0.8E-2	0	0.23E-5	0.061	0.038	0.69E-2	0.28E-3	0.38

GWP: Global warming potential; ODP: Ozone depletion potential; AP: Acidification potential;

EP: Eutrophication potential; POCP: Photochemical ozone creation potential

Impact key red: over 50%; violet: 41–50%; orange: 31–40%; green: 21–30%; yellow: 10–20%

Figs. 7–11 present each environmental impact category expressed in square meters of the total floor area of each house. Fig. 7 shows that house 2, which consists of green materials such as a wooden framed structure, straw for insulation and clay plaster and uses a gas boiler, has the lowest global warming potential: 76% lower than that of houses 1 and 5, 70% lower than that of house 3 and 80.6% lower than that of house 4. In other words, concrete structures, which constitute 18–25% of the entire building, have the highest global warming potential. Materials such as aerated concrete blocks, expanded polystyrene (EPS) thermal insulation boards, polypropylene (PP) and polyvinyl chloride (PVC) also increase the GWP considerably. The same is true of aluminium window frames and concrete roof tiles.

Figure 7: Global warming potential (GWP) expressed in m² of the total floor area of each family house

Figure 8: Acidification potential (AP) expressed in m² of the total floor area of each family house

Figs. 7–11 reveal that house 3 has the most adverse overall impact on the environment. This impact was found to be much higher in phases B5 and B6 compared to other the houses, as clearly shown in Tables 2–6. This is likely due to the materials used, which require much more frequent replacement and/or refurbishment.

Fig. 8 shows that house 3 has the highest acidification potential: 20.6% higher than that of house 4, 72% higher than that of houses 1 and 5 and up to 76% higher than that of house 2. This is due to the combination of aerated concrete blocks, concrete structures, waterproofing, aluminium windows, plasterboard tiles and pre-treated weatherboarding timber used in the house.

As far as eutrophication potential is concerned, Fig. 9 shows that house 3 again has the worst score: 32% higher than that of house 4, 57% higher than that of house 2, 67.5% higher than that of house 1 and 75% higher than that of house 5. Materials such as reinforced concrete, oriented strand boards (OSB), aluminium windows, cladding timber panel, pre-treated weatherboarding timber and the proofing insulation used in house 3 are the top contributors to EP.

Figure 11: Ozone depletion potential (ODP) expressed in m² of the total floor area of each family house

As in the previous cases, house 3 has the highest photochemical ozone creation potential score: 89.7%, 88%, 86.9% and 79% higher than that of houses 2, 5, 1 and 4, respectively (Fig. 10). Its

reinforced concrete structures, impregnated wood materials and aerated concrete blocks combined significantly contribute to the POCP. These materials also have the highest impact on stratospheric ozone depletion.

In terms of ozone depletion potential, house 3 has the highest impact by a wide margin: 97% higher than that of houses 1 and 2, 92% higher than that of house 5 and 86% higher than that of house 4 (Fig. 11).

5 Conclusion

The evaluation of five family houses with the LCA method produced significant results in relation to the environmental impact categories of global warming potential, ozone depletion potential, acidification potential, eutrophication potential and photochemical ozone creation potential. Our analysis shows that significant environmental impact of all monitored categories is visible in the product and integrated operational energy phases.

The environmental impact of buildings can be reduced by using green technologies and materials. An important barrier to the implementation of many environmental innovation technologies is the lack of awareness of the real costs of obtaining, using and disposing of materials, especially in Eastern and Central Europe. Therefore, new and cost-effective processes and technologies need to be developed to address environmental externalities and better energy use approaches. Advanced green technology and its penetration into new markets are crucial to meeting society's needs in a way that can continue into the future without exhausting natural resources and devastating the planet. On this basis, it is important to know all the possibilities of obtaining energy from different sources but also to embrace the possibilities of construction with materials and technologies that offer low-cost operation and healthy microclimate buildings and, most importantly, do not leave a large ecological footprint [32]. As assessed in study [33], it is advisable to consider partial production of hot water and/or electricity from solar energy, since the solar thermal potential in Slovakia is five months per year. Moreover, a usage of solar energy significantly reduces CO₂ emissions.

From a sustainability point of view, it is necessary to limit the use of materials with high-energy inputs in production and to exclude substances with an adverse effect on users' health. Consideration should also be given to minimizing transport requirements and reducing the amount of waste from construction by recycling and reusing it. Local, recycled and natural materials such as wood, stone, clay plaster, linoleum, wood flooring, flax, hemp, cork, pulpwood or cellulose should be used more. The environmental impact of the construction alone of conventional building is about as great as the environmental impact of the operation of a passive house over a period of 100 years. Therefore, ecological optimisation of the construction impact is an important part of sustainable architecture. One of the priorities of sustainable construction is to minimize material flows and emissions in building material production, reducing bound energy and individual environmental impact categories.

In the future, we aim to evaluate a significant number of family houses to be able to concentrate attention to the aforementioned impact categories and thus reach more accurate conclusions.

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