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Exploring Uncertainties in the Circular Footprint Formula: A Comparative Study of Aluminium and Composite Material Recyclability

Climate change remains one of the most pressing and complex global challenges the world is facing today. As a response, the European Union set the goal of a 55% reduction in greenhouse gas (GHG) emissions by 2030 relative to the levels of 1990. From 2022 to 2023 alone, the GHG emissions of the European Union fell by 8.3%, resulting in an overall GHG emission reduction of 37% in 2023 (European Commission 2024). Although progress has been made, further action is required to meet the 2030 target. Among the various sources of GHG emissions, the transportation sector is a relevant contributor, as it is one of the largest sources and has shown limited progress in climate change mitigation (European Environment Agency 2024b). The transportation sector was responsible for nearly 29% of European GHG emissions in 2022, of which about 73% originates from road transport (European Environment Agency 2024a). These numbers underscore the importance of effective transport-sector decarbonization to help meet the EU's GHG targets for 2030. One promising strategy to reduce GHG emissions is the development of lightweight vehicles, aiming to reduce fuel consumption and lower emissions (Mohammadi et al. 2023). Increasingly, automotive manufacturers are substituting conventional materials, such as aluminium and steel, with lightweight alternatives including fibre-reinforced polymers (FRP), as they exhibit great material properties such as low density and high strength (Mohammadi et al. 2023). However, greater use of FRP introduces new challenges, especially in waste collection and recycling (Gonçalves et al. 2022). This highlights the importance of evaluating the environmental impacts of material substitution, especially at the End of Life (EoL). This study analyses and compares two cockpit car cross beams (CCBs) used in car manufacturing: a conventional aluminium-steel beam (reference CCB), composed of 95% aluminium and 5% steel, and a new composite beam (substitute CCB), which partially replaces aluminium with a lightweight polymer, containing 54% aluminium, 4.5% steel, and 41.5% glass fibre-reinforced polypropylene (GF-PP). The focus is on both material composition and recyclability.

To analyse the environmental impact of both CCBs at EoL, the Circular Footprint Formula (CFF), presented by the European Commission, is applied to both CCBs (European Commission 2017). Given that the parameters of the CFF are defined by assumptions or default values (Directorate-General for Environment 2021), uncertainty arises when using the CFF. Therefore, in addition to the comparison of the recyclability of both CCBs, an uncertainty analysis is conducted to assess which parameters are the most uncertain and have the greatest influence on the results. The CFF was applied across 12 impact categories defined by the CML2001 methodology. Key parameters - allocation factor (A), quality factors (Q) and recycling factors (R) - were derived from economic approaches, literature review, and the Product Environmental Footprint (PEF) Report. These parameters were thoroughly analysed, and their impact on the CFF was modelled using an adapted uncertainty analysis across the 12 impact categories. Due to limited reliable data on composite materials, broader parameter ranges were found for the substitute CCB, while aluminium and steel exhibited narrower but more uniform ranges. Despite these differences, the analysis revealed that the substitute CCB has lower environmental impact in 11 of the 12 impact categories compared to the reference CCB. Aluminium had the greatest influence on the reference CCB, as it accounts for nearly the entire composition and is associated with the highest environmental impacts. GF-PP, which replaced part of the aluminium in the conventional CCB, resulted in lower environmental emissions, thus explaining the overall decrease in environmental impact. The Local Sensitivity Analysis (LSA) identified Q_{sin} (outgoing material quality) as the most influential parameter for all materials, while aluminium was the primary driver of overall uncertainty. Global Sensitivity Analysis (GSA) confirmed that the reference CCB's CFF output shows greater uncertainty than that of the substitute CCB, due to the wider range and more detailed industrial data available for aluminium and steel, leading to a broader spread of input values. Overall, the study demonstrates the environmental benefits of substituting conventional metals with lightweight composites like GF-PP, which can substantially reduce the automotive environmental footprint.

However, several limitations remain. First, both CCBs were modelled using virgin materials, which inflates the environmental impact. This is particularly evident for aluminium, which accounts for a significant portion of the total environmental impact. In practice, aluminium is highly recyclable, with recycling capable of reducing its energy consumption by up to 95% (The International Aluminium Institute 2020). Moreover, the CFF does not account for the number of times a material can be recycled (Bach et al. 2018). While aluminium and steel are considered endlessly recyclable (The International Aluminium Institute 2020; American Iron and Steel Institute 2020), GF-PP loses approximately 22% of its quality after each recycling cycle (Gonçalves et al. 2022). This highlights a methodological gap in the CFF, which may limit the comparability of the two CCB. Additionally, the CFF is primarily designed for packaging, which has a shorter lifespan than automotive parts, making long-term recycling predictions uncertain. It is challenging to anticipate the recycling practices for aluminium over the next 20 years, corresponding to the lifespan of a car part. Characterizing the Product Distribution Function for the uncertainty analysis posed challenges, as it requires additional input values and advanced mathematical analyses to accurately model propagation. A more extensive statistical analysis can enhance the robustness of the uncertainty analysis. As the CFF was only introduced in 2017, research on its uncertainty modelling is still limited. Moreover, the recycling methods and infrastructures for composites like GF-PP need improvement, as they currently lack standardized recycling pathways and are often landfilled (Ginder et al. October 2019). Improving recycling technologies for GF-PP could further enhance the environmental performance of composite materials.