DOI: 10.2478/sspjce-2024-0005

Assessment of a residential building in terms of carbon footprint and circular economy

Jana Budajova[1*], Silvia Vilcekova[2], Eva Kridlova Burdova[2] and Peter Mesaros[3]

Technical University of Kosice, Vysokoskolska 4, 042 00 Kosice, Slovakia
[1] Faculty of Civil Engineering, Institute of Architectural Engineering
[2] Faculty of Civil Engineering, Institute for Sustainable and Circular Construction
[3] Faculty of Civil Engineering, Institute of Technology, Economics and Management in Construction
*e-mail: jana.budajova@tuke.sk

Abstract

Built environment contributes significantly to social and economic development, but it is also resource intensive. It is therefore one of the main producers of emissions and carbon footprint. Choosing building designs with a long service life is the key to resolving environmental problems. In this paper, the life cycle of a residential building is evaluated to reduce the greenhouse gas emissions and costs associated with the construction, use and disposal of the building. Life Cycle Assessment and Life Cycle Costing methods were used to evaluate the environmental and financial impact of the residential building. The system boundaries were defined as "Cradle to Grave" and a lifetime of 60 years. The calculation showed that the building emitted 843 tons of CO_{2e}, or 19.8 kg CO_{2e}/m^2/year, and the life cycle costs were 2 026 €/m^2. Considering the phases considered, the energy consumption phase (B6) caused the highest CO_{2e} emissions, up to 50.1%.

Keywords: life cycle assessment, residential building, carbon footprint, circular economy, life cycle cost

1 Introduction

The construction sector and its related manufacturing supply chain emit greenhouse gases (GHG) due to misallocation of resources and misuse of energy. Sustainability has a wider definition and includes three aspects – environmental protection, social aspect, and economic security [1].

The circular economy is a model of production and consumption in which products and services are designed to enable sharing, reuse, repairability and recyclability. Unlike the linear economy, where resources are overused and unnecessary waste is created, in the circular economy scarce resources they use effectively, and the value of the products does not end up buried in a landfill. The circular economy tries to reflect natural processes where no waste is created. Waste is considered a resource that is returned to circulation, creating a closed cycle of materials, products, and components [2, 3]. Life cycle assessment (LCA) can support circular economy

(CE), which is already written into regulations and is becoming an important tool for environmental management in the construction industry [2]. It seeks to address issues the problems of energy consumption and carbon emissions, given the significant environmental burden created by the construction industry. Therefore, environmental assessments such as LCA have been developed for buildings [1]. Construction contributes around 35% of the total municipal waste disposed in landfills [4]. Due to growing concerns about resource use in building construction, energy consumption during building operation, end-of-life waste disposal and related environmental impacts. As a consequence of the global development of building construction, the operation, maintenance/renovation and decommissioning of buildings would place an even greater burden on the environment. Therefore, due to the increased emphasis on sustainability, the construction industry is a key target for reducing environmental impacts worldwide [5]. Carbon footprint has become an important concept against climate change and sustainability. It involves the calculation of the amount of greenhouse gases, especially carbon dioxide (CO_2), which are produced directly or indirectly by an individual, organization, event, or product. This concept helps us better understand the ecological impact of our activity and serves as a basis for the development of measures aimed at reducing emissions and a sustainable lifestyle [6, 7]. Greenhouse gas emission values are expressed as equivalents. Global warming potential (GWP) is expressed as CO_2 equivalent [8]. The assessment of a residential building in terms of carbon footprint and circular economy involves evaluating the environmental impact of the building's construction, operation, and eventual disposal, as well as considering how resources can be used more efficiently and sustainably throughout its lifecycle [9, 10]. The evaluation also includes costs that have been calculated for the entire cycle. This assessment aims to reduce greenhouse gas emissions, minimize waste generation, and promote the reuse and recycling of materials to create a more sustainable and environmentally friendly living space. Can a building be overpriced without negative environmental impacts? These are the questions we ask in this paper.

2 Materials and methods

The assessment of the life cycle of the residential building from the point of view of environmental and economic aspects was carried out in accordance with valid international standards. Based on these standards, the analysis consists of the goal and scope, inventory analyzes (the process of obtaining and gathering information about all inputs and outputs that are associated with a product or service during its life cycle), impact analyzes (evaluation and quantification of the environmental impacts associated with the product or by the service during their life cycle) and interpretation of the results.

2.1 Goal and Scope

To analyse the impact of the building on the environment for the "Cradle to Cradle" system boundary, the software OneClickLCA was used, which works in accordance with EN 15987+A2+AC, STN EN ISO 14040 and ISO 14044. In the software, materials were selected, their transport distances, operating energy, water consumption and quantification of their emissions. The effects on the environment were determined on the gross floor area of the building, which was converted to $1m^2$ for a lifetime of 50 years. Life cycle costs were also quantified using the OneClickLCA software, which worked in accordance with the ISO 15686-5 standard according to the structure of the EN 16627 standard. The system boundaries of the life cycle according to the standardized phase marking A1 to D are shown in Figures 1 and 2.

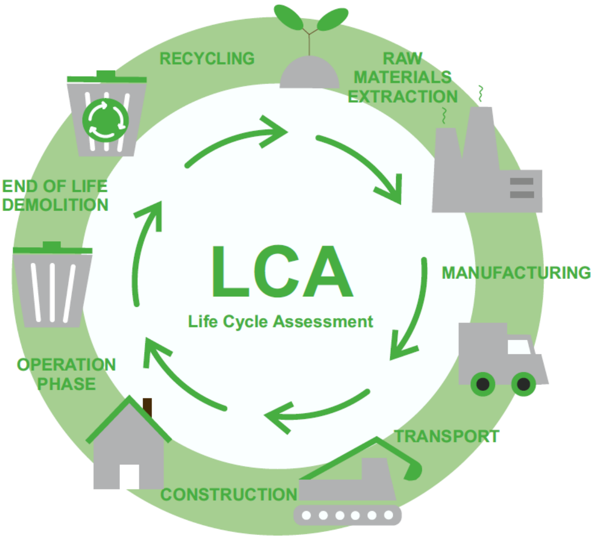

Figure 1: Life cycle assessment [Author]

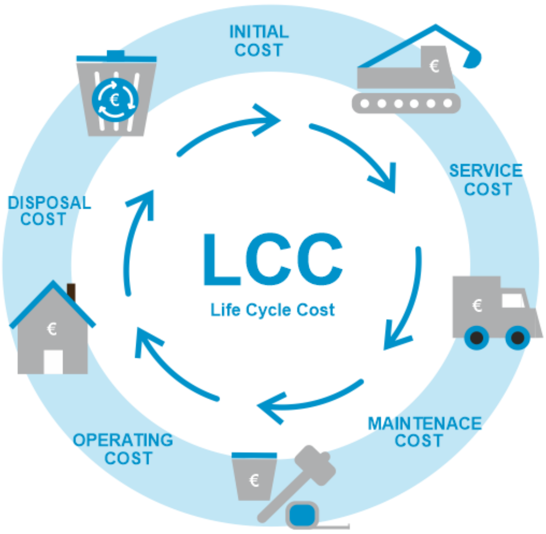

Figure 2: Life cycle cost [Author]

2.2 Life cycle inventory analysis

The selected residential building is located in Poprad. Poprad is one of the larger cities in Slovakia. It is in the north of Slovakia, near the High Tatras (figure 3). The gross floor area is 849.38 m^2 on four floors, which is a smaller apartment building in Slovakia. The residential building is part of a complex of four identical residential buildings (figure 4 and 5) and meets the thermal requirements for category A0 (zero building). The building has a brick load-bearing system made of clay bricks; the ceilings are made of reinforced concrete slabs 160 mm thick. The building is insulated with Greywall EPS (expanded polystyrene) insulation. It's important to consider the energy consumption values of the building, which are 42.4 $kWh/m^2/a$ of electricity and 68.8 kWh/m^2. Calculating the carbon footprint of the residential building per $1m^2$ of gross floor area over a 50-year period can provide valuable insights into its environmental impact. Analyzing and optimizing these values can help in implementing more sustainable practices and reducing carbon emissions.

Figure 3: Position of residential building [13]

Figure 4: Residential building

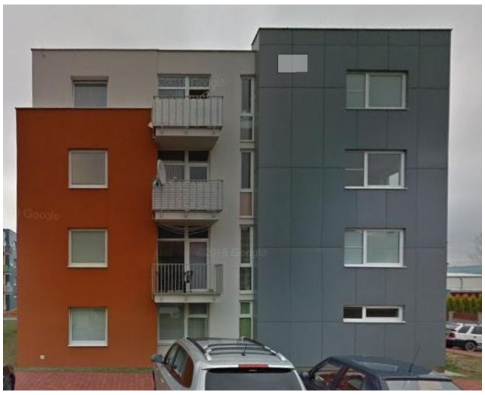

Figure 5: Residential building [14]

The materials used in the residential building, their amount and cost are shown in Figure 6.

Class	**Quantity**	**Unit**	**€**
Ready-mix concrete	338,044	m^3	51 295
Reinforcement steel (rebar)	32,272	ton	19 575
Brick	633,392	m^3	45 371
Aggregate (crushed gravel)	64,412	m^3	1 868
Formwork	99,755	m^2	2 604
Insulation, EPS, Rock wool, XPS	1 058,607	m^3	15 440
Waterproofing and vapor barrier	2 198,612	m^2	8 843
Plasters, mortars and paints	222 577,127	kg	70 786
Masonry lintel	90	m	1 046
Other structures	5 053,686	m^2	53 639

Figure 6: Total sum [Author]

2.3 Life cycle impact assessment

In the Life Cycle Impact Assessment (LCIA) step, all inventory data of the residential building were evaluated. The LCA approach allowed the assessment of many categories of environmental impacts. The main environmental impact indicators included in this study were shown in Figure 7. The residential building was also analyzed in terms of life cycle costs. Life cycle costing refers to the total cost of owning and maintaining a product or system throughout its lifetime. Nominal life cycle cost is the total cost including inflation or the time value of money, while discounted life cycle cost considers the time value of money by discounting future costs to present value. This helps in comparing costs over time and making informed decisions.

Impacts categories		**Unit**
Global Warming Potential total	GWP-Total	[kg CO_{2e}]
Global Warming Potential fossil	GWP-Fossil	[kg CO_{2e}]
Global Warming Potential biogenic	GWP-Bio	[kg $CO_{2e\ bio}$]
Global Warming Potential, LULUC	GWP-LULUC	[kg CO_{2e}]

Figure 7: Impact categories [Author]

3 Results and discussion

3.1 Life cycle assessment - Global warming potential

In the GWP-Total category, the largest share of CO_{2e} emissions is operational energy phase B6 of up to 50%, followed by the product phase with 20.9%, where used bricks, mortars, and screeds 25.5% and 18.1% have the most negative impact on the climate change (figure 8). The phase with the lowest share of CO_{2e} is the transport with share 1.2%. Consumptions of electricity and energy are the main contributors of CO_{2e}. In the GWP-Fossil (figure 9) category, the operational energy phase of B6 has the largest contribution to CO_{2e} emissions at 50.1%, followed by the product phase at 22.9%, where the largest negative impacts are from used coatings, paints, and lacquers at 25.2% and bricks at 20.8%. In the GWP-Bio (figure 10) category, the C3 and C4 phases cause 99.3% of the emissions. In the GWP-LULUC (land use and land use change) (figure 11) category, the product phase A1-A4 and B4-B5 have the largest contribution to CO_{2e} emissions up to 49% and 32.9% respectively.

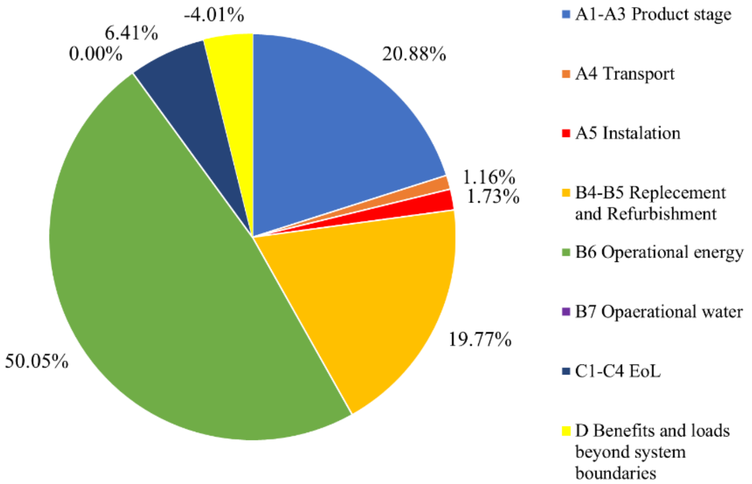

Figure 8: GWP-Total [Author]

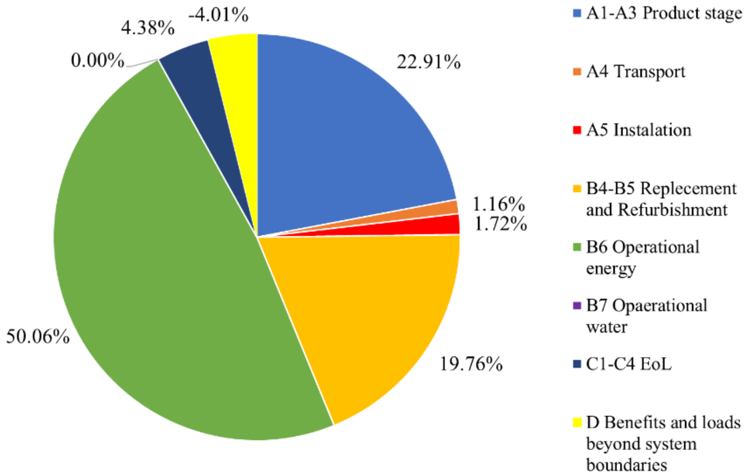

Figure 9: GWP-Fossil [Author]

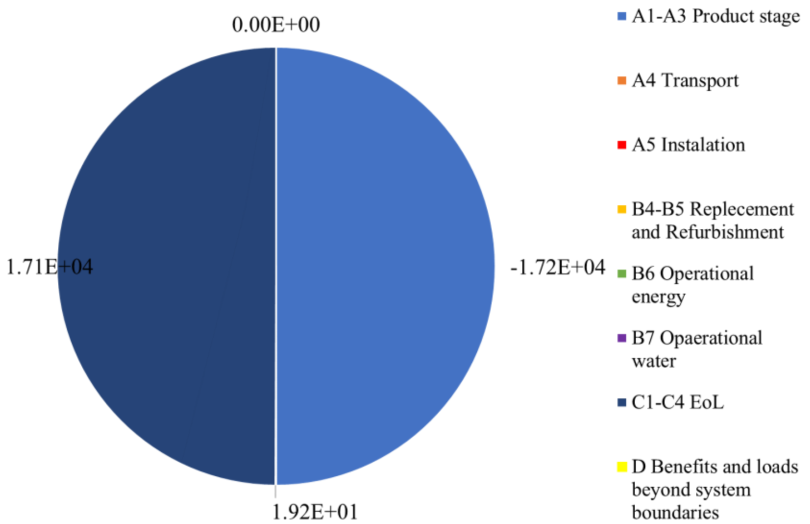

Figure 10: GWP-bio [kg CO_{2e} bio] [Author]

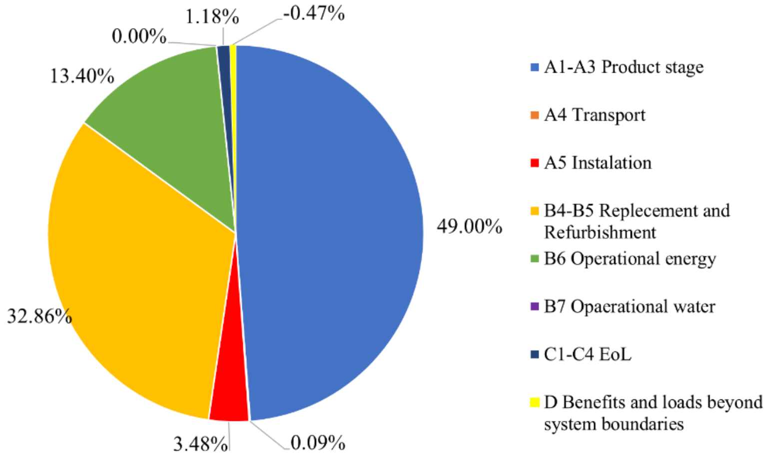

Figure 11: GWP-LULUC [Author]

The whole building comprehensively generated CO_{2e} emissions in the range of 843 tons of CO_{2e}. Converted to FU, it causes emissions of 19.8 kg CO_{2e}/m^2/year (figure 7). Stages that contribute the most to a carbon footprint, were the operational energy B6, product A1-A3 and recovery and renovation B4-B5. The energy consumption phase (B6) was represented by a 50.1% share, followed by the product phase (A1-A3) by a 20.88% share and recovery and renovation (B4-B5) by a 19.77% share. The least represented were transport (A4) and installation (A5) with a share of 1.16% and 1.73%, respectively.

3.2 Results of life cycle cost

From the calculation of life cycle costs, it emerged that the building had a nominal value of 1 720 881€. The total life cycle costs in terms of functional unit reached 2 026 EUR/m^2 (1 720 881 €/849.5 m^2) (see figure 12). Based on the context provided, the estimated distribution of life cycle costs reached, energy costs 14.7%, construction costs 67.3%, building maintenance costs 11.6%. These percentages represented the allocation of the life cycle budget to different cost categories. The EoL phase represents only a small amount of 1% (see figure 13).

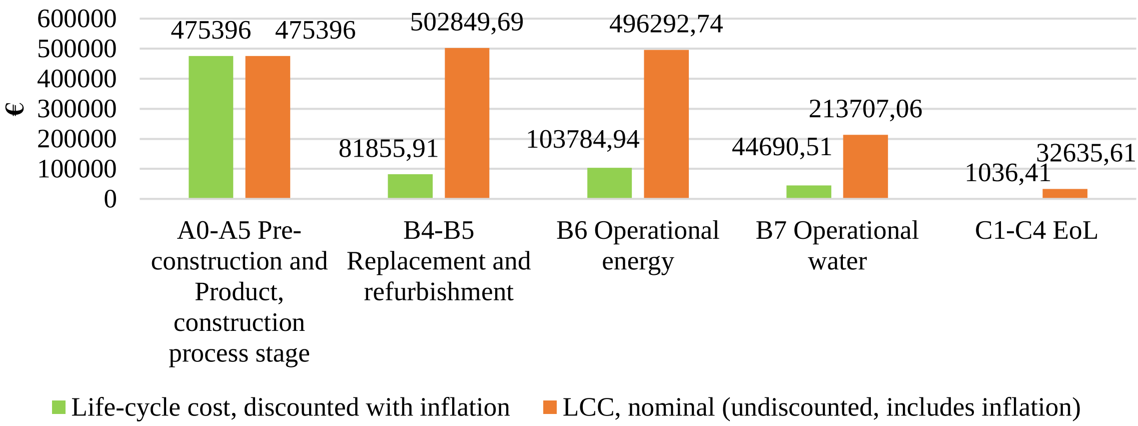

Figure 12: Life cycle stages

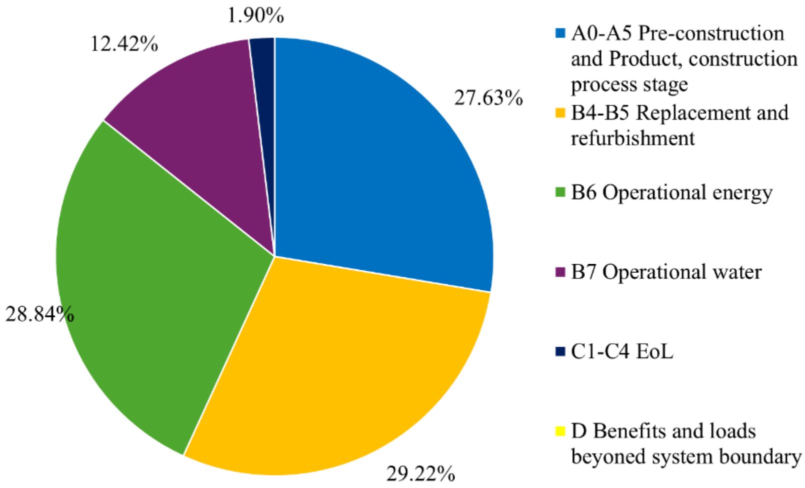

Figure 13: Life cycle cost stages [Author]

3.3 Discussion

Carbon footprint of the residential building is determined using by using LCA. The estimated useful life was calculated for a period of 50 years. The whole building generates CO_{2e} emissions in the range of 843 tons, which represents 19.8 kg CO_{2e}/m^2/year and 992 kg CO_{2e}/m^2. Compared to the study of residential buildings [11], which evaluates a 5-storey and 13-storey residential buildings from South-East Turkey, a building rated in Slovakia causes less CO_{2e} emissions. Emission ranges from 3 956 to 5 809 kg CO_{2e}/m^2. In comparison with this study, the energy consumption phase accounted for the largest greenhouse gas emissions. In this study, a different insulation material was used for the walls which may have caused higher emissions. The authors further state that by choosing the appropriate insulation material, a reduction in emissions can be achieved and this is confirmed in their study. In this study, the total life cycle costs are reached at USD 7.28 million, which is EUR 6.4 million for a five-story building and USD 1.72 million, which is 1.5 million € for a thirteen-story building over the proposed 50 lifetime. Among the most expensive (49-52%) materials and structures are concrete foundations, reinforced concrete slab. For the building investigated in this study, the total life cycle cost is 1.72 million € which is comparable with the mentioned study [11]. The study [12] examined a ten-storey building in Denmark. It has a total area of 7 000 m^2, the external wall is a sandwich construction with mineral wool, and the building uses an HVAC system with a heat pump and photovoltaic panels. The total LCC is 15.4 million €, per m^2 is 2 203 €/m^2.

4 Conclusion

The construction and maintenance of building structures involve energy-intensive processes throughout their life cycle, starting from the extraction of raw materials, product production, and even disposal. This highlights the importance of considering the environmental impact and energy consumption associated with the entire lifecycle of buildings. Energy-intensive processes consume large amounts of energy resources and produce significant emissions and waste. Absolutely, the environmental impact of construction includes various stages such as material extraction, transportation, manufacturing, operation, maintenance, and end-of-life considerations. It's important to consider these factors to minimize the environmental footprint of construction projects. These phases also have significant economic costs. Assessing the environmental impact and life cycle costs of a residence as a challenging task and it is necessary to evaluate all elements and phases of the life cycle. Results of this study point out that operational energy contributes the most to the carbon footprint (50%) as well as the biggest costs also go to operational energy. The amount of CO_{2e} emissions is affected not only by the choice of materials but also by the total gross floor area. Future research will focus on conducting an in-depth analysis and comparison of the environmental and economic aspects of different buildings, which can help identify environmentally friendly measures and sustainable practices. This approach can lead to more informed decision-making in the construction industry and contribute to the creation of greener and more efficient buildings.

Acknowledgments

This study was financially supported by Grant Agency of Slovak Republic to support project No. VEGA 1/0057/24 and by the Slovak Research and Development Agency APVV-22-0576.

References

[1] Mhatre P., Gedam V., Unnikrishnan S. & Verma S. (2021). Circular economy in built environment–Literature review and theory development Journal of Building Engineering 35 101995.

[2] Joensuu T., Leino R., Heinonen J. & Saari A. (2021). Developing Buildings’ Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components Sustainable Cities and Society 103499.

[3] Tunn, V. S., Bocken, N. M., van den Hende, E. A., & Schoormans, J. P. (2019). Business models for sustainable consumption in the circular economy: An expert study. Journal of cleaner production, 212, 324-333.

[4] Kamali M., Hewage K. & Sadiq R. (2019). Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings Energy and Buildings 204 109479.

[5] Joensuu T., Leino R., Heinonen J. & Saari, A. (2021). Developing Buildings Life Cycle Assessment in Circular Economy-Comparing methods for assessing carbon footprint of reusable components Sustainable Cities and Society 103499.

[6] East A. J. (2008). September What is a carbon footprint? An overview of definitions and methodologies. In Vegetable industry carbon footprint scoping study - Discussion papers and workshop Horticulture Australia Limited.

[7] Števo S. (2008). Uhlíková stopa bývania v globalizovaných domoch TZB Haustechnik roč. 25 pp16-20.

[8] Amoo L. M. & Fagbenle R. L. (2020). Climate change in developing nations of the world In Applications of Heat, Mass and Fluid Boundary Layers (Woodhead Publishing) pp 437-71.

[9] Ghisellini, P., Ripa, M., & Ulgiati, S. (2018). Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. Journal of Cleaner Production, 178, 618-643.

[10] Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied energy, 143, 395-413.

[11] Atmaca A. (2016). Life-cycle assessment and cost analysis of residential buildings in South-East of Turkey: part 2—a case study The International Journal of Life Cycle Assessment 21 pp 925-942.

[12] Marszal, A. J., & Heiselberg, P. (2011). Life cycle cost analysis of a multi-storey residential Net Zero Energy Building in Denmark. *Energy*, 36(9), 5600-5609.

[13] Google Maps, Available online: 12.03.2024

https://www.google.sk/maps/place/LUNA+RESIDENCE+POPRAD+-+MATEJOVCE/@49.0788993,20.3278781,376m/data=!3m1!1e3!4m14!1m7!3m6!1s0x473e3bc5e38c4fb7:0x7af2e9cb4a896bdf!2sLUNA+RESIDENCE+POPRAD+-+MATEJOVCE!8m2!3d49.0794723!4d20.3194412!16s%2Fg%2F11txjd76ds!3m5!1s0x473e3bc5e38c4fb7:0x7af2e9cb4a896bdf!8m2!3d49.0794723!4d20.3194412!16s%2Fg%2F11txjd76ds?entry=ttu

[14] Google Maps, Street View, Available online: 12.03.2024

https://www.google.sk/maps/@49.079063,20.3286721,3a,60y,150.13h,87.15t/data=!3m6!1e1!3m4!1se3SmxDWDIsN0nAhY63-gmw!2e0!7i16384!8i8192?entry=ttu