Assessment of environmental impacts and costs during life cycle stages of selected family houses

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Abstract. According to the European Green Deal, climate change and environmental degradation pose an existential threat to Europe and the world. Therefore, Europe needs a new "green" strategy to transform the EU into a modern and competitive, resource-intensive economy, with zero net greenhouse gas emissions by 2050. As a result, economic growth will be decoupled from resource use. The ever-increasing requirements for the urban environment to be carbon neutral lead to the rising needs for buildings from three dimensions of sustainability. It is well known that the construction and operation of buildings are the primary consumers of energy and material resources and significant polluters of the environment during all stages of their life cycle. This paper deals with analysing environmental impacts and life cycle cost of two family houses located in Kosice, eastern Slovakia. The total greenhouse gas emissions for family house 1 generates 45.89% more CO2 emissions during its life cycle. Discounted life cycle cost of a family house 1 is 74.33% higher and nominal even 77.22% higher than the nominal life cycle cost of a family house 2.

1. Introduction

The construction and operation of buildings are major consumers of energy and material resources and major polluters of the environment during all stages of their entire life cycle. According to the International Energy Agency (IEA), buildings were responsible for 35% of final energy consumption in 2020 and contribute up to 38% of global annual greenhouse gas emissions, of which 10% was the result of the production of building materials and products such as steel, cement and glass (IEA, 2019) [1]. For this reason, some highly efficient buildings, including green and zero-energy buildings, emphasise maximum energy savings and reduce the environmental impact. The design phase of a building has great potential in terms of saving resources, reducing energy consumption and the impact on the environment, as decisions at this stage will affect the efficiency of the whole life cycle of a building [2]. The decision at this stage focuses on how to maximise the use of natural resources to reduce the energy intensity of the building and improve the comfort of residents. Therefore, it is also called climate-responsive design [3]. The negative environmental impacts of each stage of a building's life cycle are the result of the following factors: depletion of non-renewable raw materials and energy sources, pollution and contamination by harmful emissions and negative environmental impact of technology (noise, vibration, etc.), excessive water consumption and faster depletion of renewables such as their ability to regenerate. The impact of buildings on the environment due to changed conditions during their operation, energy security and expanding the range of building materials and equipment, as well as the tendency to reduce air exchange in buildings, create the need for a comprehensive environmental assessment of buildings, i.e. carry out an assessment of the buildings in terms of their negative impact on their indoor and outdoor environments. Each building consisting of building structures, heating, ventilation and air conditioning systems (HVAC), and indoor air is unique, so an integrated tool is needed for environmental assessment,
comparison and subsequent assessment and certification of buildings. Anthropogenic carbon dioxide (CO₂), methane (CH₄), ozone (O₃) and chlorofluorocarbons (CFC) contribute significantly to the effects of global warming [4]. Environmental degradation is currently a considerable risk due to population growth, resource consumption, industrial activity, etc. This situation causes serious environmental problems that have required the sustainable development of buildings to bridge the gap between the need to reduce environmental impacts and growing housing requirements [5]. As essential components of building structures and entire buildings, building materials play an essential role with an overall negative impact on the environment and human health [6]. Life cycle assessment is the most comprehensive method for quantifying environmental impacts and for performing optimisation [7]. Technical, functional and economic parameters are key factors in the selection of building materials. Still, the responsible choice of building materials concerning the environmental impact can reduce the unfavourable picture of the construction industry [8]. Life cycle assessment (LCA) is used to quantify the environmental impact and covers the main activities during the lifetime of the product, including the extraction of raw materials, production, manufacture or operation of materials and products, their production, operation and maintenance up to final decommissioning and disposal [9]. According to a study [10], identifying parameter variations allows us to perform a more detailed LCA of energy and carbon emission materials during their life cycle. There are many LCA studies, in contrast to the LCC studies, of which there are fewer. Even fewer studies deal with life cycle energy analysis (LCEA) [11]. There are a number of critical studies about LCA, for example study of Chau et al. [12] or study of Chirjiv et al. [13]. The study [14] deals with life cycle assessment and life cycle cost implication of residential buildings. It discusses the contemporary issues, and its relationship and significance of system boundary, assumptions, and reports how it effects on economic and environmental impacts. The tools, frameworks and processes of LCA and LCC of buildings are also discussed. The study [15] presents a design framework based on the results of LCC analyses for building structures and packaging systems that holistically consider the effects of energy and natural hazard properties. Another study [16] focusing on LLCs says that demand for green buildings is growing. Still, the trend is below expected levels due to the perceived higher construction costs required by construction investors. In addition, knowledge of industry or practitioners and awareness of significant savings in equipment operating costs are questionable. This study aims to determine the cost implications of green buildings through a comparative cost analysis over the whole life cycle of two green buildings, certified industrial and one traditional building. The industrial sector is one of the largest energy-intensive sectors globally and absorbs more than 50% of the world's total energy supply. Energy consumption in the industrial sector is likely to increase more due to economic and population growth. Data for the analysis were extracted from the budget records of expenditure on construction, operation and maintenance of selected organisations. The research shows that green buildings are 17% cheaper than traditional buildings in life-cycle costs. Although the initial costs of building a green building are 29% higher, operating and maintaining green buildings result in 23% and overall savings of 15% over the entire life cycle. A study [17] says that LCC is an essential method in energy renovation in a building. The study provides an evaluation of cost-optimal energy recovery strategies for historic buildings using the LCC OPERA-MILP optimisation software. The assessment is performed based on predetermined targets depending on the LCC (optimum LCC) and energy consumption (decrease of 50%), where the environmental performance is also addressed. The results show possible reductions in LCC by 12–38% when targeting the LCC optimum. With a focus on reducing energy consumption by 50%, LCC will be decreased in 21 out of 26 cases compared to the period before energy recovery. This paper deals with analysing environmental impacts and life cycle cost of two family houses located in Kosice, eastern Slovakia. This papers is a case study comparing two construction buildings, the ceramic blocks building and wooden building. Build-up area first building is 154 m², usable floor area is 234 m² and built-in volume is 740 m³. Build-up area of wooden building is 145 m², usable floor area is 127.97 m² and built-in volume is 441.3 m³.
2. Material and Methods

2.1 Methods

The environmental performance of two family houses was assessed using the LCA method within the "cradle to grave" boundary based on EN 15978. LCA is an analytical method for evaluating the potential environmental impacts associated with the product life cycle. In other words, the LCA includes all steps that lead from the raw materials to the industrial producer, including material extraction, energy consumption, production, treatment, use, recycling and disposal or end of life. Thus, it is a holistic methodology that quantifies how a product or process affects climate change, non-renewable resources and the environment as a whole. The essence of LCA is explained in detail in standard EN ISO 14040-44. The aim of the analysis in this paper was to assess, among other things, the environmental impact of global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) and non-hazardous waste (NHWD), expressed in kilograms CO$_2$eq, CFC$_11$eq, SO$_2$eq, PO$_4^{3-}$eq, kgEthene and kg). OneClickLCA software was used to evaluate LCA [17]. OneClickLCA assessment shall be performed by ISO 14040 and ISO 14044 and the optional industry or country-specific standards such as EN 15804. The OneClickLCA program also calculates a bound carbon reference value, which speaks of the climate impact of the evaluated product or service, e.g. greenhouse gases resulting from their activities. The OneClickLCA tool also provides LCC calculations, which are an economical approach to life cycle performance. The Life Cycle Cost section identifies, accounts for, and categorises all costs incurred during the life cycle of a product or service. Life cycle costing can be used in investment decisions, product development, marketing, and mapping the value chain's environmental and energy risks. The European context's life cycle cost analysis for built-up assets are governed by ISO 15686-5 and EN 16627.

2.2 Material

This paper deals with analysing environmental impacts and life cycle cost of two family houses located in Kosice, eastern Slovakia. Selected detached family houses are situated in an area intended for small-storey residential buildings and are also located outside the inundation area. The localities in which the homes are located have slightly to cramped territorial conditions for construction. These objects of the assessed family houses are located on the outskirts or central part of the residential urban zone Košice-Sever and situated in the nearby village Rozhanovce, also in its central part. The plots on which the evaluated objects are located can be characterised by different terrain configurations, from flat to slightly sloping plots. The quality of the environment in the areas in which the assessed family houses are located are characterised by the same level of environment according to the regional classification of environmental quality. The evaluated family houses are designed and implemented according to the currently valid normative requirements and legislative requirements, which apply not only in Slovakia but also in the European Union. Before the actual assessment of family houses, the evaluated family houses' technical reports and project documentation were summarised, namely the architectural and building solutions of the assessed objects. Building materials of the family house buildings and the projects of the building services were provided: ventilation, heating, cooling and hot water preparation. In addition, documents of the connection of family houses to engineering networks and a comprehensive transport connection of family houses in the evaluated area were provided. Various tests and certificates of building materials and products built-in assessed family houses were also provided.

2.2.1 Family house 1. This family house is a detached family house, partially basement, with 1$^{st}$ floor and 2$^{nd}$ floor and a flat roof. The total built-up area of the building is 154 m$^2$. The total floor area of the building is 234 m$^2$. Built-up volume 740 m$^3$. The picture (Fig. 1) shows a section of a family house 1 located on Manesova street in Kosice. The picture (Fig. 2) shows the southwest and northwest of the family house 1.
2.2.2 Family house 2. The family house 2 is located near Kosice, in village Rozhanovce. Family house 2 is a detached family house without a basement, 1st floor and 2nd floor with a countertop roof installed on the slope from the east side. The total built-up area of the building is 145 m². The total floor area of the building is 127.97 m². Built-in volume is 441.3 m³. The picture (Fig. 3) shows the floor plan of the 1st floor and a section of the family house 3. The picture (Fig. 4) shows views of the family house 2.
3. Results and Discussion

The table (Tab. 2) is shown the result of the environmental impact of global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) and non-hazardous waste (NHWD). The figure (Fig. 4) shows the percentage of life cycle phases in the environmental impact categories for family house 1 and the figure (Fig. 5) for family house 2. In the figures, it can be seen a comparison of environmental impact categories in phases such as A1-A3 Materials (Fig. 6), A4 Transportation (Fig. 7), B4-B5 Replacement (Fig. 8) and C1-C4 End of Life. Phase A1-A3 has the largest share in all impact categories (GWP, AP, EP, ODP, POCP and NHWD), 46.6% - 72.36% for family house 1 and 41.7% - 77.43% for family house 2. The results show that it makes sense to pay increased attention to building materials from local and renewable sources.

Table 2. Results of environmental impacts of evaluated categories.

| Category          | GWP kg CO$_{2eq}$ | AP kg SO$_{2eq}$ | EP kg PO$_{4}^{3-}$ | ODP kg CFC$_{11eq}$ | POCP kg Ethene | NHWD kg |
|-------------------|--------------------|------------------|---------------------|----------------------|----------------|---------|
| Family house 1    | 120000             | 348              | -0.597              | 0.01                 | 33.70          | 41500   |
| Family house 2    | 6490              | 203              | 32.40               | 0.00                 | 30.30          | 27100   |
Figure 4. Percentage of life cycle phases in environmental impact categories for family house 1.

Figure 5. Percentage of life cycle phases in environmental impact categories family house 2.

Global warming (GWP) grouped by material element breakdown in kgCO$_2$/m$^2$ is shown in the table below (Tab. 3). Greenhouse gas emissions expressed are in almost all evaluated phases of the life cycle higher in family house 1, which is built of traditional materials currently used in the conditions of the Slovak Republic, namely brick, ceramic block, ceramic tiles, external silicate plaster, laminate floor and aluminium windows.
Table 3. Global warming (GWP) grouped by material element breakdown in kgCO₂eq/m².

| Category                                      | A1-A3 Materials Family house 1 | A1-A3 Materials Family house 2 | A4 Transportation Family house 1 | A4 Transportation Family house 2 | B4-B5 Replacement Family house 1 | B4-B5 Replacement Family house 2 | C1-C4 End of life Family house 1 | C1-C4 End of life Family house 2 |
|-----------------------------------------------|---------------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| External walls (envelope, structure and finishes) | 24027                           | 13027                         | 326                             | 139.5                           | 14253                           | 0                               | 855                             | 6387.1                          |
| External windows and rooflights               | 10633                           | 1678.7                        | 67.8                            | 12.76                           | 10764                           | 1703.3                          | 63.1                            | 11.87                           |
| Foundations (including excavation)            | 14048                           | 15971                         | 994                             | 956.2                           | 0                               | 0                               | 319.9                           | 1107                            |
| Internal floor finishes (incl. access floors) | 1302.9                          | 5997.3                        | 27.3                            | 24.42                           | 1852.3                          | 0                               | 68.21                           | 135.62                          |
| Vertical structures                            | 2663.4                          | 0                             | 40.1                            | 0                               | 0                               | 0                               | 47.63                           | 0                               |
| Upper floors (including horizontal structure)  | 12723                           | 3269.5                        | 176                             | 38.65                           | 12191                           | 4173.2                          | 1405                            | 927.7                           |
| Internal ceiling finishes (incl. suspended/access ceilings) | 137.63                          | 1377.7                        | 3.03                            | 33.85                           | 141.17                          | 0                               | 0.51                            | 515.83                          |
| Internal walls and partitions                  | 3118.3                          | 1429.5                        | 107                             | 39.91                           | 664.59                          | 1001.6                          | 31.9                            | 109.95                          |
| Roof (including coverings)                    | 1546.1                          | 2183.5                        | 42.9                            | 201.5                           | 4372.6                          | 1627.5                          | 943.2                           | 823.97                          |
| **Total**                                     | **70199**                       | **44934**                     | **1784**                        | **1447**                        | **44238**                       | **8506**                        | **3735**                        | **10019**                       |

Figure 6. Comparison of GPW for family houses 1 and 2 for individual constructions in phase A1-A3.
Figure 7. Comparison of GPW for family houses 1 and 2 for individual constructions in phase A4.

Figure 8. Comparison of GPW for family houses 1 and 2 for individual constructions in phase B4-B5.
Figure 9. Comparison of GPW for family houses 1 and 2 for individual constructions in phase C1-C4. LCC discount and nominal of assessed family houses 1 and 2 is presented in the Table 4. The results of LCC analyses show that the discounted value of the life cycle cost of family house 1 is higher than the discounted value of the costs of a family house 2 in all phases of the life cycle of the assessed family houses. This also applies to the nominal value of cost, which also takes inflation into account.

Table 4. LCC discount and nominal of assessed family houses 1 and 2.

| Categories          | LCC discount v € | LCC nominal v € |
|---------------------|------------------|-----------------|
|                     | Family house 1   | Family house 2  | Family house 1   | Family house 2   |
| A1-A4 Construction  | 258 835          | 68 359          | 258 835          | 68 359           |
| B4-B5 Replacement   | 40 242           | 1 590           | 449 879          | 46 938           |
| B6 Energy           | 11 206           | 3 275           | 69 878           | 20 420           |
| B7 Water            | 4 486            | 7 572           | 27 975           | 47 215           |
| C1-C4 End of life   | 346              | 91              | 21 747           | 5 743            |
| Total               | 315 116          | 80 887          | 828 314          | 188 676          |
| Per floor area Eur/m² | 1 347          | 632             | 3 540            | 1 474            |

The results show that the choice of wood-based building materials significantly impacts the viability of buildings compared to traditional materials, which have a considerably higher impact on CO₂ emissions than wood-based materials. Scientists and experts in assessing the sustainability of buildings point to the need to design sustainable so-called green buildings. The construction of sustainable buildings represents a new building philosophy that is part of a sustainable existence and approaches designs that use more environmentally friendly and safe building materials primarily from local renewable sources. The total greenhouse gas emissions for family house 1 are 119956.63 kgCO₂eq and for family house 2 are 64905.43 kgCO₂eq, which means that family house 1 generates 45.89% more CO₂ emissions during its life cycle. However, the life cycle cost analysis shows that the discounted life cycle cost of a family house 2 is 74.33% lower and nominal even 77.22% lower than the nominal life cycle cost of a family house 1.
4. Conclusion
As we expected, the choice of wood-based building materials has a significant impact on achieving the viability of buildings compared to traditional materials, which have a significantly higher impact on CO₂ emissions than wood-based materials. The construction of sustainable buildings, which are built from mostly local natural, almost energy-intensive materials, creates the opportunity to become raw material and energy self-sufficient. It is a way that shows the way back to nature. In this way we can improve not only the quality of the environment, but also the quality of the indoor environment of buildings.

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