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End-of-Life Stage Analysis of Building Materials in Relation to Circular Construction †

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Abstract: This article is focused on analyzing roof structure from environmental impact indicators and circularity point of view. The life cycle analysis of the roof structure includes the product phase, transport from the factory gate to the site, operational energy and operational water phase, and an end-of-life phase. Three end-of-life scenarios for built-in materials are designed to observe the reduction in environmental impacts throughout the life cycle of the structure. Scenario 1 mainly considers waste incineration, which accounts for almost 77% of the end-of-life phase. In addition, landfilling (15.4%) and recycling (7.7%) are considered. In scenario 2, landfilling accounts for 38.5% and incineration also accounts for 38.5%. Recycling (15.4%) and downcycling (7.6%) are also considered. In scenario 3, recycling and reuse represent 46.1% and 38.5%, respectively. Incineration (7.7%) and downcycling (7.7%) are also considered. The lifetime considered is 50 years and the functional unit is 1 m^2. One-Click LCA software was used for the analysis. Results for GWP-fossil are 415 $kgCO_{2eq}$, 381 $kgCO_{2qe}$ and 362 $kgCO_{2eq}$ for scenarios 1, 2 and 3. The circulation score of the roof composition for three scenario is determined to be 2%, 16% and 36%. It can be concluded that the end-of-life phase of the materials influenced these results to a large extent.

Keywords: roof structure; end-of-life; environmental impact; LCA; material circularity

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1. Introduction

The end of life of buildings is being taken into account in improving waste management and in the environmental care construction sector [1]. Demolition waste makes up a significant proportion of the total waste generated and is intrinsically important both in terms of waste management and resource efficiency [2]. Due to the serious sustainability issues caused by the built environment, there are increasing demands to adopt circular economy principles in building design, such as flexibility and reversibility [3]. That study also shows that 14% of GHG emissions from a flexible building can be avoided if the foundation, supporting structure and ceiling elements are left in place for the next building. Such direct reuse leads to a significantly higher environmental value than recycling the same materials. Another study [4] found significant variations in lifetime carbon emissions between 145 properties ranging from 21 to 193 t CO_{2eq}, with lifetime carbon emission intensities ranging from 0.5 to 2.6 t CO_{2eq}/m^2. There is a strong correlation between lifetime carbon emissions and two factors: floor area and the number of inhabitants, followed by the number of bedrooms, the property type, the window frame material, the type of heating system, the age of the main occupant, the type of glazing and the thickness of the attic insulation. The authors of [5] concluded that carbonation of concrete in the post-use phase does not affect the validity of previous studies, showing that timber-framed buildings have significantly lower carbon emissions than concrete-framed buildings. The study found

that carbonation of crushed concrete leads to significant CO_2 absorption. However, CO_2 emissions from fossil fuels used to crush concrete significantly reduce the carbon benefits gained from increased carbonation due to crushing. Long-term storage of crushed concrete will increase carbonation absorption but may not be practical due to space limitations. Overall, the effect of carbonation of concrete after use is small. According to [6], buildings could initiate smaller material flows and have improved environmental properties if they are intended for future disassembly and reuse. However, material flows in the life cycle of a building are complex maps, especially those initiated by material replacement and end of life. The results of study review [7] reveal the state of the art of the different biobased building products commercialized in the state of France, in which the energy recovery from bio-based insulation wastes expected in 2050 saves 4.1 million m^3 of land, 75,000 tons of fossil fuels and EUR 89 million while avoiding the rejection of 312,771 tCO_2eq. The results of another study [8] indicate that end-of-life recycling of biocomposite materials contributes to a reduction in environmental and economic costs in the construction industry. Strategic reuse of demounted concrete elements in new buildings may be one of the solutions that will support the transition to circular construction. In another study [9], a simple classification system for concrete quality proposed elements for reuse, where three main parameters were proposed, namely the calculation of the residual life, the extent of cracks and the target exposure class. The main goal of the research [10] was the development of a new lightweight construction material composed of gypsum, in which the conglomerate was partially replaced by dissolved expanded polystyrene (EPS) waste and the addition of textile fibers from end-of-life tires. The results obtained after the physico-chemical and mechanical characterization of the new gypsum composite show how to obtain a 31.3% lighter material with a 66.7% lower thermal conductivity and a 33.3% higher bending strength in boards compared to traditional gypsum material. This improvement in technical performance leads to a reduction in the consumption of natural resources and a large amount of waste recovered and reintroduced into the production process. Study [11] emphasizes that, due to the challenges of a roundabout, the circularity of buildings should be evaluated at the initial design stage to reduce the risks of circulation and environmental problems identified in the later stages of the project. Another study [12] points out that the implementation of circular building components can contribute to the transition to a circular economy. This is confirmed by a study [13] which says that bio-based circular building materials are "materials obtained in whole or in part from renewable biological origin or by-products and biological waste of plant and/or animal biomass that can be used as raw materials for building materials and decorative objects in construction, in their original forms or after being elaborated". Study [14] shows that simple green roof systems, without several artificial layer materials, are an environmentally responsible option. That study suggests leaving away rockwool, the egg carton-like plastic layers, and expanded clay when possible, or exploring for and developing alternative materials, in order to have minimal environmental impact.

Buildings are a significant contributor to climate change. This is why life-cycle assessments (LCA) are becoming increasingly popular for documenting environmental impacts during the detailed design stages of building projects. The LCA methodology calculates the potential environmental impacts caused by a product, such as a building [15]. The LCA methodology is implemented in this research work, whose main goal is to analyze the designed vegetation roof assembly from environmental impact categories during the whole life cycle and material circularity point of view. The three end-of-life scenarios are compared to determine the reduction in environmental impacts and investigate how the circularity score changes. The results of this research task are addressed to developers of new sustainable/green building materials, as well as to architects in the design of low-emission buildings considering building circularity. The limiting factor of this study is the number of compositions investigated.

2. Materials and Methods

2.1. Life Cycle Assessment Method

2.1.1. Goal and Scope

Roof structure designed for office buildings and placed in the city of Košice, Slovakia, is subjected to the analysis using the life cycle assessment (LCA) method. The goal and scope of the study is to determine environmental impact indicators and identify reductions in impacts based on end-of-life scenarios for a lifetime of 50 years. The analysis is performed for the "Cradle to Grave" system boundary and includes the following stages: A1–A3 (Product stage), B6 (Operational energy), B7 (Operational water) and C1–C4 (End-of-Life Stage). Functional unit (FU) is set to 1 m^2. One Click LCA software compliant with standards ISO 14040, ISO 14044, ISO 14025, EN 15804+A2 and EN 15978 is used for the analysis. The environmental impacts of the materials are based on EPDs and values representing average materials. CML is used as an impact assessment method. The core environmental impact indicators according to EN 15804+A2 are: Global Warming Potential-total (GWP-total), Global Warming Potential—fossil (GWP-fossil), Global Warming Potential—biogenic (GWP-biogenic), Global Warming Potential—LULUC (GWP-LULUC), Depletion Potential of the Stratospheric Ozone Layer (ODP), Acidification Potential—Accumulated Exceedance (AP-AE), Eutrophication Potential—Aquatic Freshwater (EP-AF), Eutrophication Potential—Aquatic Marine (EP-AM), Eutrophication Potential—Terrestrial (EP-T), Formation Potential of Tropospheric Ozone (POCP), Abiotic Depletion Potential of non-fossil resources (ADP-elements) and Abiotic Depletion Potential of fossil resources (ADP-fossil fuels), Water use (W) and other environmental impacts. These include impacts on human health, terrestrial toxicity, freshwater toxicity, seawater toxicity, air and water pollution, soil degradation and physical disturbances such as soil erosion and changes in landscape quality [16].

2.1.2. Life Cycle Inventory

Vegetation roof assembly is designed and investigated in terms of its environmental impact. The composition of the roof assembly is shown in Table 1. The roof structure is designed as a single-layer flat roof without an air gap and compliant current thermal and technical requirements. The composition meets current requirements set for thermophysical characteristics according to STN 73 0540-2+Z1+Z2. It is a diffusely closed structure using a vapor barrier and is designed as walkable roof structure. The thermal resistance of the roof is 10.172 $m^2 \cdot K/W$ and exceeds the required value of 9.9 $m^2 \cdot K/W$.

Table 1. Materials of roof structure.

Material		Thickness [m]	Thermal Conductivity λ [W/m·K]	Density ρ [kg/m³]	Area Density [kg/m²]
Intensive substrate	-	0.400	-	1405	562.0
Filter geotextile	PP	0.0012	0.200	-	0.200
Drainage board	EPS	0.075	0.037	-	0.950
Waterproofing membrane	PES	0.0018	0.2	-	0.300
Waterproofing foil resistant to overgrowth of roots	PVC-P	0.0018	0.145	-	2.150
Separation geotextile	PE	0.0002	0.200	-	0.190
Mechanical anchor	PE/PP	-	-	-	0.136
Thermal insulation	XPS	0.140	0.035	35	4.200
Thermal insulation	XPS	0.140	0.035	35	4.200
Adhesive for thermal insulation		0.010	-	1120	0.200
Vapor barrier	PE	0.003	0.200	900	0.140
Reinforced concrete ceiling slab	Concrete + rebar	0.200	1.74	2500	500.0
Total thickness		0.970			1074.1

The environmental impacts for the product phase (A1–A3) are determined on the basis of the results presented in the Environmental product declarations (EPD) and the Ecoinvent database. Transportation (A4) methods and distances of the products from the factory gate to the site are presented in Table 2.

Table 2. Transportation processes.

Material		Distance [km]	Transportation Method
Intensive substrate	-	150	Dumper truck, 19-ton capacity
Filter geotextile	PP	520	Trailer combination, 40-ton capacity
Drainage board	EPS	520	Trailer combination, 40-ton capacity
Waterproofing membrane	PES	100	Trailer combination, 40-ton capacity
Waterproofing foil resistant to overgrowth of roots	PVC-P	1500	Trailer combination, 40-ton capacity
Separation geotextile	PE	520	Trailer combination, 40-ton capacity
Mechanical anchor	PE/PP	1700	Trailer combination, 40-ton capacity
Thermal insulation	XPS	430	Trailer combination, 40-ton capacity
Thermal insulation	XPS	430	Trailer combination, 40-ton capacity
Adhesive for thermal insulation		1500	Trailer combination, 40-ton capacity
Vapor barrier	PE	430	Trailer combination, 40-ton capacity
Ceiling slab	Concrete	60	Trailer combination, 40-ton capacity
Rebar	Steel	370	Trailer combination, 40-ton capacity

The operational energy (B6) includes the electricity consumption for automatic irrigation and represents a value of 13.5 kWh. The water consumption for irrigation of 0.3 m^3 represents the operational water (B7).

The scenarios for the end-of-life phase are presented in Table 3. Scenario 1 represents the market scenario that is most typical for that material in that market. End-of-life is considered in EPDs used in the analysis for Scenario 2. For products without EPDs, the end of life is set as the best practice. The purpose of Scenario 3 was to set the end-of-life phase to further reduce impacts through reuse, recycling and incineration of waste.

Table 3. End-of-life scenarios.

Material		Scenario 1	Scenario 2	Scenario 3
Intensive substrate	-	Landfilling	Recycling	Reuse
Filter geotextile	PP	Incineration	Landfilling	Recycling
Drainage board	EPS	Incineration	Incineration	Reuse
Waterproofing membrane	PES	Incineration	Landfilling	Recycling
Waterproofing foil resistant to overgrowth of roots	PVC-P	Incineration	Landfilling	Recycling
Separation geotextile	PE	Incineration	Incineration	Recycling
Mechanical anchor	PE/PP	Incineration	Landfilling	Recycling
Thermal insulation	XPS	Incineration	Incineration	Reuse
Thermal insulation	XPS	Incineration	Incineration	Reuse
Adhesive for thermal insulation		Incineration	Landfilling	Incineration
Vapor barrier	PE	Incineration	Incineration	Recycling
Ceiling slab	Concrete	Landfilling	Crushed to aggregate	Crushed to aggregate
Rebar	Steel	Recycling	Recycling	Reuse

2.2. Building Circularity

The Building Circularity Indicator (BCI) is a metric used to measure the circularity of a building's components, products, and materials. Circular economy principles aim to minimize linear flows, such as waste, and maximize restorative flows, such as recycling and reusing materials [17]. The BCI for the roof structure is calculated using the One-Click LCA software, specifically the Building Circularity tool. This tool likely considers various factors related to the life cycle of the materials used in the roof structure. Different weighting factors of individual materials were chosen for the evaluation of the materials. The calculation was performed for two parts, namely for materials recovered and for materials returned.

Virgin materials are new materials considered if they are found in the project. New materials typically have higher emissions compared to recycled, renewable, or reused materials. The multiplier for virgin materials is set to 0, indicating that the environmental impact of new materials is not favorable in this context. Renewable materials can be regrown. The default multiplier for renewable materials is set to 1, suggesting that they are considered environmentally friendly compared to new materials. Recovered recycled materials are materials obtained for the project that have been recycled. They generally have lower emissions compared to newly manufactured materials. The default multiplier for recovered recycled materials is set to 1, indicating that their environmental impact is comparable or better than that of new materials. If little or no processing is required for recovered recycled materials, they have almost no emissions. The default multiplier for cases where little or no processing is required is set to 1, suggesting that minimal processing is associated with minimal environmental impact.

Materials returned consist of materials that can be reused as materials with multiplier 1. It can be stated that reusing materials for other projects reduces emissions for the current project. This also includes materials that can be recycled with multiplier 1. Recycling produces some emissions, but the material can be structurally chained for reuse. Materials that can be downcycled have a multiplier of 0.5. Downcycled materials result in a product that is not as strong as the original and requires new materials to achieve similar strength. Materials that can be used as energy, i.e., combustible materials, have a multiplier of 0.5. It can be mentioned that combustion produces emissions, but recovered energy can be utilized (e.g., for heating, electricity, manufacturing). Materials that are disposed of (landfilled) have a multiplier of 0. Landfilled materials do not fully decay or decompose, leading to long-term environmental impact. These multipliers serve as a factor to adjust the environmental impact of a project or product based on the end-of-life fate of its materials. For instance, materials that can be reused or recycled are considered more environmentally friendly (multiplier of 1), while materials that end up in landfills have the highest environmental impact (multiplier of 0). Downcycled and combustible materials fall somewhere in between. Adjusting for these factors helps us assess the overall sustainability of a product or project.

3. Results and Discussion

Figures 1–3 present results for environmental impact indicators according to EN 15978 and EN 15804+A2. They present the percentage share of life cycle stages on the environmental impact indicators for three scenarios of EoL.

The operational energy phase (40.87%) and the product phase (40.65%) are the largest contributors to the GWP-fossil expressed as equivalent mass of CO_2 for scenario 1. The share of the other life cycle phases is negligible. The materials with the highest contribution to GWP-fossil are ready-mixed concrete (34.12%), rebar (26.43%, vegetation substrate (18.02%) and XPS insulation (12.49%). The share of the plastic waterproofing membrane and PVC root barrier is 1.76%. According to one study [18], low-density and high-density PE waterproofing membrane and the root barrier count for GWP 9.5%. Study [19] points out that the high thickness of the substrate (400 mm) required for adequate insulation increases the environmental impact of the systems, with values between 13.5% and 52.4% higher than the average roof systems. As a result of the change in the end-of-life scenario,

the share of life-cycle phases per GWP-fossil has changed for scenarios 2 and 3. For scenario 2, the largest share is also for operational energy (44.53%) and product phase (44.29%). For scenario 3, the largest share is, again, for operational energy (46.86%) and the product phase (46.60%). The share of the other life cycle phases is negligible. Noticeably, as the share of recycling and reuse of materials increases, the share of impacts in the end-of-life phase decreases, and the share of impacts is assigned to the operational and product phases.

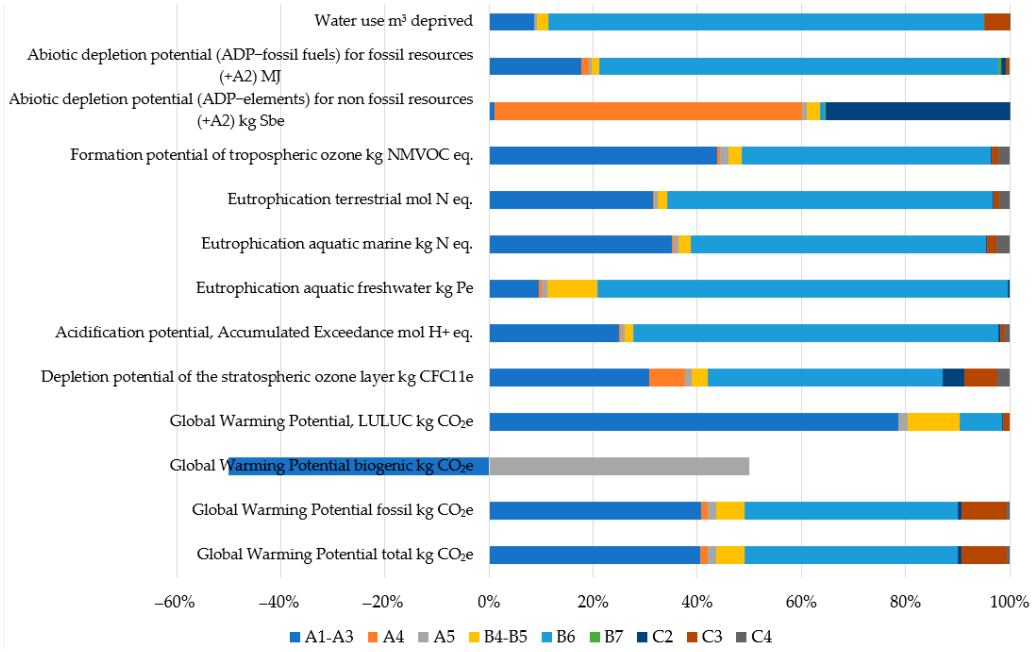

Figure 1. Environmental impact indicators—scenario 1.

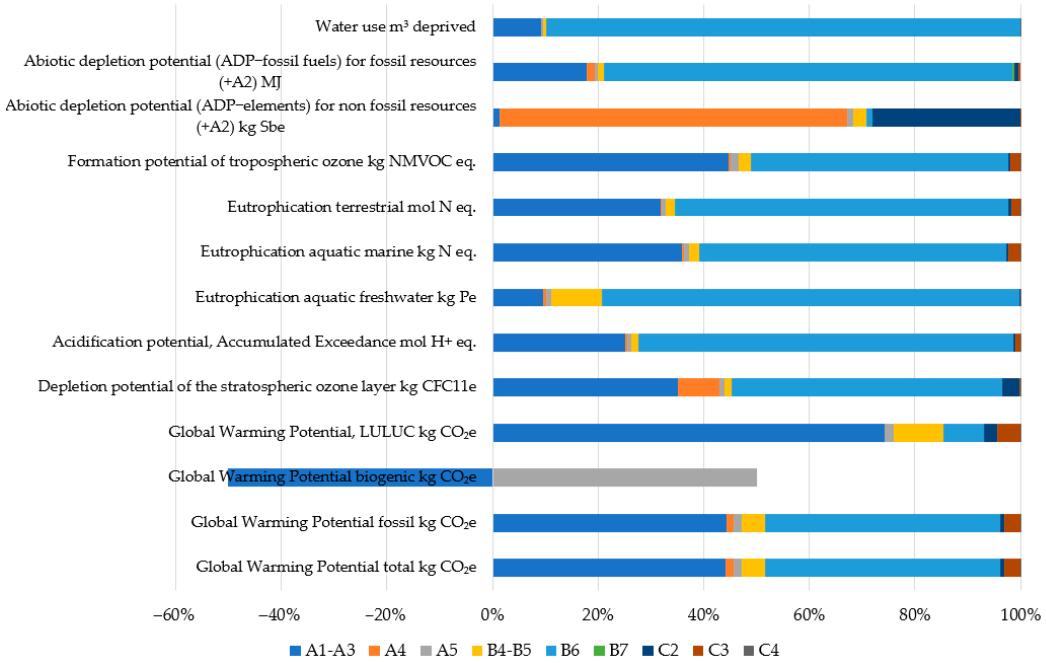

Figure 2. Environmental impact indicators—scenario 2.

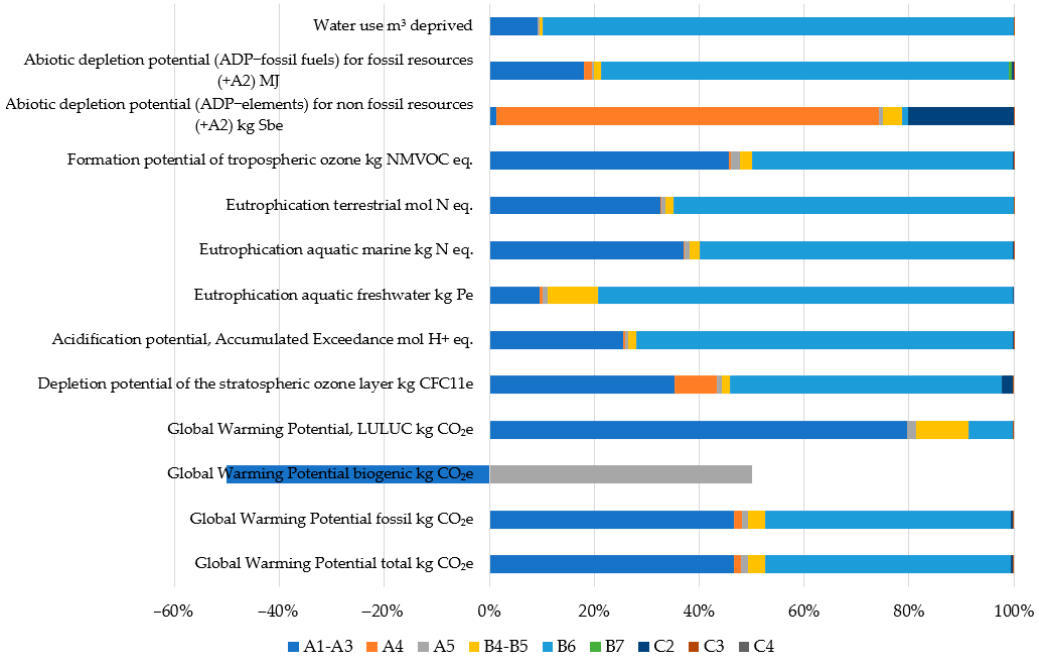

Figure 3. Environmental impact indicators—scenario 3.

Negative GWP-biogenic values in the product phase are attributed to waterproofing membranes. The largest contribution to ozone depletion potential expressed as equivalent emissions of CFC11 is from operational energy (45.07%), followed by the product phase (30.75%), transport from the factory gate to the site (6.89%) and the recovery process (6.36%) for scenario 1. As a result of the change in the end-of-life scenario, the contribution of the life cycle phases to ODP has also changed for scenarios 2 and 3. For Scenario 2, the operational energy (51.35%), the product phase (35.04%), the transport from the factory gate to the site (7.85%) and the transport to the disposal site (3.32%) also have the largest share. For scenario 3, the largest shares are again operational energy (51.87%), product phase (35.40%), transport from the factory gate to the site (7.93%) and transport to the disposal site (2.14%). The share of the other life cycle phases is negligible. It can be seen that, as the share of recycling and reuse of materials increases, the share of impacts in the end-of-life phase decreases, and the share of impacts is attributed to the operation phase, the product phase and also the transport from the factory gate to the recovery and disposal site, and the assessment process for Scenario 1.

Figure 4 shows the results for indicators where there are significant differences between the three scenarios in relation to the end-of-life phase.

These indicators are GWP-fossil, Abiotic depletion potential for fossil resources and Water use. As can be seen from the figure, the largest contributors to ADP-fossil fuels are transport to the disposal site, the recovery process and landfilling. For scenarios 2 and 3, landfilling is not considered, and thus the impacts are significantly lower compared to scenario 1, especially in the case of scenario 3, where there is a greater share of material reuse, as mentioned above.

In scenario 1, XPS isolation has the largest impact on the GWP-fossil in the C3 module with a contribution of 60.90% out of a total of 36.09 kg CO_{2eq}, considering combustion. In scenario 2, PE foil has the largest impact on GWP-fossil with a share of 35.93%, out of a total impact of 11.55 kg CO_{2eq}, considering incineration. In scenario 3, polyurethane foam has the largest contribution with 65.08% of the total impact of 0.63 kg CO_{2eq}.

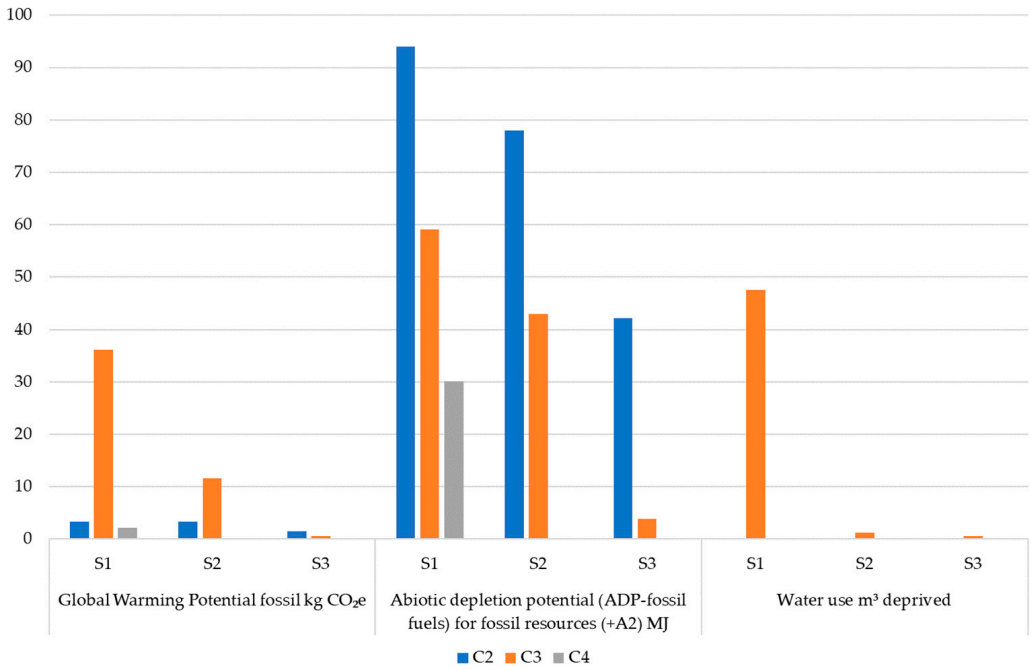

Figure 4. End-of-life scenarios for selected environmental impact indicators.

Figures 5–7 present the results of roof structure circularity for three scenarios of end-of-life. The highest circularity score is 36% for scenario 3, followed by scenario 2 with a percentage of 16%, and the lowest is 2% for scenario 1. Roof composition consists of virgin materials (100%). There are no renewable or reused materials in the composition. Scenarios 2 and 3 present scenarios according to which 56% of materials could be downcycled (56%) and recycled in percentages of 2.7% and 1.3%, respectively. According to scenario 1, 2.8% of materials could be used as energy and up to 94.5% put into landfill. Scenario 2 presents a scenario according to which 1.3% of materials could be used as energy and 40% put into landfill. And finally, according to scenario 3, 42.6% of materials could be reused and 0% landfilled.

Material Recovered	**0 %**	
Virgin	100 %	
Renewable	0 %	
Recycled content in A stage	0 %	
Reused	0 %	
Material Returned	**4.1 %**	**2 %**
Reuse as material	0 %	
Recycling	2.7 %	
Downcycling	0 %	
Use as energy	2.8 %	
Disposal	94.5 %	

Figure 5. Circularity for scenario 1.

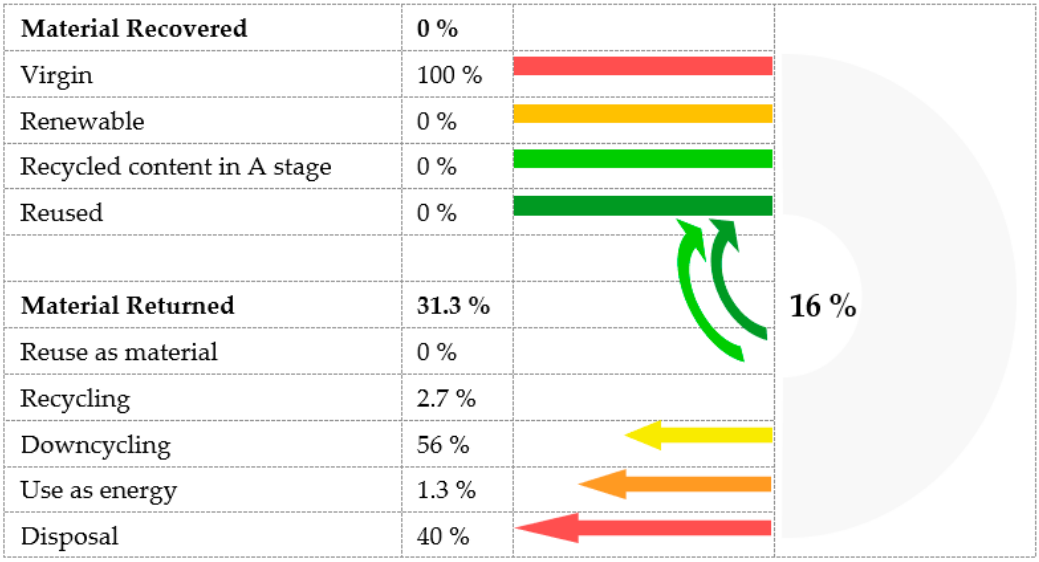

Figure 6. Circularity for scenario 2.

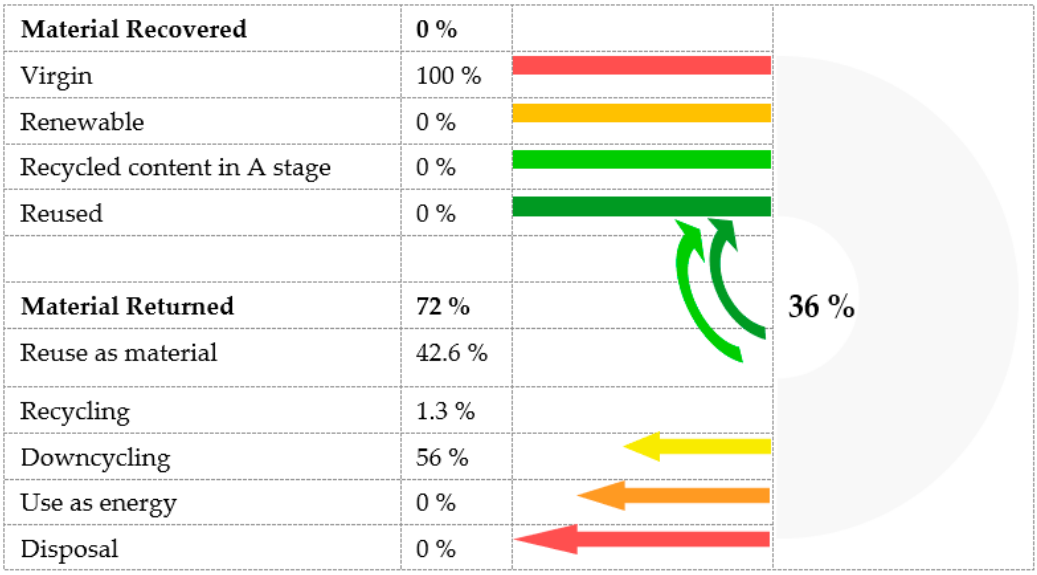

Figure 7. Circularity for scenario 3.

Another study contributes to the understanding of the application and decarbonization potential of circular strategies in the building industry by investigating real-life cases of new build, renovation, and demolition [20]. This study shows that circularity can be considered as a key strategy for mitigating carbon emissions in the building industry and that decarbonization potentials vary greatly between different building projects and applications of circular strategies, indicating that effective implementation of circular building strategies to capture potential environmental benefits is imperative.

4. Conclusions

In this study, the roof structure was evaluated in terms of environmental impact indicators and building circularity by using the LCA methodology during the whole lifespan. The three end-of-life scenarios were compared to determine the reduction in environmental impacts and investigate how the circularity score changed. The results show that the operational energy phase (40.87%) and the product phase (40.65%) are the largest contributors to the GWP-fossil expressed as CO_{2e} for scenario 1, in which waste incineration accounts for almost 77%, landfilling 15.4% and recycling 7.7%. In scenario 2, part of the load shifted to operational energy (44.53%) due to better waste

utilization. The product phase contributed 44.29%. In this scenario, landfilling accounts for 38.5%, incineration also 38.5%. recycling 15.4% and downcycling 7.6%. For scenario 3, the largest share is again for operational energy (46.86%) and the product phase (46.60%). The share of the other life cycle phases is negligible. In this scenario 3, recycling and reuse represent 46.1% and 38.5%, respectively. Incineration is considered for 7.7% of materials and downcycling is also considered for 7.7%. It should be highlighted that as the share of recycling and reuse of materials increases, the share of impacts in the end-of-life phase decreases, and the share of impacts is assigned to the operational and product phases. The materials with the highest contribution to environmental impacts are ready-mixed concrete (34.12%), rebar (26.43%), vegetation substrate (18.02%) and XPS insulation (12.49%). The circularity of the roof composition for three scenario is determined to be 2%, 16% and 36%. The circularity score increases with the share of recycling and reuse of materials. Research focused on increasing the circularity scores of materials and whole buildings within the construction industry will be continued. The emphasis on reducing waste in manufacturing, construction, and demolition aligns with the principles of sustainability and resource efficiency. The concept of circularity involves designing and managing buildings in a way that minimizes waste generation, encourages reuse and recycling of materials, and promotes a closed-loop system. By incorporating circularity into construction practices, the industry can contribute to a more sustainable and resilient future. The potential benefits mentioned, such as creating more sustainable and resilient buildings and achieving cost savings, underscore the value of adopting circular practices. Circular economy principles help address environmental concerns by reducing waste and lead to economic advantages through resource optimization and improved efficiency. It is encouraging to see a focus on sustainability and circularity in the construction industry, as these efforts play a crucial role in advancing a more environmentally conscious and economically viable future. As the research progresses, the findings may provide valuable insights and contribute to the broader goal of enhancing sustainability in the built environment.

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