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Potential for Reducing the Carbon Footprint of Buildings †

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Abstract: The construction sector produces more than 35% of the total amount of waste in Europe and for around 36% of emissions. This paper deals with the life cycle analysis of three alternatives of a residential building in terms of carbon footprint. At the same time, the analysis focuses on the end-of-life phase and its significance for the reduction of the carbon footprint. From the results obtained, it can be concluded that variant three has the lowest CO_{2eq}/m^2 emission levels compared to those of the other two variants. Based on the overall investigation of the end-of-life phase, this study found that the reuse of brick material contributed the most to the reduction of the overall emissions.

Keywords: building; life cycle assessment; carbon footprint; end of life

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1. Introduction

Globalization and growth in this century is accompanied by a huge amount of building materials used for housing and have expanded the need for aggregates in concrete-based materials. The residential wastes obtained via natural resource extraction include concrete, stone, block concrete, solid and tiles, hollow fired clay bricks, mortar, mineral plaster, asphalt, sand and glass [1]. In the European Union, the built environment produces more than 25% of all waste, highlighting the demand to support a circular economy. To illustrate the level of circularity, the characteristic indicators mainly target the amount of primary materials and the amount of non-renewable waste and the lifetime of the product [2]. The construction sector, which accounts for 37% of global greenhouse gas emissions and 36% of global energy resources consumption, is transitioning to a low-carbon and low-energy model [3]. The construction of residential buildings requires the extraction of a large amount of natural resources. Buildings are capital-demanding and require important physical, economic and social financing [4]. One study [5] examines the potential strategies to reduce the embodied energy and greenhouse gas emissions through the flexible reuse of non-residential buildings for a residential objective compared to the new construction of residential buildings. In a renovated building, compared to the construction of a new apartment building, approximately 56% of the embodied energy, 34–48% of the CO_2 equivalent emissions and 72% of the weight of the materials can be saved [5]. The circular economy is a new economic model that aims to overcome today's linear "take, make, dispose" model, delinking global economic development from limited resource consumption [6]. Bio-based circular building materials are materials obtained in whole or in part with a renewable biological origin or from the by-products and biological waste of plants and/or animal biomass that can be used as raw materials for building materials and decorative objects in construction in their original forms. The literature shows that the use of these materials can represent a consistent solution for mitigating the climate impacts of the construction sector, according to the circular economy model [7]. To assess the potential impact of the materials, products or systems, the LCA method has been to approach their environmental, economic or social consequences to affect decision making. This has led the construction industry on an eco-efficient path that allows you to do more with less [8]. This study investigated the potential of producing geopolymer bricks from industrial waste, including ferrosilicon and aluminum slag. Design Builder was used to establish that the proposed manufactured brick samples and results, showing an energy reduction of 5.70–14.90% and carbon dioxide reduction of 0.47–7.67%, which were compared to those of ordinary brick. For the manufactured brick samples, the return on investment was determined to be 8.76–15.79 years [9]. Residential and service sector buildings contribute significantly to climate change through energy consumption in these buildings and indirectly through construction activities and the production and disposal of building materials [10]. The decarbonization of the construction industry plays an essential role for achieving the climate change mitigation goals. The results of this study show that the annual greenhouse gas emissions would be decreased by around 40% under the reference scenario, while the annual greenhouse gas emissions can be reduced by around 90% using the ambitious variant, in which all the decarbonization strategies are implemented simultaneously [11].

The aim of this paper is to evaluate three residential building alternatives in terms of GHG emissions and end-of-life waste management.

2. Materials and Methods

An analytical method of environmental management called a life cycle assessment, LCA, is used in the research. LCA is a method of comparing the environmental impacts of products, goods or services during their life cycle. It acknowledges emissions to all components of the environment during production, use and disposal of the product. The processes of extraction of raw materials, production of materials and energy, and ancillary processes or sub-processes are also included [12,13]. The LCA methodology consists of four phases [14]:

- The definition of the objectives and scope. This is used to define how much of the product life cycle will be included in the assessment and what the assessment will be used for. It describes the criteria used to compare the systems and the time reprezentativeness chosen.
- Inventory analysis. This includes a description of the material and energy flows within the product system, and in particular, its interaction with the environment, the raw materials consumed and the emissions into the environment. It describes all the significant processes and ancillary flows of energy and materials.
- Impact assessment. The results of the indicators of all impact categories are calculated here; the relative significance of each impact category is assessed via normalization and, where appropriate, via weighting. The impact assessment tends to result in a tabular summary of all the impacts.
- Interpretation. Includes a critical review, the sensitivity of data and the presentation of results.

2.1. Goal and Scope

The original residential building (Figure 1) is located in the village Raslavice in north-eastern Slovakia. The building is designed as a detached three-story building without a basement, with a gable roof with a slight slope. Residential units are located on each floor. The gross floor area (GFA) is 418.1 m^2. A condensing boiler is used for hot water preparation and heating. The energy consumption total for heating is 34.44 kWh/m^2. Variant B1 is constructed on strip foundations reinforced with perimeter wreaths, with monolithic ceilings and a staircase. The external walls are made of aerated concrete blocks. In variant B1, the external wall materials have been changed, and two additional alternatives have been created. The external walls of variant B2 are made of sand-lime blocks. The external walls of variant B3 are made of hollow bricks.

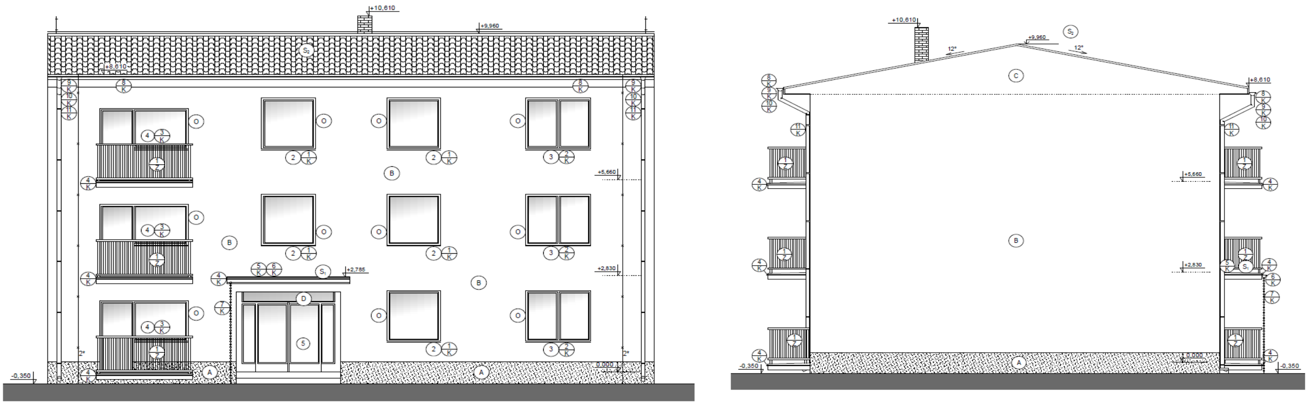

Figure 1. View of the building.

2.2. Life Cycle Inventory

The designed materials were manually entered into the software. This method of input eliminated the possible misclassification of materials within the software database that can occur during automatic uploading. The proposed construction materials were entered into the software, as designed. That is, the materials with the same parameters and the same manufacturer were entered. For the LCA, One Click LCA software, Levels life cycle assessment tool was used, which works in accordance with the ISO standards. For the materials that were not included in the OneClick database, materials with comparable parameters were selected. The windows were not in the database, so similar plastic windows were selected. Waterproof materials with the required parameters from the manufacturer mentioned in the project were replaced by waterproof materials from another manufacturer. LCA also included operational energy consumption and operational water consumption. For the proposed materials, the transport distance between the production plant and the point of use was considered in the analysis, so that the environmental impact of transport was also considered during analysis.

The building was designed and reviewed to understand its potential quantified environmental impacts. The materials of the original B1 building are shown in Table 1. The building's emissions were calculated per functional unit m^2 of GFA for a period of 60 years.

Table 1. Materials of building B1.

Material	B1	Unit
Structural timber, spruce,	3.37	t
Rock wool insulation boards, glass wool, expanded polystyrene	2415.07	m^2
Paint	1474.47	m^2
Aggregate	56.31	m^3
Reinforcement/steel	10.72	t
Waterproofing membrane	874.83	m^2
Ready-mix concrete	142.25	m^3
Gypsum plasterboard	139.29	m^2
Windows	55.67	m^2

Table 2 shows the end-of-life phase scenarios for the building alternatives B1, B2 and B3. Scenario 1 represents the market scenario that is the most typical in Slovakia. The purpose of Scenario 2 was to set the end-of-life phase so that the impacts are further reduced through reuse. Scenario 3 represents the landfilling of the waste.

Table 2. End-of-life scenarios.

Material	Scenario 1	Scenario 2	Scenario 3
Aerated concrete block	Crushed to aggregate	Reuse as material	Landfilling
Sand-lime block	Crushed to aggregate	Reuse as material	Landfilling
Hollow brick	Crushed to aggregate	Reuse as material	Landfilling

2.3. Life Cycle Impact Assessment (LCIA)

The LCA method has a fixed structure and was carried out according to the international standards ISO 14040 and EN 15978, STN EN 15804+A2+AC and PCR (Product Category Rules) as a supplement to STN EN 15804+A2+AC, which is an additional set of rules for specific product categories. Figure 2 shows the system boundary for LCA. Commercially available databases of processes as well as material and energy flows were used for the efficient processing of this LCA study. The LCA method can be defined as the assemblage and assessment of inputs, outputs and potential environmental impacts of a product system during its life cycle [15].

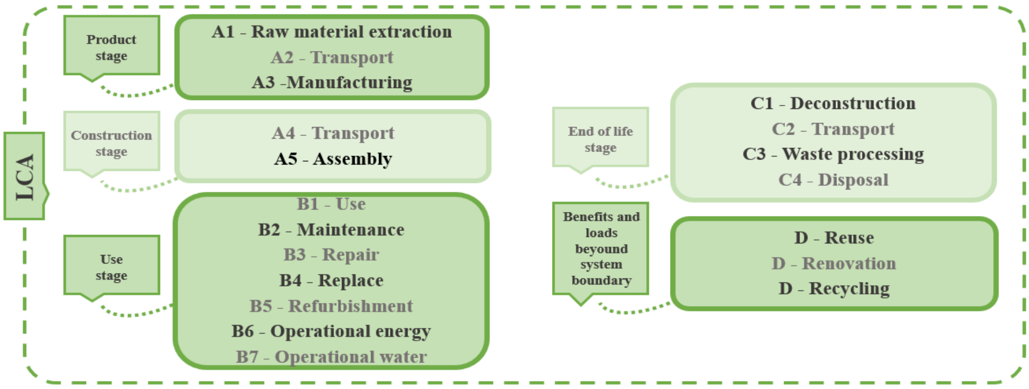

Figure 2. System boundary for LCA.

The LCA methodology allows different categories of environmental impacts to be assessed. According to STN EN 15804+A2+AC, the global warming potential—total (GWP—total) is the sum of three subcategories of climate change, consisting of GWP—fossil, GWP—biogenic and GWP—LULUC) [16]. The temporal changes in aboveground biomass, along with the impact on biodiversity caused by LULUC due to forestry activities, were factored into the calculation. A separate impact category is biogenic carbon storage (CO_2 bio), which has a beneficial impact on the environment. Biological CO_2 storage represents the carbon sequestered in growing vegetation when plants remove carbon dioxide from the air during photosynthesis, which is then converted into oxygen. Sequestration is expressed in kilograms of CO_2 bio-equivalents.

3. Results and Discussion

Table 3 shows the results of the investigated impact categories for the three variants of the building.

Table 3. Results of impact categories.

Impact Category	Unit	B1	B2	B3
GWP—total	(kg CO_{2eq})	8.60×10^5	8.92×10^5	8.35×10^5
GWP—fossil	(kg CO_{2eq})	8.58×10^5	8.90×10^5	8.33×10^5
GWP—bio	(kg CO2e bio)	0	0	0
GWP—LULUC	(kg CO2e)	1.65×10^3	1.67×10^3	1.64×10^3

According to the results for the GWP—total, variant B2 achieves the worst result, 8.92×10^5 kg CO_{2eq}, and B3 achieves the best result, 8.35×10^5 kg CO_{2eq}. Figure 3 shows the results for the GWP—total expressed in kg CO_{2eq} emissions per gross floor area (GFA). The GWP—total values expressed per m^2 of GFA are 2.06×10^3, 2.13×10^3 and 2.00×10^3 kg CO_{2eq}/m^2 for B1, B2 and B3, respectively. Variant B3 has the lowest emission levels, and variant B2 has the highest. The building materials (A1–A3) produce the largest share of CO_{2eq} emissions at 33.71% (2.90×10^5 kg CO_{2eq}) material replacement and refurbishment (B4-B5) produce 28.88% (2.48×10^5 kg CO_{2eq}) and operational energy (B6) produce 22.93% (1.97×10^5 kg CO_{2eq}). The main contributors to emissions are sand-lime bricks (21.2%), aerated concrete blocks (13.1%) and ready-mix concrete (6.3%).

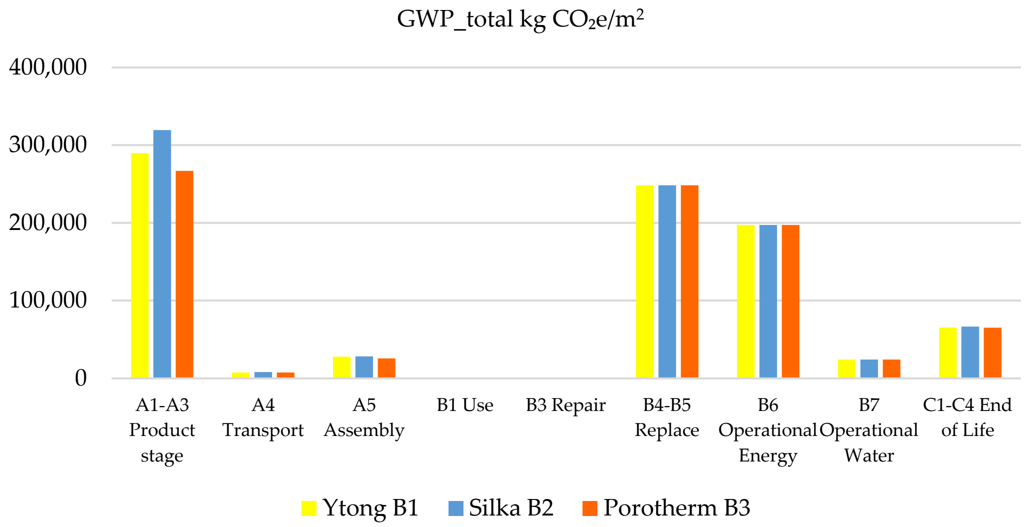

Figure 3. GWP—total in kg CO_{2eq}/m^2.

According to the results for GWP—fossil (Figure 4) and GWP—LULUC (Figure 5), variant B2 achieves the worst result (8.90×10^5, 1.67×10^3 kg CO_{2eq}) and B3 achieves the best result (8.33×10^5, 1.64×10^3 kg CO_{2eq}). Figures 4 and 5 show the results for GWP—fossil and GWP—LULUC expressed in kg CO_{2e} emissions per gross floor area (GFA). The results for GWP—fossil are 2.05×10^3, 2.13×10^3 and 1.99×10^3 kg CO_{2eq}/m^2 for B1, B2 and B3, respectively. The results for GWP—LULUC are 3.95, 4.0 and 3.92 kg CO_{2ee}/m^2 for B1, B2 and B3, respectively.

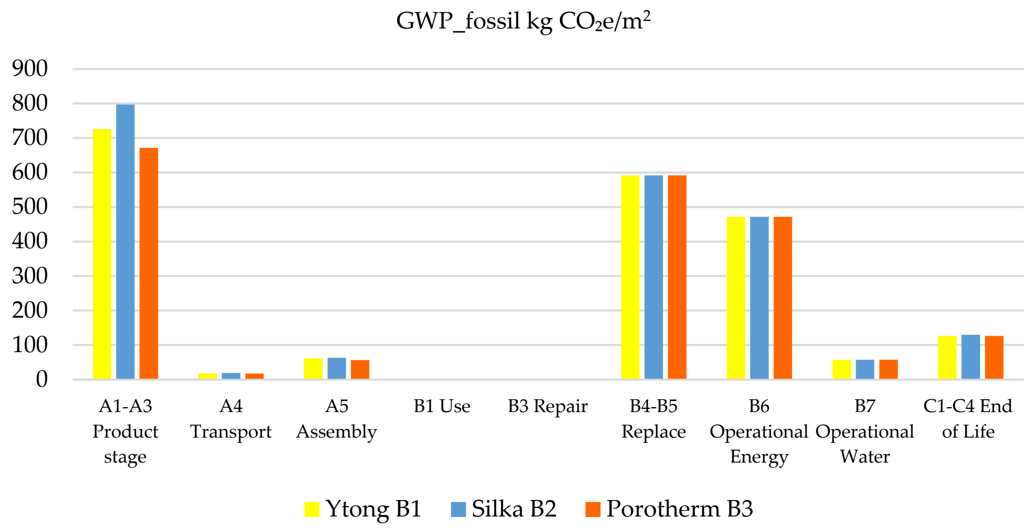

Figure 4. GWP—fossil in kg CO_{2eq}/m^2.

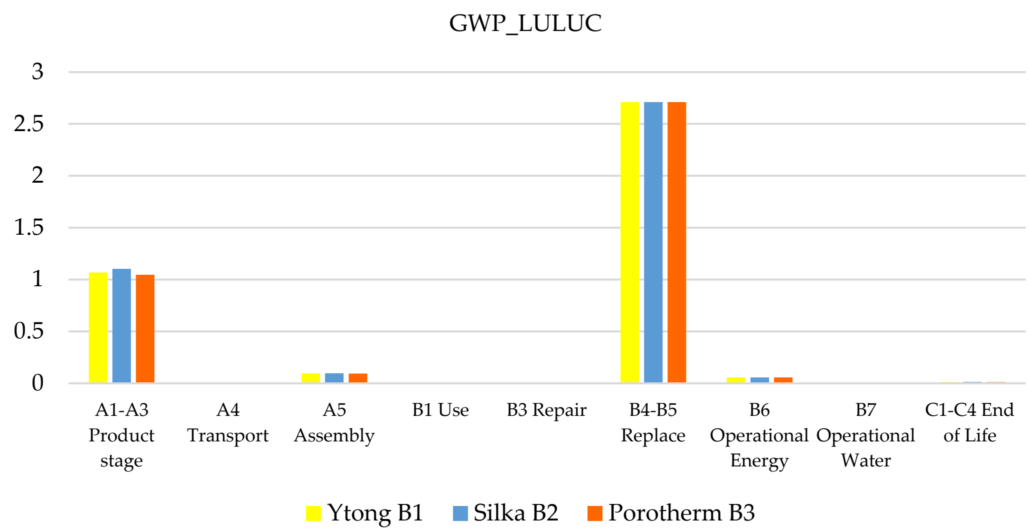

Figure 5. GWP—LULUC in kg CO_{2eq}/m^2.

End of life (EoL) is the last phase of the product life cycle (Figure 6). The product will be recycled, incinerated, used as a new product or deposited in landfill. When materials are incinerated or recycled, they can become useful. Incinerating waste releases usable energy and heat. And by recycling materials, "new" materials are created. In the EoL phase, we, thus, obtain the so-called secondary products. Secondary products have their own life cycle. In this way, the LCA results of the original product can be improved [17].

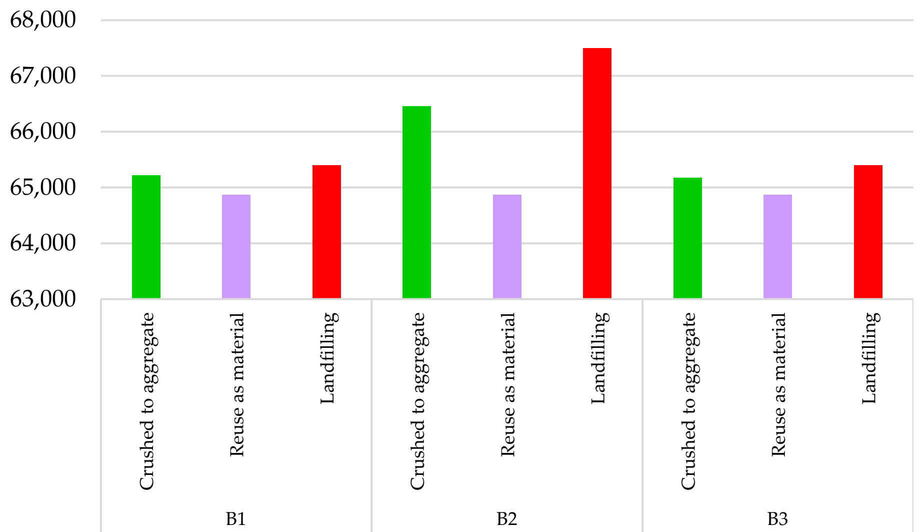

Figure 6. End of life (EOL).

In the original design, the envelope wall materials used for the three variants of building were aerated concrete block (B1), sand-lime block (B2) and hollow brick (B3). The end-of-life phase C1–C4 was changed from the original design. For variants B1, B2 and B3, the last phase of the life cycle for the aerated concrete blocks, lime-sand blocks and hollow bricks was changed from brick/stone crushed into an aggregate to reused as a material and being landfilled. This further reduced the overall emissions by 0.54%, 2.39% and 0.48% in B1, B2 and B3, respectively.

Through the change of EoL of the waste to being reused as a material, the total emissions were further reduced by 0.54%; 2.39% and 0.48% in variants B1, B2 and B3, respectively. Replacing it with landfill, the total emissions increased by 0.021%; 0.129% and 0.027% in B1, B2 and B3, respectively. Only the main material was changed in the variants, but if we also modified the end-of-life phase with other materials, the total emissions would be reduced even more. In a case study from Italy [18], the EoL phase was varied in a similar three-story building. The study suggests the key role of recycling different waste streams, particularly, the reinforcing steel fraction. The positive role of recycling construction plastics also appears interesting, particularly in terms of the impact on the non-renewable energy potential.

From the comparison of the three residential building alternatives, it can be concluded that variant B2 with the lime-sand walls was the best in almost all the categories of impacts. On the contrary, building B3 with the classic hollow bricks was assessed as the best. The greenhouse gas emissions were reduced by 6.39% by using a different external wall material. During the life cycle assessment, the environmental influences relating to the end-of-life phase of the residential building were also examined, with a focus on waste management in phases C1-C4. In buildings B1, B2 and B3, different EoL scenarios were compared. This study found that the re-use of brick waste as brick recyclate contributes the most to the reduction of greenhouse gas emissions.

4. Conclusions

This LCA study examines and quantifies the environmental influences associated with the end-of-life phase of a residential building, with a specific focus on demolition waste management. The analysis compared the environmental characteristics of alternative scenarios characterized by distinct criteria for the demolition of the mentioned building, the management of the demolition waste and the evaluation of the prevention of the burden of recycled materials. The results point to the important role of recycling and material reuse, which represent the most-eliminated impacts in the key categories, as well as in other studies [18,19], where they investigated the importance of the sustainable management of demolition waste. The results of the study are in line with the objectives set out in the European Union's Circular Economy Action Plan. This study quantifies the benefits of using an appropriate selective demolition technique that has the potential to increase both the quality and quantity of residues sent for resource recovery and safe disposal. In addition, the data obtained from the study can be used to establish criteria that can advance the overall environmental performance during the end-of-life phase of the residential building analyzed.

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