

## RESEARCH PAPER

## Sustainability building materials and circularity score of residential buildings

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## ABSTRACT

Building materials used, approaches and technologies related to the operation of residential buildings influence the environment and climate change. For this purpose, an assessment of environmental impacts and circularity of 11 residential buildings (marked as A) was carried out using the life cycle assessment (LCA) methodology. LCA analysis consisted of four parts. First, the goal and scope were defined. Then, inventory analysis (LCI) entered the assessment using input data. They were needed to quantify inputs and outputs, resource and energy flows, emissions, and other leakages. Life cycle impact assessment (LCIA) quantified the pollutants into impact categories. The last part was the interpretation of the results. Investigated buildings were assessed within a moderate climate zone and "Cradle to Cradle" system boundaries over a lifetime of 60 years. The product and energy consumption phases generally contributed to the highest GHG emissions. In terms of materials, aerated concrete (up to 89.4%), concrete (20-51%) and clay brick (38-47%) caused the highest values for the GWP indicator. The end-of-life phase, including incineration, landfilling and reuse of materials, was quantified in the 0.1-74% range. Quantified global indicators are Global warming potential (GWP), Depletion potential of the stratospheric ozone layer (ODP), and Abiotic depletion potential for non-fossil resources (ADP-E). In this study, regional indicators are Acidification potential (AP), Eutrophication potential (EP) and Formation potential of tropospheric ozone (POCP). A building that achieves higher circularity is the building that makes the most use of renewable or reused resources, so it uses less raw materials. The circularity score representing materials recovery was 23% to 48%. The best circularity score of building E (48%) was due to downcycling (45.8%) and use as energy (32.1%) of applied materials. The lowest circularity score was found for building I, with a value of 23%. The most suitable building in terms of environmental impact and circularity was identified using multicriteria analysis.

**Keywords:** Sustainability; building materials; life cycle assessment; circular economy

## INTRODUCTION

Sustainability is becoming a significant element in the construction sector, especially in environmental and social challenges arising from climate change, degradation of natural resources and pollution [1]. Rapidly growing urban areas, increasing pressure for sustainable development and the need to reduce greenhouse gas emissions are bringing energy efficiency, material choice and waste management issues to the center of interest [2-3]. The construction of sustainable residential buildings is one of the key steps towards achieving ecological balance, energy efficiency and long-term sustainability within the urbanization and construction sector [4-6]. Therefore, two crucial methods that are fundamental to achieving sustainable development in the field of residential construction - Life Cycle Assessment (LCA) and Circular Economy (circularity) - are gaining relevance in this regard [7-8].

Life Cycle Assessment (LCA) is an analytical method for evaluating the environmental impacts of products or processes throughout their life cycle. In the residential construction, LCA focuses on all phases of a building's life cycle, from design through construction, operation, demolition, and final disposal [7].

Circular Economy (CE) is a management model that, in contrast to the traditional linear model ("take-make-dispose"), is based on principles (so-called "R-principles") that support the reuse of materials, recycling and lifespan extension of products and buildings [9]. For residential construction, it also promotes the principles of Design for Disassembly and Adaptability (DfD and DfA), energy and water efficiency, and the selection of sustainable and eco-friendly materials. The circular approach seeks to create a closed cycle in which materials and products are circulated for as long as possible, reducing waste and the need for new raw materials [9, 13-14, 16-17].

LCA and circularity are closely linked, as both approaches emphasize the optimization of environmental impacts throughout the life cycle of a building. LCA provides a quantitative tool to assess the environmental impacts of building construction and operation, while circularity offers practical strategies and principles to minimize these impacts. Integrating circularity into LCA can significantly optimize the design of buildings, increasing its environmental

performance and the efficient use of materials, energy and other resources throughout the building's life cycle [15, 17].

Circular research in the construction industry is still in its early stages. It faces various shortcomings and challenges that must be overcome for circularity models to become a common standard in the industry. The main challenges include inconsistencies in evaluation methods and definitions, lack of evidence on economic and environmental benefits, technological and innovation barriers, legal restrictions and the need for a cultural change in the construction sector. Current research often focuses on individual phases of the building life cycle (e.g. construction, deconstruction). Still, it lacks a comprehensive approach to integrating circularity throughout the entire life cycle of a building, including operation and maintenance. All these areas require further research, innovation and collaboration between academic, industrial and policy sectors [10-13].

This paper aims to examine 11 existing residential buildings in terms of environmental impacts and circular economy. The data obtained from this assessment was further analyzed in a multi-criteria analysis to determine the optimal design of the residential building. The results of this study form the basis for conducting more detailed analyses to optimize existing residential building designs by implementing circular economic approaches into the life cycle assessment of the building. Furthermore, the findings from this case study will provide information on the current state of residential building construction to guide stakeholders and policies towards sustainable construction.

## MATERIAL AND METHODS

## Life cycle assessment

## 1. Goal and scope

This study aims to analyse 11 multistorey residential buildings from environmental impacts and circularity scores. For the analysis, One Click LCA software (version: 0.29.1, database version: 7.6) complied with international standards EN 15804, EN 15978, ISO 14040 and ISO 14044 were used. The

considered system boundary was "Cradle to Cradle", with life cycle stages shown in Fig. 1.

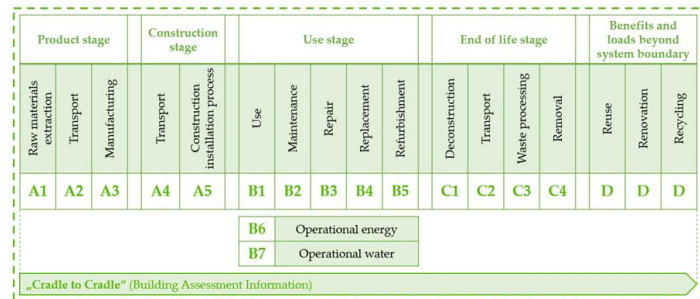


Fig. 1 System boundary

The functional unit (FU) was set at one square meter (m<sup>2</sup>) of usable floor area and an estimated design life of 60 years. In addition, the circularity investigated of buildings is linked to the end-of-life (EoL) phase.

To evaluate the buildings, a multicriteria analysis using MCA7 software was performed. Decision methods, namely the weighted sum method (WSA), ideal

point method (IPA), concordance and disagreement method (CDA), and TOPSIS method (Korvin; 2010), were applied.

2. Life cycle inventory

Based on the inventory analysis, the environmental impacts were calculated. In this study, buildings were built or undertook construction in the years from 2017 to 2023. Characteristics of the buildings are presented in Table 1. Built-in materials and their quantities were determined and used in the analysis. All buildings are reinforced concrete frames (columns and beams) supplemented with fill masonry. The roofs of the selected buildings are conventional flat roofs. Energy supply is provided by gas condensing boilers or district heating. The public water supply provides water for drinking, sanitary facilities and fire safety systems. The public grid is used as an electricity source. Calculated energy for the building operation was obtained from project documentation and energy performance reports.

The environmental assessment results were expressed per 1 m<sup>2</sup> of FU. The One Click LCA (OCL) software followed the CML and PEF methodology and the European approach to level(s) assessment. Various databases and data sources, such as Ecoinvent 3.8, OneClickLCA, GaBi, Okobaudat, and EPDs, were used in the analysis. For materials without declared environmental information, average values of environmental indicators are considered.

Table 1 Characteristics of the buildings A-K

	Building A	Building B	Building C	Building D	Building E	Building F
Location	Trnkov	Košice	Bratislava	Bratislava	Humenné	Košice
Build-up area	330.1 m <sup>2</sup>	1 286 m <sup>2</sup>	2 477.6 m <sup>2</sup>	4 957 m <sup>2</sup>	297 m <sup>2</sup>	1 866.3 m <sup>2</sup>
Usable floor area	1 166.1 m <sup>2</sup>	4 608.1 m <sup>2</sup>	11 721 m <sup>2</sup>	3 607 m <sup>2</sup>	1 177.8 m <sup>2</sup>	7 981.4 m <sup>2</sup>
Number of apartments	12	50	123	89	11	134
Number of polyfunctional spaces	0	2	0	0	0	0
Number of floors	4	7	8	8	4	7
Elevator	1	1	2	2	2	2
Construction year	2022	2020	2019	2021	2017	2019
	Building G	Building H	Building I	Building J	Building K	
Location	Poprad	Poprad	Raslavice	Košice	Trenčín	
Build-up area	271.4 m <sup>2</sup>	437.6 m <sup>2</sup>	170.3 m <sup>2</sup>	5 500 m <sup>2</sup>	348.3 m <sup>2</sup>	
Usable floor area	849.4 m <sup>2</sup>	5 059 m <sup>2</sup>	418.1 m <sup>2</sup>	42 000 m <sup>2</sup>	1 266 m <sup>2</sup>	
Number of apartments	14	45	6	350	9	
Number of polyfunctional spaces	0	0	0	0	2	
Number of floors	4	13	8	10	3	
Elevator	0	1	0	9	1	
Construction year	2009	2020	2019	2021	2022	

3. Life cycle impact assessment

In this study, life cycle impact assessment (LCIA) was applied as a method for assessing the potential environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to disposal. LCIA helps quantify and understand environmental burdens, enabling informed decision-making and sustainable practices. Impact category indicators included in the calculation are shown in Table 2. LCA categories are divided into different levels, such as global, regional, and local impact categories [18].

Global environmental indicators monitor the state of the environment worldwide, including greenhouse gas emissions, air and water quality, biodiversity, and deforestation, such as GWP potential for climate change, ODP potential for ozone depletion and ADP-E for non-fossil resources.

Regional indicators target a specific region, monitoring air and water quality, land use, biodiversity, waste, and energy consumption such as AP, EP and POCP. These measurements help identify environmental problems and shape conservation and sustainable development strategies.

Local indicators measure the state of the environment in the local area and include air and water quality, waste management, green spaces, noise pollution, and community involvement in environmental impact indicators such as ADP-FF and WD.

Table 2 Parameters describing environmental impacts

Impacts categories	Abbreviation	Unit
Global Warming Potential total	GWP-total	kg CO <sub>2e</sub>
Global Warming Potential fossil	GWP-fossil	kg CO <sub>2e</sub>
Global Warming Potential biogenic	GWP-bio	kg CO <sub>2e</sub> bio
Global Warming Potential, LULUC (Land Use and Land Use Change)	GWP-LULUC	kg CO <sub>2e</sub>
Depletion potential of the stratospheric ozone layer	ODP	kg CFC11 <sub>e</sub>
Acidification potential	AP	mol H <sup>+</sup> <sub>e</sub>
Eutrophication potential of aquatic freshwater	EP-AF	kg Pe
Eutrophication potential of aquatic marine	EP-AM	kg N <sub>e</sub>
Eutrophication potential of terrestrial	EP-T	mol N <sub>e</sub>
Formation potential of tropospheric ozone	POCP	kg NMVOC <sub>e</sub>
Abiotic depletion potential for non-fossil resources	ADP-E	kg Sb <sub>e</sub>
Abiotic depletion potential for fossil resources	ADP-FF	MJ
Water deprivation	WD	m <sup>3</sup>

Building circularity was assessed using the building circularity indicator (BCI) to generate a circularity score. OCL software and the Building Circularity tool were used to calculate this score. Different weighting factors of materials were considered for the evaluation of the materials. The calculation is done in two parts: Recovered and returned Materials. Virgin materials, which are new, have higher emissions than recycled materials. Therefore, they have a weighting factor of 0. Renewable materials have a weighting factor of 1 because they can be regrown. Materials that do not require much processing have a weighting factor of 1. Recovered and recycled materials reduce material emissions, so they have a weighting factor 1. Materials returned consist of materials that can be reused as materials or used as energy, materials that can be recycled or downcycled and materials that are disposed of (landfilled). Recyclable materials that can be used as the original product have a weighting factor of 1. Materials that can be reused as materials reduce the emissions, so the default multiplier is set to 1. Materials that can be recycled produce some emissions for the recycling process; therefore, the default multiplier is set to 1. Materials that can be downcycled have a default multiplier of 0.5. Combustible materials produce emissions from the combustion process but end up with recovered energy that can be used for various purposes (e.g. heating, electricity, manufacturing). Due to the generated emissions from combustion, the default multiplier is set to 0.5. In the disposal of (landfilled) materials, the default multiplier is set to 0.

## RESULTS AND DISCUSSION

### Global impact categories

The life cycle assessment of residential buildings is presented through global, regional, and local impact categories. Global indicators are presented in Fig. 2 for each life cycle stage. The study found that building K causes the largest CO<sub>2e</sub> emissions, 3 576.81 kg CO<sub>2e</sub>/m<sup>2</sup>. Among the materials that contribute the most to the GWP is autoclaved aerated concrete, which accounts for up to 89.4%. It is followed by clay brick with a share of 78%, reinforcement steel with 59.2%, and concrete with 50.9%. Higher values were also achieved for PVC frame windows, lime-cement plaster, cement screed and precast concrete. The product phase (A1-A3) contributed a large share to the GWP category (2 474.45 kg CO<sub>2e</sub>/m<sup>2</sup>). This was followed by the operational energy (B6) with a 673.96 kg CO<sub>2e</sub>/m<sup>2</sup> value. Transport (A4) and EoL (C1-C4) had the lowest environmental impacts. The benefits and loads from incineration, landfilling, and reuse under module D for the global indicators were presented at 5.42%.

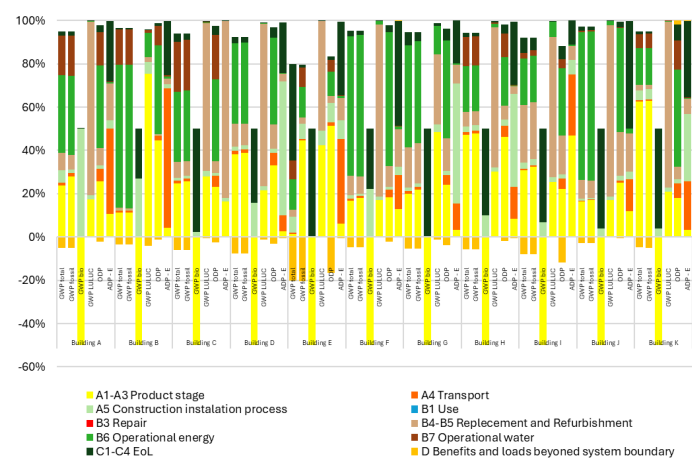


Fig. 2 Global indicators expressed for each life cycle phase in percentages

A study from New Zealand that evaluated two two-storey buildings within the system boundary "Cradle to Cradle" found that the lightweight timber building emitted only 13.7 kg CO<sub>2e</sub>/m<sup>2</sup>/year while the lightweight steel building emitted 15.4 kg CO<sub>2e</sub>/m<sup>2</sup>/year. Operational energy in both buildings was the most significant contributor to carbon emissions at 49.5 to 57.6% over the entire building life cycle, followed by the A1-A3 product phase. Due to the estimated lifetime of buildings up to 90 years, they require more operational energy than

the other phases of the building life cycle [19]. Petrovic et al., in a study from Sweden, found a very similar result. The authors evaluated a smaller residential building made of wood with a 100-year lifetime where the "Cradle to Grave" system boundary was used. The production phase contributed 30%, the maintenance phase contributed 37%, contributing the most to the total carbon emissions, up to 67%, while the operational energy contributed only 21%. The EoL phase was the least represented, with only 2%. Concerning materials, concrete contributed the most with 6.1 t CO<sub>2e</sub>, which made up 19% of the total emissions [20]. Chandrakumar et al. analyzed the total carbon emissions of a residential building in New Zealand with a 90-year lifetime within the "Cradle to Grave" system boundary. Their research determined that the building emitted 16 kg CO<sub>2e</sub>/m<sup>2</sup>/year. Results of CO<sub>2e</sub> for residential buildings in other countries ranged between 10 and 90 kg CO<sub>2e</sub>/m<sup>2</sup>/year. Operational energy (60%), maintenance and replacement (13%) and product phase (12%) contributed the most to climate impacts [21]. Another study from Canada examined a two-storey residential building from environmental impacts over a 60-year lifetime within the system boundary of the "Cradle to Grave". The study showed that operational energy caused almost half the total environmental impacts, followed by the production phase with a 7 to 51% share for all indicators evaluated [22]. According to Rashid et al., in the pre-use phase, concrete in foundations was identified as the largest contributor to GWP, acidification and eutrophication [23]. A study by Vitale et al. assessed residential buildings in Italy. It stated that the use phase had the largest contribution to total emissions at 77% and 84% for the global warming and non-renewable energy indicators, respectively [24]. A study in China evaluated a residential building which emitted 2993 kg CO<sub>2e</sub>/m<sup>2</sup> over its estimated 50-year lifetime. The operational energy contributed 68.9% of the total GHG emissions, and the product phase contributed 23.9%. In terms of materials, concrete was again the most widely used building material, with the contribution of 44% of the total GHG emissions [25]. In a study from Saudi Arabia, authors found that operational energy had the most significant impact on GWP over the 50-year life cycle. By applying renewable energy sources, it would be possible to reduce CO<sub>2</sub> emissions from electricity by 53%, but this doesn't remain very important when considering the overall environmental impact of the building [26]. Another study from Brazil also found that operational energy is the most critical, and foundations, masonry and coatings have the greatest impact. Concrete, ceramic tiles, and steel contributed the most [27]. A life cycle energy analysis of eight residential buildings from Australia was performed. Embedded energy accounted for 10 to 30%, while operational energy accounted for 65 to 90%. Demolition energy was less than 4% of life cycle energy [28]. Regarding the ADP-E category, building C is the largest contributor, with 30.09 kg Sbe/m<sup>2</sup>. For almost all the buildings assessed, the largest emissions were caused by the operational energy (B6) required for heating and hot water preparation, which was 37-72%. The product phase (A1-A3) was 37-70%. The materials with the highest CO<sub>2e</sub> emissions are concrete, at 20-51%; clay bricks, at 38-47%; and aerated concrete, at 89.4%.

### Regional impact categories

Considering regional indicators, building B caused emissions of 14.89 mol H<sub>+</sub>/m<sup>2</sup> for the AP category and 31.38 mol N<sub>e</sub>/m<sup>2</sup> for the EP-T category. The energy consumption phase (B6) was the worst in terms of these indicators and had a share of 65%-89%. Building E caused emissions of 1.65 kg P<sub>e</sub>/m<sup>2</sup> in the EP-AF category, 2.29 kg N<sub>e</sub>/m<sup>2</sup> in the EP-AM category, and 7.32 kg NMVOC/m<sup>2</sup> in the POCP category. The product phase (A1-A3) was also the worst in terms of these indicators, accounting for 63%-85% of the total emissions. The EoL phase (C1-C4) had the lowest impact. Module D representing potential benefits and loads beyond the system boundary ranged from 0.1%-37%. Materials with the highest contribution used in building B were precast concrete slab (34.2%-42.91%), transport concrete (25.5%-29.2%) and clay bricks (4.7%-6.5%). For building E, materials with the highest contribution were multi-layered hardwood floors (85.1%-90%) and concrete (3.01%-4.4%). Results of regional indicators are presented in Fig. 3 for each life cycle stage.



Fig. 3 Regional indicators expressed for each life cycle phases in percentages

Local impact categories

Regarding local indicators, building F achieved values of 44,610.58 MJ/m<sup>2</sup> and 5,693.46 m<sup>3</sup>/m<sup>2</sup> for ADP-FF and WD, respectively. Building K also achieved the worst results for ADP-FF and WD, with 39,797.21 MJ/m<sup>2</sup> values and 7,118.72 m<sup>3</sup>/m<sup>2</sup>, respectively. On the other hand, building D (20,991.6 MJ/m<sup>2</sup>; 2,146.8 m<sup>3</sup>/m<sup>2</sup>) reached the lowest values. Operational energy (B6) contributed the most to local indicators, ranging from 42.6%-92.5% for all buildings. The EoL phase (C1-C4) had the lowest impact. For Module D, benefits and loads beyond the system boundary, local indicators ranged from 0.07%-29.3% for all buildings. Regarding building F, the three materials with the highest contribution were concrete (22.9% and 71.9% for ADP-FF and WD), reinforcement (1.2% and 16.3% for ADP-FF and WD), and EPS insulation (20.5% and 0.6% for ADP-FF and WD). Related to building K, concrete (34.3% and 97% for ADP-FF and WD), reinforcement (16.3% and 1% for ADP-FF and WD), and EPS insulation (21.6% and 0.6% for ADP-FF and WD) contributed mostly to the local impacts. Results of local indicators are presented in Fig. 4 for each life cycle stage.

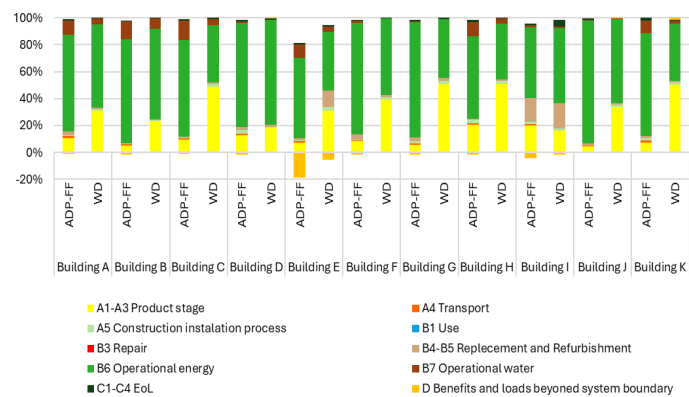


Fig. 4 Local indicators expressed for each life cycle phase in percentages

Building circularity

The best circularity score of 48% was achieved for building E (Fig. 5), followed by a score of 38% for building A and 32% for building G. Building E consists of virgin materials with a percentage of 64.2%. No reused materials are built in. This building would return 59.5% of the materials: reused as materials (17.1%), recycled (3.5%), materials used for downcycling (45.8%), used as energy (32.1%), and only a minimal proportion of materials would be landfilled (1.5%). Building I had the lowest circularity score, representing 23% (Fig. 6). This building consists of 95.8% of virgin materials, 0% reused as materials, 2.5% recycled materials and 7.2% used as energy. Although materials used for downcycling were represented by 70.7%, only half were counted according to the

weighting factors. Among all the buildings, landfilling was the highest at 19.6% in building I. For building E, 44 t of materials were placed in the landfill, i.e. 11 t of construction materials, 1 t of waste construction materials and 32 t of replacement and refurbishment materials. 100% concrete, as the material with the largest weight, is used for downcycling, such as crushed to aggregate. The material circularity was 25%. Also, wood and wood-based materials have the largest amount, and 100% of them can be used for downcycling (natural materials) and energy (incineration). The circularity score of these materials was 62%. Steel components and reinforcements were materials with the smallest amount but showed up to 93% recycling, as 97% of steel can be recycled and reused as a material. Regarding building I, up to 165 tons of materials were disposed of in the landfill. They included 64 t of construction materials, 89 t of earth masses, asphalt and stones, seven waste construction materials, and 5 t of material replacement and refurbishment.

In a study from Iran, the authors also used One Click LCA software to evaluate two house alternatives, where recycling and reuse percentages can be set for each material in the building. The authors determined that the use of new materials and the consequent use of new sources reduced the circularity of the house by 7% compared to a building that used both original and recycled materials. When using low-emitting materials, the authors achieved a circularity of up to 37% in the primary building and 6% in the new building [29]. In a study from Sri Lanka, the circularity of a building with a lifetime of 60 years was analyzed by using One Click LCA software. In that study, the end-of-life scenario was like ours (concrete crushes to aggregate, steel recycling, reuse as material and incineration). Also, the circularity is higher for bricks (62%), as in our study. The authors found that after demolition, bricks (with content higher than 90%) and steel (with content higher than 85%) can be reused as materials or recycled at the end of the building's lifetime [30].

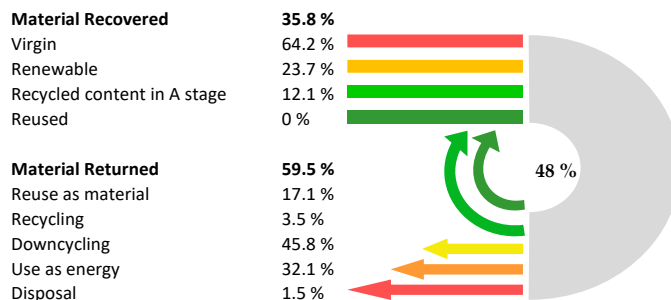


Fig. 5 Circularity score for building E

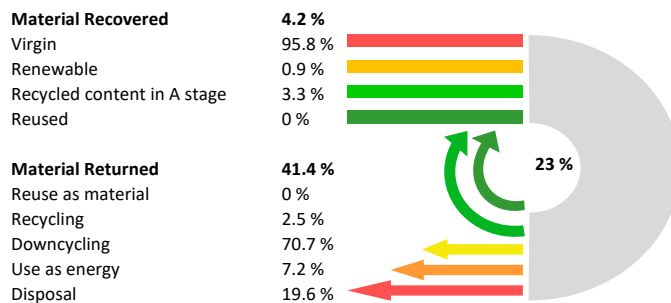


Fig. 6 Circularity score for building I

Based on multicriteria analysis, the most optimal building was found. According to the CDA evaluation criteria, building D was the best, taking second place among all other evaluation criteria (IPA, WSA, TOPSIS). According to the evaluation criteria of IPA and WSA, the most optimal building is A, and according to TOPSIS, it is building C. Building G was ranked second (CDA) and third (IPA, WSA and TOPSIS). Building K ranked worst according to all evaluation criteria. Aerated concrete (2 799.6 t CO<sub>2e</sub>) and reinforced concrete (124.8 t CO<sub>2e</sub>) have the highest contribution. The circularity of this building was

also low, only 27%, and no renewable or reused materials were used. The results of the multicriteria analysis are presented in Table 3.

**Table 3** Results of multicriteria analysis

	Building	CDA	Building	IPA	Building	WSA	Building	TOPSIS
1	D	4.2051	A	0.2063	A	0.7937	C	0.7054
2	G	4.6376	D	0.2312	D	0.7688	D	0.6851
3	A	4.8072	G	0.2563	G	0.7437	G	0.6814
4	H	6.2326	H	0.3365	H	0.6635	H	0.6442
5	J	6.6161	C	0.3427	C	0.6573	J	0.6224
6	C	7.3376	J	0.3864	J	0.6136	E	0.6146
7	E	7.5859	E	0.3963	E	0.6037	I	0.5648
8	I	9.8051	I	0.4745	I	0.5255	B	0.5049
9	F	9.8467	F	0.5714	F	0.4286	F	0.504
10	B	10.358	B	0.6046	B	0.3954	A	0.4956

Finally, it can be stated that buildings D, A and C were scored the best according to the MCDA methods. About the different phases of the life cycle of buildings, it can be stated that operational energy (B6) causes significant emissions for all assessed environmental indicators. This was followed by the product phase (A1-A3). Transport (A4) makes the smallest contribution. The materials with the largest contribution to GWP are aerated concrete, concrete, clay bricks and reinforcing steel. The circularity score for residential buildings ranges from 23% to 48%. In the case of the lowest score of building, most of the materials were intended for landfill, no materials were reused, and few were intended for recycling, downcycling and/or energy recovery. As the volume of materials going to landfill in the EoL phase decreased and the volume of materials in buildings that could be reused and recovered increased, the building circularity score increased.

The construction sector must contribute to the circular economy and use resources sustainably. First, this must involve preventing waste. If not, it must be reduced, reused or recycled properly. All companies should invest in clean and energy-efficient production technologies. They should strive to achieve 100% responsible and sustainable use of resources for all raw materials with full transparency of supply chains. The circular economy must be understood as long-term sustainable and closed materials loops. As a result, there is no waste (or only a minimum) and the materials after EoL are used in the next life cycle of the system. In practice, the circular economy strives to develop easily recyclable products, extend their lifespan, minimize waste and turn waste into resources. Circularity in the construction sector is closely related to eco-design (design and development of recyclable building materials), long life of materials and buildings, facility management, and deconstruction of buildings followed by collection, recycling and reusing materials.

**CONCLUSION**

The analysis of 11 new residential buildings built in Slovakia shows that considering the circularity of buildings requires more attention from all stakeholders. The lack of choice of local, natural, recycled and other innovative closed-loop materials leads to a failure to meet the requirements of circularity, sustainability and decarbonisation. Therefore, research in this area needs to be strengthened.

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