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Circularity Index: Performance Assessment of a Low Carbon and Circular Economy

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Abstract
The circular economy (CE) is defined as a sustainable economic system in which socioeconomic development is sustained via the reduction of non-renewable resource extraction and material recirculation. In practice, however, the additional resource inputs and losses involved with various CE initiatives, including recycling, can often trump many of the environmental gains associated with the concept. The purpose of this paper is to update Cullen's [1] circularity index approach and its two quantitative indicators to achieve a more comprehensive circularity assessment, in terms of quantity and quality. In particular, we use these indicators to assess the degree of (1) reuse and repurposing; (2) decarbonisation; and (3) resource use intensity (the amount of material required to provide a unit of service), relative to a system entirely reliant on virgin material extraction. The resulting circularity index (CI) value is derived from an aggregation of the two indicators and is measured from 0 (zero circularity) to 1 (100 percent circularity). We applied the CI to UK car-based passenger mobility with respect to carbon emissions and material cycles. We compared an internal combustion engine vehicle (ICEV) to a battery electric vehicle (BEV). The results show that in 2015 the average UK ICEV's CI value was 0.01 and a BEV's CI value was 0.1. The introduction of low-carbon strategies such as electrification, resource efficiency, and shared-mobility improves the CI value to 0.5. This suggests that if UK car-based passenger transport is to approach full circularity additional innovations, both social and technological, will be required. It is our view that the CI approach can facilitate the operationalisation of CE strategies assessment and environmental performance at the micro (e.g. product, company), meso (e.g. sectorial) and macro (e.g. national/global) levels. It also holds relevance for the development of public policies and corporate strategies that promote evidence-based sustainable solutions.

Q2 ***Keywords:***

2.1 Introduction

The goal of the Circular Economy (CE) is to encourage a sustainable and regenerative cycle of production and consumption. CE is a set of sustainable policies and strategies that target

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reduced material intake and waste generation, in order to lessen economic and environmental costs [2, 3]. CE has been widely supported in recent years due to its potential to decouple socioeconomic development from natural resource extraction and use. It is gaining popularity in many different countries, sectors, and organisations [4]. Several strategies have been proposed to facilitate the shift from a linear economy to a circular one. These include eco-design, resource efficiency measures, waste R's hierarchy (e.g. reduce-reuse-recycle), industrial symbiosis, etc. [5].

One way to quantify the degree of a system's resource circularity is through a circularity index (CI). The resulting value is a number, usually ranging from 0 (zero circularity) to 1 (100 percent circularity). The higher the number, the more sustainable the system is deemed to be. Examples of CIs include the Material Circularity Indicator - MCI [6], the Circular Economy Index – CEI [7], the Global Circularity Metric [8] and Cullen's [1] Circularity Index approach. Most CIs focus on circularity quantity, that is to say the degree to which a product or system has closed material loops. It is typically measured as the proportion of materials that comes from reused or recycled sources relative to the total amount of material required.

It is our view that a circularity index should not be solely focused on aspects related to *quantity* but expanded to encompass other characteristics such as resource *quality*. Although far from common, circularity quality in quantitative terms is a measure of environmental performance, with a higher quality reflecting a lower dependency on virgin materials or fossil fuels, for example [9, 10]. Cullen [1] proposed a CI approach that accounts for material quality using energy intensity for material production as a proxy. He used this approach to calculate energy requirements for primary and secondary produced materials.

With the intention of further aligning Cullen's [1] CI to the principles of the CE, the aim of this present paper is to propose a modification of his approach. We do this to better reflect material inflow and outflow patterns, and to capture a system's lifecycle environmental impacts, relative to a reference system or baseline (Section 2.2). The updated approach is applied to a case study on UK car-based mobility. We calculate the circularity of UK-registered cars in terms of their material cycles and lifecycle carbon emissions. The two types of car categories considered were the "internal combustion engine vehicle – ICEV" and the "battery electric vehicle – BEV". In addition, and for the BEV, we considered the common sustainability strategy of lightweighting via material substitution and its impact on the car's circularity. We also explore aspects of Grubler *et al.* [11]'s low energy and material demand scenario and the challenges we may face on the adoption of their suggested targets and transport transition ideals (Section 2.3). We then summarise our findings and offer brief recommendations (Section 2.4).

2.2 Circularity Index Approach

The Circularity Index approach as proposed by Cullen [1] calculates material recirculation in both terms of quantity and quality. For the latter, Cullen calculates the ratio of energy needed for material recovery relative to that needed for primary material production. The index's indicators alpha (α) and beta (β) are shown in equations 1 and 2, respectively. The overall CI value is obtained by multiplying the result of alpha with that of beta, as shown in Equation 3. The parameter alpha is a value between 0 and 1 (referred to in Graedel *et al.* [12] and Fellner and Lederer [13] as the 'recycling rate'). Beta is necessarily less than 1 (and can be negative). The CI value (Equation 2.3) is between 0 (zero circularity) and 1 (full circularity).

$$\alpha = \frac{recovered\ EOL\ material}{total\ material\ demand} \tag{2.1}$$

$$\beta = 1 - \frac{energy\ required\ to\ recover\ material}{energy\ required\ to\ primary\ production} \tag{2.2}$$

$$CI = \alpha \bullet \beta \tag{2.3}$$

Q4 Figure 2.2 shows the estimates of alpha, beta, and the overall CI values for five energy-intensive materials (aluminium, concrete, paper, plastic, and steel). It also suggests that there is a long way to go before any one global material production stream reaches anywhere near the ideal state of circularity (CI = 1).

Cullen [1] incorporated quality metrics in an attempt to mitigate the potential negative effects of growing energy use in the pursuit of resource circularity. He argues that there are *practical* limits to how much an economy can be circular due to factors linked to resource availability, the reliance on non-renewable energy sources, and technical/technological constraints. Existing infrastructure often relies on non-renewable sources of energy, which can severely undermine circular economy progress. Fundamentally, even with optimal conditions, there are also thermodynamic considerations that will prevent 100 percent closed loops: there is simply a hard physical limit to just how circular any economy can be, as dictated by the Second Law. This limit is referred to as the *theoretical* limit.

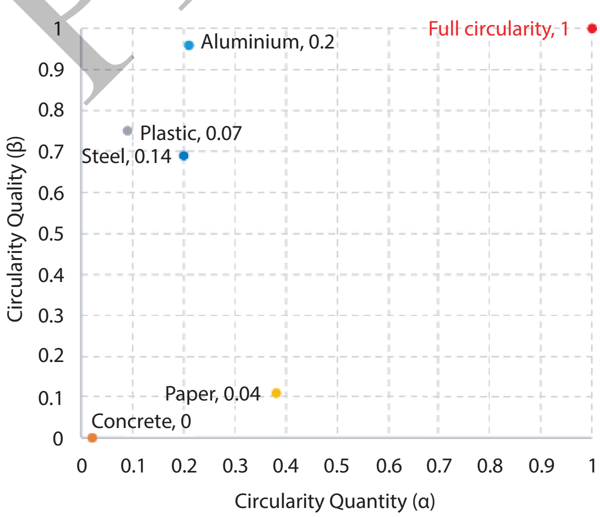

Figure 2.1 α, β and CI of five materials. Note: The number next to the material label corresponds to the overall CI value (obtained via α x β).

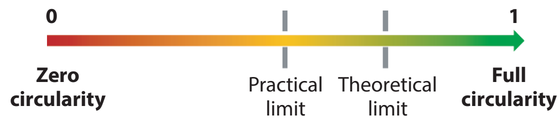

Figure 2.2 CI degrees.

Figure 2.1 depicts the circularity index range from 0 (zero circularity) to 1 (100 percent circularity) and the imposed limits (benchmarks). While we must acknowledge the practical and theoretical limits of our systems, if we value sustainability improving and measuring circularity is desirable and, consequently, it is worth considering how we might close the gap between where the system is now and full circularity.

Cullen's [1] approach, while a step in the right direction, especially when it comes to more comprehensive quantitative circularity assessments, overlooked the following issues: (1) his circularity quantity value (as derived from the alpha indicator) is obtained via the assumption that all reused or recycled materials that leave a system will be reincorporated eventually back into the same system. In reality, some materials never re-enter and are instead used in lower-value applications (e.g. secondary steel from the car industry is used in buildings and not vehicles because of its deteriorated quality); (2) his circularity quality value (beta indicator) captures the energy associated with the material inputs of specific processes within the system but fails to account for the system's entire life cycle and its environmental impacts. This means that his original approach is one dimensional.

2.2.1 A More Comprehensive CI Approach

2.2.1.1 Alpha Indicator: Circularity Quantity

We modified Cullen's [1] alpha indicator to reflect the fact that some material flows will never re-enter a system once they have left. The practical implication of this is a reduction in the total quantity of these flows and, consequently, a lowering of the theoretical circularity quantity value. It is worth noting that secondary metal contamination, due to the proliferation of alloys, is a primary cause of reduced *quantities* of resource inflows (affecting alpha) and is detrimental to flow quality (affecting beta). Appropriate measurement of the impact of secondary metal contamination requires an understanding of a product lifecycle including metal recycling processes, contaminant levels, recycling efficiencies, and energy use.

As different streams of material inputs and outputs are likely to have different levels of circularity, particularly at the meso (e.g. sectorial) or micro level (e.g. product, company), our alpha indicator is a product of two separate equations (alpha inflows and alpha outflows), as shown in Equations 4 to 6.

$$\alpha_{inflow} = \frac{circular\ inflow(from\ recycling, repurposing, reuse)}{total\ material\ inflow} \tag{2.4}$$

$$\alpha_{outflow} = \frac{circular\ outflow\ (sent\ to\ recycling, repurposing, reuse)}{total\ material\ outflow} \tag{2.5}$$

$$\alpha = \alpha inflow \bullet \alpha outflow \tag{2.6}$$

The scope of macro, meso, and micro levels of analysis refers to the level of granularity or detail at which circularity is being measured [14]. At the macro level, the scope of analysis is broad and covers the entire economy or a large geographical area, such as a country or region. At the meso level, the scope of analysis is more focused and covers specific sectors or industries. At the micro level, the scope of analysis is highly detailed and covers specific companies or products.

2.2.1.2 Beta Equation: Circularity Quality

We modified Cullen's beta equation to capture the various environmental impacts produced throughout a system's lifecycle relative to a reference system, as captured by the denominator in Equation 7. In the case study provided in Section 3, the value corresponds to carbon emissions, but the equation can be applied to other impacts, including acidification and toxicity, etc. This allows for a multidimensional perspective, and quantification, of a system's environmental performance throughout its lifecycle.

$$\beta = 1 - \frac{life\ cycle\ emissions\ of\ circular\ system}{life\ cycle\ emissions\ of\ linear\ system\ (baseline)} \tag{2.7}$$

Unlike, the alpha indicator (which measures quantity), the beta (because it assesses quality) must be calculated with a reference baseline, and in this respect the beta value is relative. An appropriate reference point for the beta CI value may be the carbon emissions created per unit of service when only virgin materials are consumed in its provision. Such a system would be completely "linear", in the sense that the sequences of the processes involved would be unidirectional (Figure 2.3a). Any positive delineation from this baseline is thus a measure of increased circularity, as made manifest by an increase in the proportion of secondary materials that are reincorporated back into the system (Figures 2.3b). It may also result from a decrease in the energy required per unit of service. In this regard, the beta CI value could be a useful mechanism to evaluate the resource sustainability of lightweighting, lifetime extension, repurposing and sustainable lifestyle transition practices (see description in Carmona *et al*. [15]).

The beta CI value is affected by the system's energy mix, with the degree of influence dependent on the subject at hand. If the subject of the beta CI value is carbon dioxide emissions, for example, a system with a high proportion of renewable energy source inputs will have a higher beta CI value compared to the entirely linear system baseline, where all energy production requires fossil fuel combustion. In Cullen's [1] rendition of the CI approach, there was no way of distinguishing the environmental impact of 1 kJ of energy consumed, when the origin of that kJ was produced by a wind turbine relative to another kJ produced by a gas turbine. Our modified beta CI indicator supports a more holistic environmental performance assessment, while Cullen's original beta indicator only measured energy consumption, as a proxy for environmental sustainability.

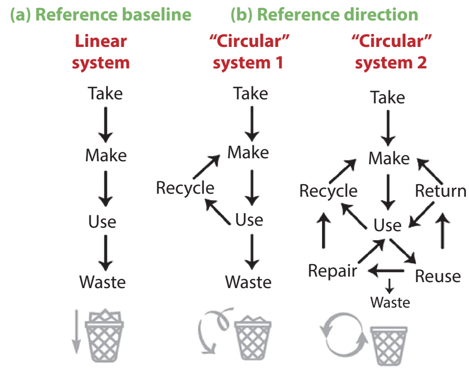

Figure 2.3 A graphical depiction of different types of systems (a) Reference baseline (b) Reference direction.

The flexibility of the new beta CI indicator means that it can also calculate the environmental performance of service units, relative to passenger mobility, visual comfort, shelter and nutrition, for example (see Carmona *et al.* [16]; Whiting *et al.* [17] for more information on resource services). The service approach is increasingly recognised as a useful way of evaluating resource production and consumption because it offers additional insights for advocates of the circular economy, especially when it comes to resource decoupling [18, 19]. A service approach is thought to be helpful when measuring resource efficiency because it focuses on societal activity and is linked to the material aspects of human needs and wellbeing rather than economic output or physical products [20, 21]. In this regard, a service approach is also more aligned with CE principles, given that circular economy thinking is not primarily concerned with maximised production or GDP.

2.2.1.3 Alignment with CE Principles

It is our view that the development of the alpha and beta indicators more readily aligns Cullen's [1] circularity index with the Ellen MacArthur Foundation [22] principles. The latter are fundamental to the advancement of the circular economy. Table 2.1 shows how we tied our updated metrics to the ideals promoted by the EMF, and thus the philosophical underpinning of the circular economy in general.

Table 2.1 Summary of the CI framework for a sustainable low carbon and circular economy.

EMF principles	CI measuring aspects	CI Indicator
Keep products and materials in use	EOL recovery, reuse, and repurposing	Alpha
Phase out waste and pollution	Decarbonisation	Beta
Decouple resource use to allow for the regeneration of natural systems	Service efficiency (unit of service provided relative to resource input)	Beta

2.3 Case Study: UK Car-Based Passenger Mobility

The transportation sector is critical to socioeconomic development because it enables the mass movement of people and products. It is a key matter for the circular economy because it is one of the biggest consumers of energy and materials. It is also responsible for 37 percent of CO_2 emissions from end use sectors globally [23]. The UK transport sector was selected due to ease of data accessibility and its quality. Due to the prevalence of car-based mobility, we focused on conventional (internal combustion engine vehicle – ICEV) and electric cars (battery electric vehicle - BEV) as opposed to public transport options. The vehicle data was obtained from Geyer [24], World Auto Steel [25] and Rodrigues *et al.* [26]. The data scope was vehicle's design, manufacturing, use phase, and end-of-life processes. The timespan for the data was restricted to a single year: 2015.

Figure 2.4 shows a summary of the average ICEV and BEV material composition in the UK and their respective alpha circularity index (CI) value. A large difference between the input alpha value (0.22) and output alpha value (0.91) is observed, which indicates that is correct to assume that not all material outflows are reintegrated back into the same system eventually. In reality, these outflows are of low quality and are typically downcycled. If they are reincorporated back into the system, they are first mixed with virgin materials.

Figure 2.5 shows the results obtained for the carbon emission lifecycles for an average UK-registered ICEV and BEV. It also shows their respective beta CI values relative to carbon emissions. It states the reference baseline beta CI value for the average ICEV and BEV carbon emissions respectively. In both cases, the baseline represents a vehicle manufactured with entirely virgin material, that is reliant on fossil fuels (for the BEV the electricity is provided via coal) and disposed of via landfill. The significant variation between the beta values for each vehicle is during the operational phase. This suggests that electric vehicles, while more circular than ICEVs, in terms of carbon dioxide, will not close loops sufficiently to advance circularity beyond 0.1 (Figure 2.7a). This is primarily because there is no evidence to suggest that electric vehicles result in an increased circularity with regards to material cycles (Figure 2.4).

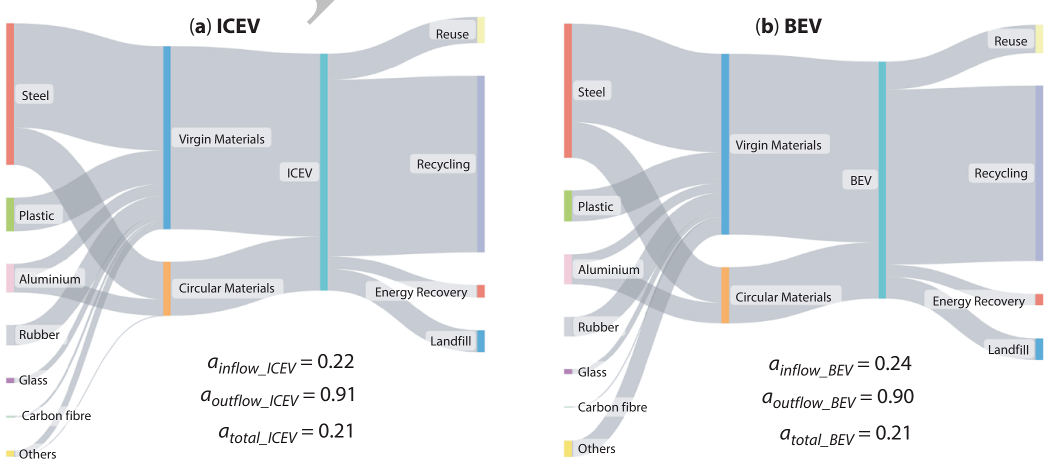

Figure 2.4 Material composition and alpha values (a) ICEV (b) BEV.

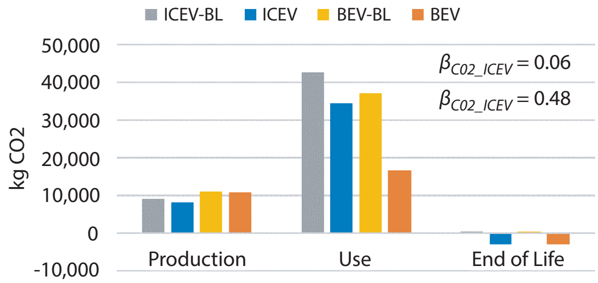

Figure 2.5 ICEV and BEV lifecycle carbon emissions. Note: BL – baseline.

In addition, we simulated three distinct lightweighting scenarios for the average BEV relative to the aforementioned reference baseline. The three scenarios (Figure 2.6) all involved the *substitution* of a proportion of conventional steel (with an eye on maintaining car performance) in the vehicle body with one of the following: (a) advanced high strength steel (AHSS); (b) Aluminium and (c) Aluminium and carbon fibre.

As demonstrated by Figure 2.7b, the introduction of lightweighting relative to the reference baseline has a negligible effect on the overall CI value (0.09 is the best performance). In the aluminium-carbon fibre scenario, lightweighting has a negative effect on environmental performance relative to the BEV baseline. This is because carbon fibre manufacturing is highly energy intensive while recycling is not currently practiced for this material.

In summary, lightweighting via material substitution, as opposed to lighting via absolute material reduction in mass terms, is not a good strategy for the advancement of circularity, in terms of carbon emissions. Rodrigues *et al.* [26] came to similar conclusions regarding the benefits of lightweighting via substitution in the car industry when it came to service provision. They discovered that the practice doesn't improve unit efficiency per passenger kilometre. In addition, lightweighting in general carries the risk of further secondary metal

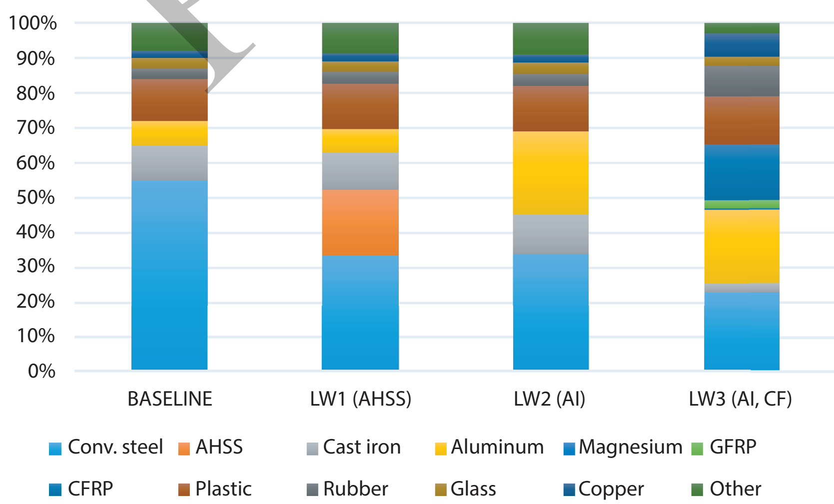

Figure 2.6 Material composition of BEV car body baseline and lightweighting scenarios. Note: AL – aluminum, CF- carbon fiber.

contamination and higher energy intensity for recycling and recovery, due to the reliance on alloying. This practice negatively affects both the alpha and beta values, reducing the overall circularity of the system. This is thus indicative of the futile nature of employing this type of lightweighting to close material loops.

Grubler *et al.* [11]'s low energy and material demand (LEMD) scenario indicates that substantial improvements can be made when it comes to the development and maintenance of a low carbon circular economy, only if resource consumption is halved by 2050. This is something they believe is possible in vehicle manufacture and operation if:

- Industry dematerialises by 89 percent and increases material efficiency by 72 percent.
- Vehicle fuel efficiency improves by 50 percent, which for the UK requires going from 1.4 to 0.7 MJ/pkm.
- Stock efficiency increases by 40 percent, which means reaching 25,383 pkm per UK-registered vehicle.

Under the LEMD scenario, with the aforementioned targets in mind, the overall CI value (combined alpha and beta) reaches 0.48 relative to the reference baseline (Figure 2.7b).

The results obtained for the overall CI value are promising, but as Grubler *et al* [11] make clear, the transition to a more circular economy requires a low energy and low material demand. They argue that this necessitates 100 percent electrification of currently motorised transport. However, this carries its own issues due to the availability and environmental impact of lithium and rare earth extraction and disposal (see Valero and Valero [27]). Grubler *et al.* [11] also state the need for policies that transition people away from their car and onto public forms of transport and non-motorised options. However, current UK infrastructure, lifestyle choices and expectations have locked most people into car ownership [28, 29]. Dematerialisation is also a key aspect in the transition to a low carbon circular economy. While it may be easier for the car industry to dematerialise, if the right incentives

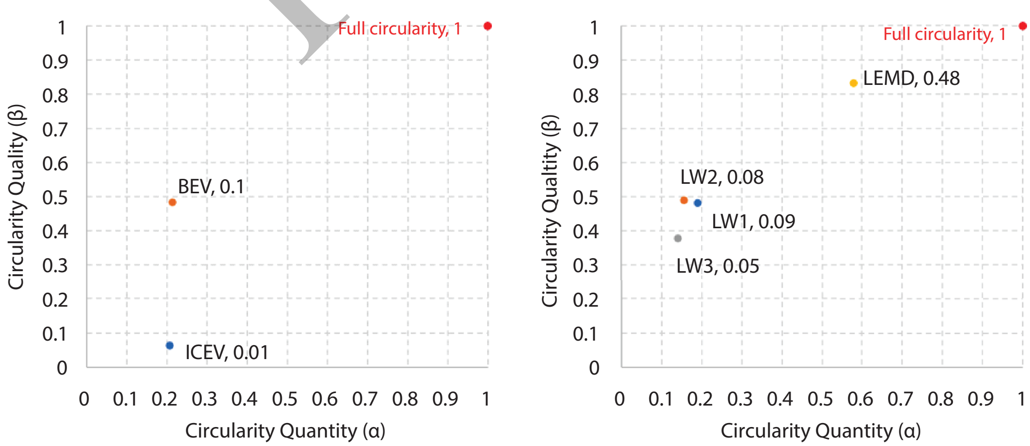

Figure 2.7 Alpha, beta and CI for: (a) ICEV and BEV current state (b) BEV lightweighting (LW) and low energy and material demand scenarios (LEMD) Note: The number next to the label corresponds to the overall CI value (obtained via α x β).

are provided, industry leaders must be careful not to simply transmaterialise (switch out one material for another). They must also be aware of the trade-offs that become apparent when trying to optimise energy savings relative to material savings and vice versa (see Whiting *et al.* [30]).

2.4 Conclusions & Recommendations

In this paper, we improved Cullen's [1] circularity index approach by expanding his alpha and beta indicators to better reflect the dynamics of material inflows and outflows and the environmental impacts across the life cycle of a system. The beta indicator is now more robust, as it can be used to examine a range of environmental impacts, not just energy consumption. Finally, we have tied Cullen's circularity index approach to the philosophical underpinnings of the circular economy, as first proposed by the Ellen MacArthur Foundation [23]. We hope that this will increase the adoption of this index among those stakeholders interested in quantitatively evaluating the circularity of their system.

System circularity is measured by a wide range of stakeholders, including businesses, governments, and academics. The CI updated in this paper can communicate to these stakeholders the degree of circularity at various stages (design, operation, decommission) and scopes (macro, meso, micro). If done properly, the results can guide management and operational decisions, without the need for excessive or extra expertise and training. Indeed, they would only be asked to consider three values (alpha, beta, and overall CI).

With regard to our case study, our results suggest that the UK car sector is far from circular when it comes to closing the carbon emission and material cycles. However, there are some advancements that could be made in our progress towards circularity in terms of carbon emissions. The main improvement in the car sector will come from a transition towards full BEV fleets, although this has a negligible impact on material cycle circularity. That said, a low carbon circular economy is not without it challenges, nor environmental impacts, given the toxicity of rare earth mining and disposal, not to mention the logistics of having a much-expanded supply chain of rare earths and lithium. To better understand these issues, the research here can be expanded beyond carbon emissions to include acidification, eco-toxicity, mineral depletion, etc. We have identified that the common practice of lightweighting via material substitution, has a negligible to detrimental effect on the alpha, beta, and the overall CI value. In order to significantly improve the CI values, the UK would need to adopt much more stringent decarbonisation methods, which would involve a move away from car ownership to public transport, for example. However, given the UK population's dependency on private ownership of vehicles, and the country's infrastructure, it is difficult to imagine that this will be a simple, easy, or even desirable path for the majority of the UK's inhabitants.

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