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RESEARCH ARTICLE

Material Circularity Assessment in Road Scheme Design

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Abstract

There is growing recognition of, and interest in, the potential benefits of the application of circular economy approaches to road infrastructure. This work reports the calculation and consideration of the Ellen MacArthur Foundation's Material Circularity Indicator (MCI) as a road scheme design-stage circularity metric and considers the practicality of its calculation and its potential to inform sustainable design.
The MCI measures the degree to which a product's component materials minimise linear flows and maximize restorative flows, while also accounting for the duration and / or intensity of material use relative to an 'industry-average' product.
The MCI was calculated for a major road scheme's baseline design and principal detailed design stage design options – during scheme design. Calculations used scheme design data, with future material recycling efficiency estimated on the basis of current UK practice and the MCI's utility factor derived from historic traffic flow intensity. The scheme's baseline design had an MCI of 53.4%, which was improved to 61.3% through the integration of design oportunities that reduced resource consumption and increased material reuse and recycling. Calculation of the MCI facilitated evaluation of resource flow and material circularity and is considered to have value in informing road scheme design-stage resource management, decision making and sustainability.

Keywords Road Design · Material Flow Analysis · Circular Economy · Circular Economy Metric · Material Circularity Indicator · Infrastructure

1. Introduction

Six of the nine key 'planetary boundaries' that measure environmental health across the earth's land, water and air have been exceeded - largely due to the impacts of the linear 'take-make-use-waste' economy (Circle Economy Foundation, 2024). Road infrastructure often ranks second in the built environment after buildings for material input flow and stock (Grossegger *et al* 2024) and hence, has a key role to play in the transition to more sustainable resource use. Adoption of circular economy strategies offers a means of reversing the overshoot of planetary boundaries and reducing the global reliance on material extraction (Circle Economy Foundation, 2023).

Roads are generally well suited to the application of circular economy approaches as:

- They are long-lasting assets, frequently with long-term ownership / management enabling and encouraging long-term decision-making;
- Although road construction and maintenance use large amounts of material, roads employ standardised designs with a relatively limited range of materials used;

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- Reuse and closed loop recycling of road materials is technically possible and frequently economically advantageous; and
- National road authorities have the potential to store and move 'surplus' resource between road schemes within their network to facilitate retention of resource value through material reuse and recycling.

National Highways' A303 Amesbury to Berwick Down (Stonehenge) Pathfinder Project (Smith *et al*, 2023) demonstrated the practical integration of circular economy approaches into major infrastructure design. The project identified a range of opportunities (Smith *et al*, 2021) and noted the importance of distinguishing between 'circular economy enablers' and 'circular economy outcomes' when assessing impact / progress towards the circular economy. The Pathfinder Project also identified the Ellen MacArthur Foundations' Material Circularity Indicator (MCI) (Ellen MacArthur Foundation, 2015) as a potential metric to monitor the circularity of material resource management within the context of the scheme's wider sustainability metrics. However, project level demonstration and evaluation of the MCI was constrained by the scheme's delivery schedule and ultimate cancelation (New Civil Engineer, 2024).

Despite growing interest in the circular economy within road infrastructure (Liu and Kringos, 2024), circularity metrics are not yet widely used during road design. Whilst National Highways' ambition is to be a '…resource efficient organisation with whole life lifecycle understanding of the flow of materials' and with a commitment to develop performance metrics and baselines for circularity (National Highways, 2023), there is currently no requirement for UK road scheme designers to apply a circularity indicator metric.

Key factors holding back the sector's transition to the circular economy include the absence of regulatory requirements, industry inertia, limited technical guidance, and a lack of circular economy expertise and communication within European National Road Authorities (Mantalovas et al., 2020). Challenges to the use of circularity metrics include a lack of consistent methodology and challenges in data collection and interpretation.

2. Research Objective

The work reported sought to demonstrate the application of the Material Circularity Indicator as a road scheme design-stage circularity metric. This paper describes the calculation of the MCI during the detailed design stage of the M5 Junction 10 Improvements Scheme (Gloucestershire County Council, Highways, no date, and Gloucestershire Highways, no date) and considers the practicality of calculation, including data sources and limitations and the metric's potential value in informing scheme design.

3. Literature Review

3.1. The Circular economy

The concept of the circular economy has been defined in many ways (Kirchherr, Reike and Hekkert, 2017). The Ellen McArthur Foundation's characterisation of the concept (Ellen MacArthur Foundation, 2015) as 'an economy that is restorative by design, and aims to keep products, components and materials at their highest utility and value, at all times, distinguishing between technical and biological cycles' is widely accepted and was used for the current work.

3.2. Circular economy metrics and road schemes

While a range of circular economy metrics and sustainability indices have been developed and applied to construction projects (Khadim *et al*, 2023, Güngör *et al*, 2024 and Bragança *et al*, 2025), there are currently few reports of their application to roads.

Mantalovas *et al* (2023) developed a framework and indicator to quantify and assess the circularity potential of reclaimed asphalt through consideration of technical aspects, market conditions and legislative restrictions. However, the approach was intended to help inform the management of reclaimed asphalt at national or market level rather than support the design of a specific road scheme.

Earlier work identified the MCI as a potential design stage metric, as much of the requisite data required for its calculation is available during scheme design and limitations associated with the metric would be avoided through its consideration within the context of pre-existing complementary sustainability indicators (Smith *et al*, 2023). The MCI has recently been used within asphalt product Environmental Product Declarations, with product MCI results between 0.522 (%MCI = 46.9%) and 0.864 (%MCI = 84.9%) reported in the context of a cradle-to-gate life cycle assessment (Higgins Asphalt, 2023). The MCI has also recently been used with the Circular Economy Index (CEI), a financial value-based indicator, to compare potential alternative approaches to pavement maintenance (Liu *et al*, 2025). The study found in-situ rejuvenation to be the most circular strategy. Both in-situ rejuvenation and warm mix asphalt having higher MCI (MCI = 0.77), than resurfacing (MCI = 0.66) due to higher virgin material use. In-situ rejuvenation also achieved the highest CEI by minimizing material inputs, while warm mix asphalt and resurfacing had lower CEI due to higher costs of virgin materials.

3.3. The Material Circularity Indicator

The Ellen MacArthur Foundation and Granta Design's Circular Indicators Project (Ellen MacArthur Foundation and Granta Design, 2019) sought to develop circularity indicators suitable for product design. The MCI measures the degree to which a product's component materials minimize linear flows and maximize restorative flows, while also accounting for the duration and / or intensity of material use relative to an 'industry-average' product.

Calculation of the MCI involves calculation of the 'Linear Flow Index' (LFI), by dividing the amount of material flowing in a linear fashion by the sum of the amounts of material flowing in a linear and a restorative fashion (or total mass flow). The index gives a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow. The MCI is calculated by combining the LFI with a utility factor (X), which reflects the length and /or intensity of the product's use. Typically, either lifespan or use intensity is used to calculate utility, rather than both. The resulting MCI can be reported as a percentage with higher values indicating greater circularity. Fig.1, provides a diagrammatic representation of the material flows taken into account to support calculation of the LFI and MCI.

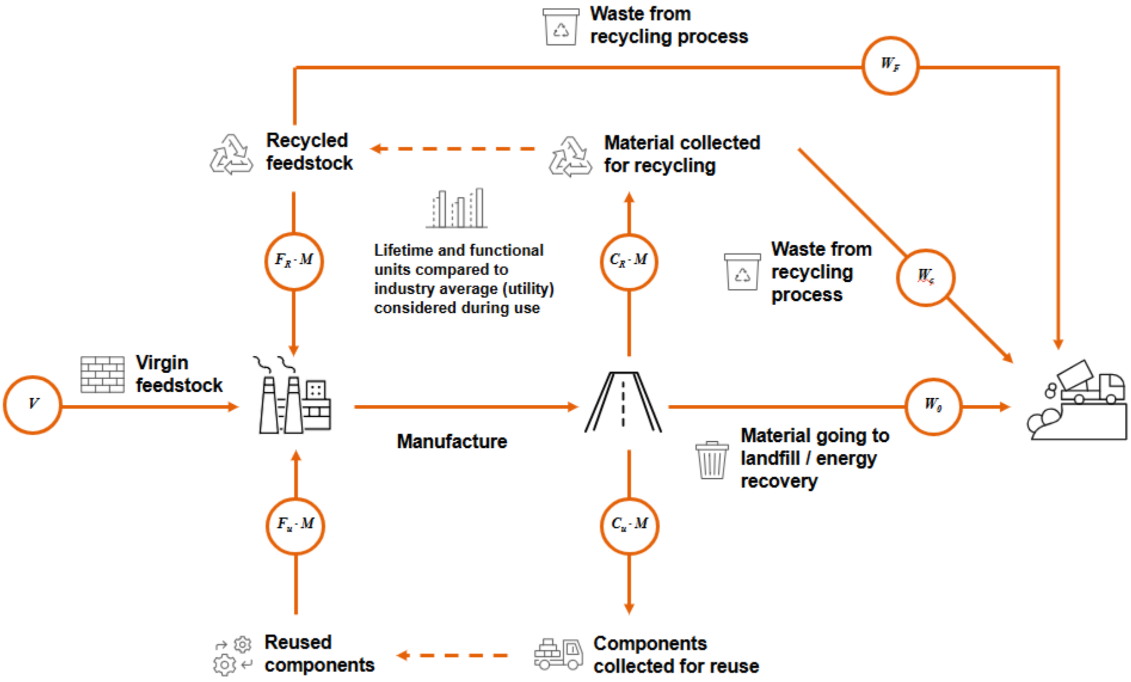

Figure 1. Material Flow used to calculate the Material Circularity Indicator (Re-drawn from Ellen MacArthur Foundation and Granta Design, 2019)

Definitions of the terms, symbols and equations used in the calculation of the MCI are given in Tables 1a and b. Further details of the formulae and underlying assumptions are given in the Ellen McArthur Foundation's Circularity Indicators Methodology (Ellen MacArthur Foundation and Granta Design, 2019).

The MCI is focussed on how a product's component materials circulate and its utility; but not, what the materials are, or the risks and impacts associated with the materials; necessitating the use of other complimentary indicators e.g., measures of a material's scarcity, toxicity and energy, water, biodiversity, socioeconomic and greenhouse gas impact. Reviews of the MCI methodology (Güngör et al, 2024 and Pineda-Martos et al, 2025) noted limitations associated with:

i. Not directly accounting for the complexities associated with material separability and the consequences of incorporating multiple materials irreversibly within complex products;
ii. The assumption that there are no material losses during reuse, and no explicit recognition or advantage given to closed loop recycling;
iii. A lack of recognition of material quality loss during recycling ('downcycling' / 'cascading'); and
iv. Improving the MCI of a product or a company will not necessarily translate as an improvement of the circularity of the whole system.

It is however, noted (J. Goddin, personal communication, 2025) that:

i. Complexities associated with material separability and the consequences of incorporating multiple materials irreversibly within products can and should be addressed through MCI calculation data entry;
ii. Material losses during reuse can be accounted for through the collection efficiency;
iii. Closed-loop benefits are also likely to impact complimentary indicators such as economic and environmental indicators related to material quality; and
iv. It is recognised that it is necessary to look at circularity holistically and at different levels.

Finally, a key consideration in the application of the MCI to road scheme design is the calculation's flexibility in the derivation of the MCI's utility factor – which can be calculated using asset operational lifetime and / or intensity of use. It is however, noted that a consistent approach is required to enable comparison of results between different design options for road schemes.

Table 1a. MCI Symbols, Definitions and M5 Junction 10 Improvements Scheme DF3 Baseline Input Values (Symbols and definitions from Ellen MacArthur Foundation and Granta Design, 2019.)

Symbol	Definition	Input Value used for calculation of the M5 J10 Design Fix 3 Baseline Design
M	Mass of a product	2,496,729 tonnes.
F_R	Fraction of the mass of a product's feedstock from recycled sources	F_R = 0%.
F_U	Fraction of mass of a product's feedstock from reused sources	F_U = 0%, except soil = 10%.
F_S	Fraction of a product's biological feedstock from sustained production.	F_S = 0%.
C_C	Fraction of mass of a product being collected to go into a composting process	C_C = 0%.
C_E	Fraction of mass of a product being collected for energy recovery.	C_E = 0%.
C_R	Fraction of mass of a product being collected to go into a recycling process	C_R = 95%.
C_U	Fraction of mass of a product going into component reuse	C_U = 0%, except soil = 10%.
E_C	Efficiency of the recycling process used for the portion of a product collected for recycling.	E_C = 95%.
E_E	Efficiency of the energy recovery process for biological materials.	Not applicable - no biological material was included in the calculation.
E_F	Efficiency of the recycling process used to produce recycled feedstock for a product	E_F = 95%.

Table 1a (cont.). MCI Symbols, Definitions and M5 Junction 10 Improvements Scheme DF3 Baseline Input Values (Symbols and definitions from Ellen MacArthur Foundation and Granta Design, 2019.)

Symbol	Definition	Input Value used for calculation of the M5 J10 Design Fix 3 Baseline Design
B_C	The carbon content of a biological material.	Not applicable - no biological material was included in the calculation.
L	Actual average lifetime of a product	Scheme-specific material or product lifetimes have not been developed beyond 'industry average' lifetimes at DF4.
L_{av}	Average lifetime of an industry-average product of the same type	See Discussion – not used in the MCI calculation.
U	Actual average number of functional units achieved during the use phase of a product	93,000 motor vehicles/day.
U_{av}	Average number of functional units achieved during the use phase of an industry-average product of the same type	82,000 motor vehicles/day.

3.4. The M5 Junction 10 Improvements Scheme and PAS 2080

The Gloucestershire County Council M5 Junction 10 Improvements Scheme has a total site area of approximately 182 hectares and consists of three main components: enhancements to M5 Junction 10, widening along the A4019 and the construction of a new link road connecting the A4019 to the B4634 (Gloucestershire County Council, Highways, no date). The scheme is categorised as a Nationally Significant Infrastructure Project (NSIP) under the UK's 2008 Planning Act and hence requires Development Consent Order (DCO) before construction (Gloucestershire Highways, no date).

The scheme is being delivered in stages that broadly align with National Highways' Project Control Framework (PCF) (Highways England, 2018). Design Fix 3 (DF3) is a design milestone during the preliminary design (PCF stage 3) and Design Fix 4 (DF4) a milestone during the detailed design stage (PCF Stage 5).

Compliance with PAS 2080:2023 (British Standards Institution, 2023) and achieving the scheme's Quality Commitment target 30% carbon reduction relative to the DF3 baseline design footprint (Gloucestershire County Council, Galliford Try and Arcadis, 2025) were key drivers for identification and integration of circular economy approaches and opportunities during the scheme's detailed design. PAS 2080 is a specification for whole life carbon management in projects and programmes within the built environment. It supports the transition to a net-zero economy by 2050 and emphasises close collaboration across value chain members. A core feature of PAS 2080 is the 'carbon reduction hierarchy', Fig. 2, which outlines the approach to identify potential opportunities to minimise whole life carbon emissions through:

- Avoid – align project and / or programme outcomes with net zero transition at the system level, evaluating the basic need at the asset or network level;
- Switch – assess alternative solutions and adopt those that reduce whole life emissions. This includes reconsidering scope, design approach, materials and technologies while maintaining whole life performance requirements; and
- Improve – identify and adopt solutions and techniques to improve resource use and asset or network design life. Including application of circular economy principles to assess materials / products for their potential for reuse or recycling at end-of-life.

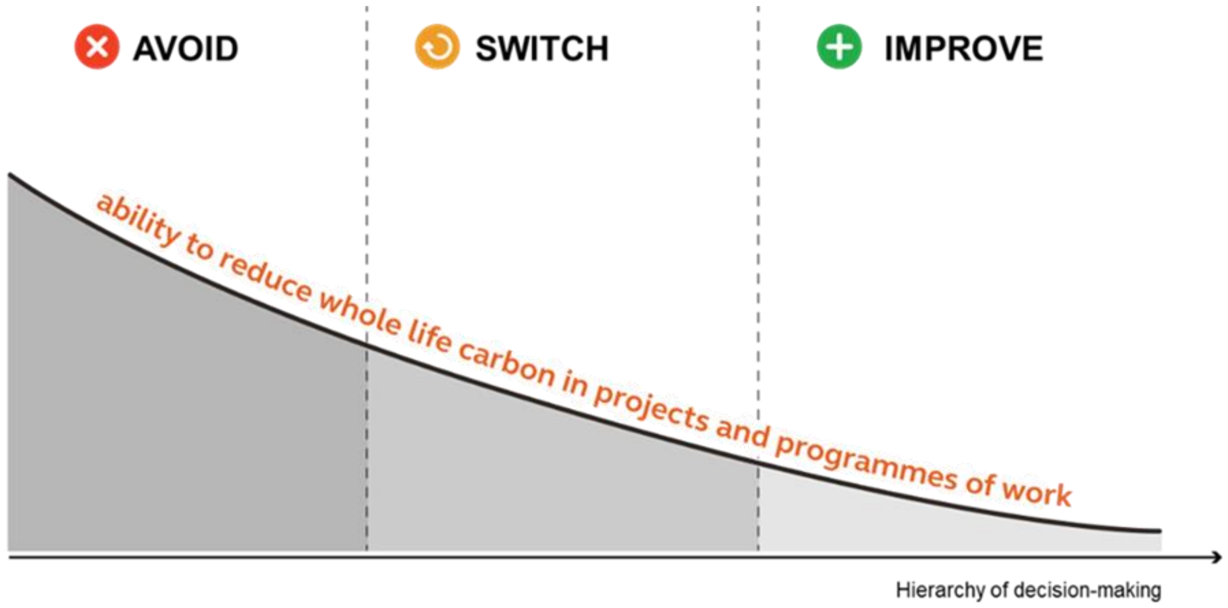

Figure 2. The Carbon Reduction Hierarchy for reducing project whole life carbon - Redrawn from PAS 2080:2023 Carbon management in buildings and infrastructure (British Standards Institution, 2023)

3.5. Carbon and the Circular Economy

Minimising greenhouse gas emissions through design is a core principle of the UK Government's Infrastructure Carbon Review (HM Treasury, 2013), and recognition of the circular economy's critical role in achieving national, regional and client net zero targets (Ellen MacArthur Foundation, no date; Committee on Climate Change, 2019; Enkvist et al., 2022; FIDIC, Ramboll and Arcadis, 2023) is a significant driver for adopting circular economy approaches in infrastructure projects.

Whilst carbon management and circular economy approaches are frequently aligned, it is important that designers / practitioners recognise that they are not synonymous. The circular economy offers the potential for carbon and wider sustainability benefits including capturing additional value from resources, mitigating risks from material supply and price volatility as well as wider benefits through building economic, natural and social capital (Highways England, 2016, British Standards Institution, 2017 and Ellen MacArthur Foundation, 2024). Progress towards the circular economy is a valuable objective and outcome in its own right and circular economy metrics have the potential to help inform and improve design decision making.

4. Method

Arcadis was commissioned by Galliford Try, the M5 Junction 10 Improvement Scheme’s architect (New Civil Engineer, 2023), to undertake the detailed design including the identification and assessment of opportunities to improve the design.

4.1. Carbon Modelling and Management

The scheme required an Environmental Impact Assessment (EIA) (European Commission, no date), with the carbon and climate assessment (the assessment and management of impacts on climate, as well as the effects of climate change on the project) undertaken in accordance with National Highways’ requirements (Highways England, Transport Scotland, Welsh Government and Department for Infrastructure, 2019 and National Highways, Transport Scotland, Welsh Government and Department for Infrastructure, 2021), including compliance with PAS 2080. Road scheme carbon impact is modelled at defined project delivery milestones, with data accuracy and availability improving, but the ability to reduce scheme whole life carbon decreasing as the project progresses from design to delivery and operation.

4.1.1. Design Fix 3 Baseline The carbon baseline represents the scenario for what carbon emissions and removals would have been in the absence of planned measures to reduce emissions (British Standards Institution, 2023). The scheme's Design Fix 3 (DF3) carbon baseline, based on the DF3 Bill of Quantities (DF3 BoQ) provides a robust and transparent baseline against which to identify and demonstrate carbon reductions secured during the development and delivery of the scheme. The carbon baseline includes 'Upfront Carbon', the emissions associated with raw material extraction and processing, the energy used in producing the construction materials, transporting the materials to site, and constructing the road, encompassing Product (A1-A3) and Construction (A4 and A5) stages. Transport, A4, includes material transport; Construction, A5, includes construction fuel and energy use, waste arisings, waste transport and employee commuting during construction; and temporary works (Royal Institution of Chartered Surveyors, 2017).

The DF3 baseline emissions referred to in this paper are similar to, but not the same as those previously reported in the EIA (M5 Junction 10 Improvements Scheme, 2021 and 2024), as the calculations and project input data had been reviewed and revised to reflect improved data availability at DF3.

4.1.2. Detailed Design Paved roads are typically constructed in layers on natural or improved ground, referred to as 'sub-grade'. The upper layers consist of compacted bituminous and hydraulically bound granular materials, over several layers of unbound granular material specific to different pavement loadings. Asphalt mixture (bituminous bound aggregates) is used for flexible pavement, whereas concrete (cement bound aggregates) is used for rigid pavement. The M5 J10 DF3 and DF4 BoQ reflect 'generic fully flexible carriageway design' comparable to that illustrated in Fig. 3.

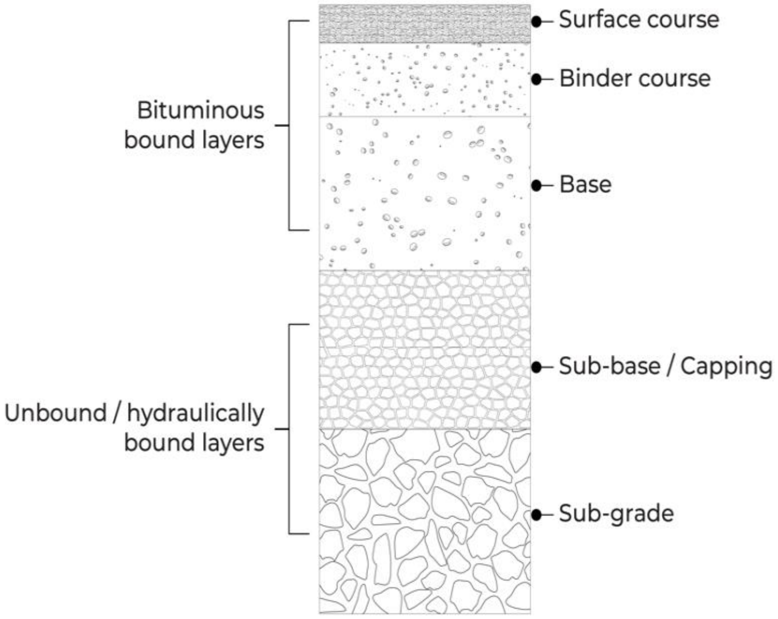

Figure 3. Typical cross section of a new (asphalt) flexible pavement (Redrawn from Mantalovas et al, 2023.)

During detailed design (Highways England, 2018) the design team developed and evaluated a number of potential scheme design changes, including quantifying the associated potential to reduce scheme carbon emissions. Five key design change opportunities are summarised in Table 3.

The A1-A5 carbon impact associated with potential design changes was assessed by:

i. Determining the impact of the design change on the types and quantities of material required for construction - as recorded in the DF3 BoQ; then
ii. Determining the impact of the changes to material requirements and associated transport on A1-A5 carbon emissions, using the method and tools previously used to determine the scheme's DF3 carbon baseline; and then
iii. Comparing the A1-A5 carbon impact of the design opportunity with the DF3 carbon baseline.

This initial assessment of the carbon impact of design options focussed on ‘Upfront carbon’ (A1-A5) and did not consider emissions associated with ‘In use’ (B1-B5) or ‘End of life (C1-C4) stages (Royal Institution of Chartered Surveyors, 2017).

4.2. Circular Economy Metrics

The M5 Junction 10 Improvements Scheme was considered to be the ‘product’ for MCI calculation. An Excel spreadsheet was used to calculate the MCI of the DF3 Baseline BoQ and key DF4 design options. The Excel spreadsheet was checked by reference against commercial MCI calculation software (Madaster and BCI Assets).

Calculation of the MCI during scheme design necessitated the use of scheme-specific data recorded in the DF3 BoQ (the same construction material type, quantity and source used for the carbon baseline), road specific data (intensity of operational use) and generic data / assumptions about the future management of ‘end of life’ materials arising from maintenance activities, Fig.4. Input data values used to calculate the LFI and MCI metrics for the DF3 baseline design are given in Table 1a. Formulae used and DF3 baseline values obtained are given in Table 1b.

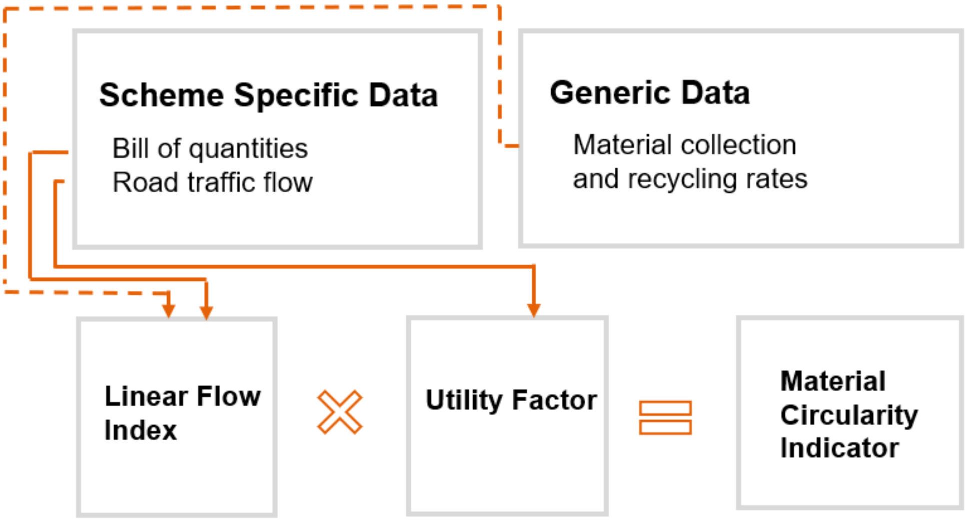

Figure 4. Data sources used to calculate the M5 J10 Material Circularity Indicator

4.2.1. *Derivation of the LFI - Feedstock and Material Flow*

Earlier work (Smith *et al*, 2023) noted that MCI calculation, being driven by the mass of materials, is, in the context of road schemes, largely determined at scheme level by a relatively small number of material types. The scheme DF3 MCI was calculated using quantities (tonnes) of aggregate, asphalt, concrete and soil for the overall scheme sourced from the scheme’s DF3 BoQ with the following input values:

- 0% (by mass) recycled content for the DF3 baseline design;
- 0% reused content except for 10% of soil for the DF3 baseline design;
- 95% efficiency of recycling processes used to produce feedstock used within the road’s construction (E_F);
- 95% of the mass of ‘end of life’ material generated during maintenance being collected for recycling (C_R);
- 95% efficiency of recycling processes used for recycling of materials generated during maintenance (E_C); and
- No significant (by mass) quantities of biological materials are used within construction of the scheme and no ‘end of life’ materials will be managed by composting or incineration.

Analysis of aggregate and asphalt were each separated into two fractions during calculation of circular economy metrics to enable consideration of the significant differences in expected durability / operational lifetimes.

In the absence of robust data, the efficiency of collection of ‘end of life material’ arising from maintenance (C_R), and the efficiency of the recycling processes (E_F and E_C) were modelled at 90 & 98% and 95 & 100%, with default values of 95% used in the DF3 baseline calculation and subsequent design-stage modelling. Results are summarised in Fig.5.

4.2.2. Derivation of the MCI – Asset Utility Calculation of the MCI requires knowledge of asset operational lifetime or intensity of use data to create a ‘utility factor’ (F(X)) on the basis of ‘actual values’ rather than theoretical maxima or guaranteed values. However, this information is not generally available for a road scheme before construction and operation.

Whilst the scheme has a design life of 40 years (National Highways, Transport Scotland, Welsh Government and Department for Infrastructure, 2021), the DF4 BoQ reflects a ‘generic carriageway design’ with potential for alternative maintenance requirements and strategies. Scheme-specific material or product lifetimes had not been developed beyond ‘industry average’ for components / materials at DF4. The utility factor calculation was therefore based upon intensity of use (vehicles/day). The UK Department for Transport (2024) provides official statistics for daily traffic flow data by road class with an average of 82,000 vehicles/day reported for ‘Major Roads and Motorways’ and 93,000 vehicles/day reported for the M5 in 2023.

5. Results

Derived values obtained from the DF3 Baseline design input values are listed in Table 1b with the key material types, quantities and associated circular economy metrics summarised in Table 2. DF4 design change options, with associated potential carbon reduction relative to the DF3 carbon baseline and circular economy metrics are summarised in Table 3 and Fig.5.

Table 1b. M5 Junction 10 Improvements Scheme Derived Values

Symbol	Definition	DF3 Baseline Derived Values
V	Mass of virgin material. Material that is not from reuse, recycling or, biological materials from sustained Production.	2,456,729 tonnes
W	Mass of unrecoverable waste associated with a product	143,633 tonnes
W_0	Mass of unrecoverable waste through a product’s material to landfill, waste to energy and any other type of process where the materials are no longer recoverable.	84,336 tonnes
W_C	Mass of unrecoverable waste generated in the process of recycling parts of a product	118,595 tonnes
W_F	Mass of unrecoverable waste generated when producing recycled feedstock for a product	0 tonnes
X	Utility of a product, where: $X = \frac{L}{L_{av}} \cdot \frac{U}{U_{av}}$	1.1341 based on intensity of use (vehicles/day)
$F(X)$	Utility factor built as a function of the utility X of a product defined as: $F(X) = \frac{0.9}{X}$	$F(X) = 0.794$ based on intensity of use (vehicles/day).
LFI	Linear Flow Index $LFI = (V + W)/(2M + \Sigma_X (W_{F(x)} - W_{C(x)}) /2)$	0.5269
MCI	Material Circularity Indicator of the M5 Junction 10 Improvements Scheme DF3 baseline design $MCI = 1 - LFI \cdot F(X)$	0.5808
$\%MCI$	$\%MCI = (MCI-0.1)/0.9$	53.42%

Table 2. M5 Junction 10 Improvements Scheme DF3 Baseline Metrics

Material	Quantity Required / tonnes	% by mass contribution to scheme	A1-A3 Carbon Emissions / tCO$_2$e	Linear Flow Index	Material Circularity Indicator	%MCI
Aggregate – general applications	1,922,774	76.44	14,365	0.5433	0.5688	52.09
Aggregate – filter drains	310	0.01		0. 5433	0.5688	52.09
Asphalt – surface course	34,102	1.36	1,886	0. 5433	0.5688	52.09
Asphalt base and binder	103,828	4.13	5,742	0. 5433	0.5688	52.09
Concrete	30,713	1.22	3,922	0. 5433	0.5688	52.09
Soil	405,003	16.10	8,765	0.4421	0.6492	61.02
‘Scheme Total’	2,496,729	99.25	34,680	0.5269	0.5808	53.42

Note:

i. ‘Scheme Total’ is the sum of the metrics associated with the four bulk materials modelled. ‘Scheme Total’ differs from the scheme’s total mass (all materials) used for calculation of carbon emissions which includes consideration of all materials listed in the BoQ, with total mass of 2,515,527 tonnes.

ii. The scheme’s DF3 baseline carbon emissions were reported as 117,296 tCO$_2$e. This is the sum of Product Stage (A1-A3) and Construction Process stage (A4&A5) emissions excluding land use / land use change impacts (Gloucestershire County Council, Galliford Try and Arcadis, 2025).

iii. The component material carbon emissions presented within Table 2 are embodied carbon (A1-A3, Product stage).

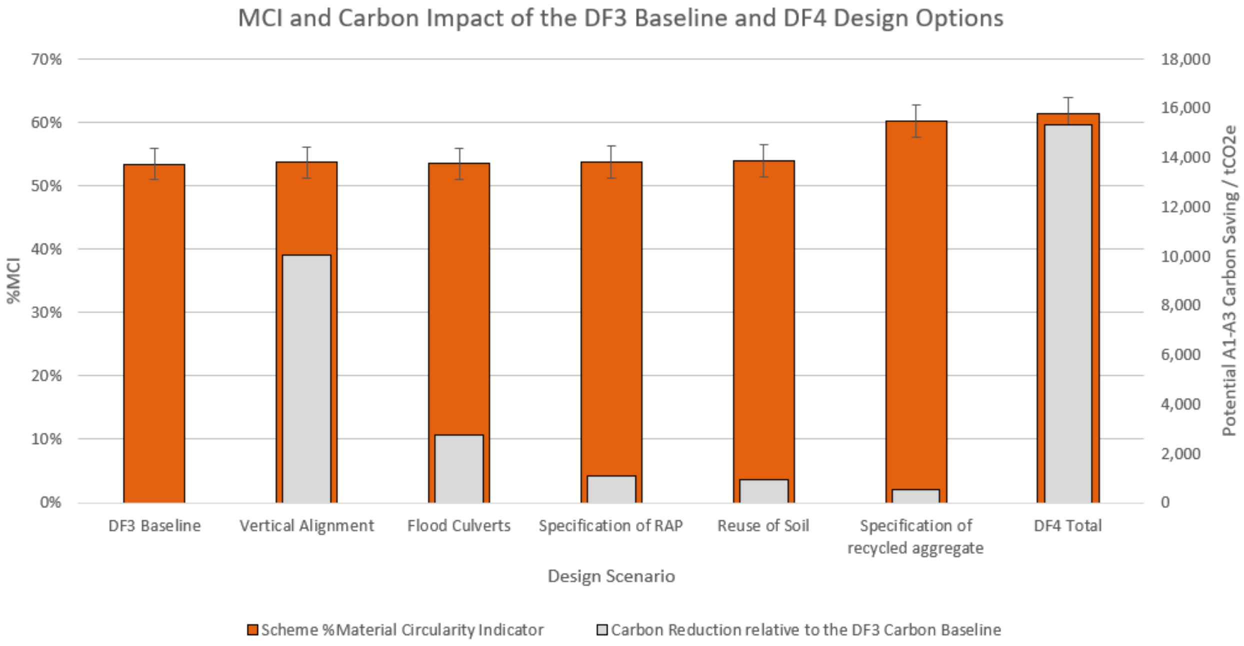

Figure 5. Graph Showing the Material Circularity Indicator and potential carbon savings associated with the M5 J10 DF3 baseline and key DF4 design options

Table 3. MCI and A1-A3 Carbon Impact of Key Design Change Options

Design Change Option	A1-A3 Carbon Impact relative to the DF3 Baseline / tCO_2e	Material	Scheme Requirement / tonnes	LFI	MCI	% MCI
1) West Cheltenham Link Road Vertical Alignment The DF3 baseline design is built on an embankment which is 'overdesigned' relative to the requirements of the Design Manual for Roads and Bridges (Highways England, Transport Scotland, Welsh Government and Department for Infrastructure, 2020) creating the potential to reduce the vertical height and make horizontal / lateral revisions to the carriageway. Impact upon DF3 Baseline: • Reduce aggregate – general use required by 327,899 tonnes (17%). • Overall reduction in modelled scheme mass of 13%.	Reduction in scheme emissions of 10,058 tCO_2e	Aggregate – general use	1,594,875	0.5433	0.5688	52.09
		Aggregate – filter drains	310	0.5433	0.5688	52.09
		Asphalt – surface course	34,102	0.5433	0.5688	52.09
		Asphalt base and binder	103,828	0.5433	0.5688	52.09
		Concrete	30,713	0.5433	0.5688	52.09
		Soil	405,003	0.4421	0.6492	61.02
		TOTAL	**2,168,830**	**0.5244**	**0.5826**	**53.62**
2) West Cheltenham Link Road Flood Culverts The DF3 baseline design utilises over 600 pre-cast concrete boxes which require scour protection, excavation 1-2 m below the culverts and replacement of existing material with engineering fill. The DF4 design option is a flood plain / integral viaduct. Impact on DF3 Baseline: • Reduce general aggregate required by 6,856 tonnes (0.36%). • Reduce concrete required by 4,982 tonnes (16.22%) • Reduce soil required by 549 tonnes (0.14%) • Overall reduction in modelled scheme mass of 0.5%.	Reduction in scheme emissions of 2,725 tCO_2e	Aggregate – general use	1,915,918	0.5433	0.5688	52.09
		Aggregate – filter drains	310	0.5433	0.5688	52.09
		Asphalt – surface course	34,102	0.5433	0.5688	52.09
		Asphalt base and binder	103,828	0.5433	0.5688	52.09
		Concrete	25,731	0.5433	0.5688	52.09
		Soil	404,454	0.4421	0.6492	61.02
		TOTAL	**2,484,342**	**0.5269**	**0.5808**	**53.42**
3) Specification of RAP in Pavement Design The DF3 baseline design assumes a 'general mix' asphalt will be used project wide. The DF4 design specifies use of warm mix asphalt with 10% Recycled Asphalt Pavement (RAP) in pavement design. Impact upon DF3 Baseline BoQ: • Specification of 10% (3,410 tonnes) of asphalt surface course sourced from recycled material. • Specification of 10% (10,382 tonnes) of asphalt base and binder sourced from recycled material.	Reduction in scheme emissions of 1,070 tCO_2e.	Aggregate – general use	1,922,774	0.5433	0.5688	52.09
		Aggregate – filter drains	310	0.5433	0.5688	52.09
		Asphalt – surface course	34,102	0.4934	0.6085	56.50
		Asphalt base and binder	103,828	0.4934	0.6085	56.50
		Concrete	30,713	0.5433	0.5688	52.09
		Soil	405,003	0.4421	0.6492	61.02
		TOTAL	**2,496,729**	**0.5242**	**0.5828**	**53.65**

Table 3 (cont.). MCI and A1-A3 Carbon Impact of Key Design Change Options

Design Change Option	A1-A3 Carbon Impact relative to the DF3 Baseline / tCO_2e	Material	Scheme Requirement / tonnes	LFI	MCI	% MCI
4) Reuse of Excavated Material There is potential to utilise material excavated from construction of ditches and ponds on site. Impact upon DF3 Baseline BoQ: • Reused soil content increased from 10% (40,500 tonnes) to 20% (81,000 tonnes).	Reduction in scheme emissions of 950 tCO_2e	Aggregate – general use	1,922,774	0.5433	0.5688	52.09
		Aggregate – filter drains	310	0.5433	0.5688	52.09
		Asphalt – surface course	34,102	0.5433	0.5688	52.09
		Asphalt base and binder	103,828	0.5433	0.5688	52.09
		Concrete	30,713	0.5433	0.5688	52.09
		Soil	405,003	0.3915	0.6893	65.48
		TOTAL	**2,496,729**	**0.5187**	**0.5850**	**53.89**
5) Specification of Recycled Aggregate There is potential to source aggregate for general fill activities from recycled sources. Impact upon DF3 Baseline BoQ: • Specification of 20% (385,4555 tonnes) of recycled aggregate - general use.	Reduction in scheme emissions of 530 tCO_2e	Aggregate – general use	1,922,774	0.4436	0.6480	60.89
		Aggregate – filter drains	310	0.5433	0.5688	52.09
		Asphalt – surface course	34,102	0.5433	0.5688	52.09
		Asphalt base and binder	103,828	0.5433	0.5688	52.09
		Concrete	30,713	0.5433	0.5688	52.09
		Soil	405,003	0.4421	0.6492	61.02
		TOTAL	**2,496,729**	**0.4501**	**0.6417**	**60.19**
6) Cumulative Impact of the five DF4 Opportunities Benefits associated with the design change opportunities 1-5 are assumed to be additive for the purpose of modelling circular economy metrics and carbon impact.	Reduction in scheme emissions of 15,333 tCO_2e	Aggregate – general use	1,588,019	0.4436	0.6480	60.89
		Aggregate – filter drains	310	0.5433	0.5688	52.09
		Asphalt – surface course	34,102	0.4934	0.6085	56.50
		Asphalt base and binder	103,828	0.4934	0.6085	56.50
		Concrete	25,731	0.5433	0.5688	52.09
		Soil	404,454	0.3915	0.6893	65.48
		TOTAL	**2,156,443**	**0.4382**	**0.6516**	**61.29**

6. Discussion

There is growing recognition of the need for, and ambition for the built environment, including pavement engineering (National Highways, 2023, Liu and Kringos, 2024) to transition towards the circular economy (Enkvist et al, 2022, FIDIC, Ramboll and Arcadis, 2023, Circle Economy Foundation, 2024 and Ellen MacArthur Foundation, 2024). The importance of quantifiable metrics for effective management and decision-making, has long been recognised - 'If you cannot measure it, then it is not science' (Thompson, 1883). Material flow analysis is a core method within industrial ecology and a key concept within the circular economy (British Standards Institution, 2017). An understanding of material flows, from source, to consumption, addition to stock, dwell time, discharge, recirculation and final sink is required to assess environmental impacts and effective resource management (Grossegger, MacAskill and Al-Tabbaa, 2024).

This paper reports the application of the MCI as a road scheme design stage circularity indicator. Calculation of the MCI for the scheme's baseline design and five design revisions considered during detailed design provide insights into data requirements, practicality of calculation, and the metric's potential value in better understanding and guiding the transition from linear to circular design.

6.1. Derivation of the M5 Junction 10 Improvements Scheme MCI

6.1.1. Materials Considered LFI and MCI calculations considered quantities and flows of aggregate, asphalt, concrete and soil, which collectively account for >99% by mass of the construction materials listed in the DF3 BoQ (Table 2) and hence, analysis of these four materials gives a close approximation of the MCI for the scheme as a whole. Focussing on high mass materials is consistent with published road construction and maintenance material flow analyses, in which waste and secondary materials are often omitted due to lack of data, with few studies extending the material selection to associated equipment like traffic control systems, guard rails and road lights (Grossegger, MacAskill and Al-Tabbaa, 2024).

6.1.2. Data Sources MCI calculation can be based-upon either 'actual data' (such as product lifetime and recycling rates) or design data. However, as a unique road scheme, 'actual M5 J10 life cycle data' was unavailable during design. MCI calculation therefore used scheme design data and generic 'end of life' material flow data.

Except for road-scheme asset longevity, end-of-life material management routes and efficiency, and the asset intensity of use needed to calculate the utility factor, the data required to calculate the MCI had previously been developed from the scheme's BoQ to support carbon management during EIA, preliminary and detailed design.

The available resource data is considered to provide a transparent and reproducible basis for design stage circularity assessment with the reported values intended to demonstrate the calculation of the of the MCI during road scheme design rather than represent a fully optimised scheme design or environmental product declaration. Data availability and accuracy are expected to improve during scheme delivery and hence, MCI calculation could be refined, potentially in parallel with scheduled carbon modelling, as more data becomes available during and after construction.

6.1.3. Approach to Derivation of the Utility Factor The following information was considered in the approach to derivation of the utility factor:

- The DF3 and DF4 BoQ reflect a 'generic carriageway design' with potential for alternative maintenance requirements and strategies.
- The scheme has a design life of 40 years (National Highways, Transport Scotland, Welsh Government and Department for Infrastructure, 2021).
- Typical product lifetimes are considered to be:
    - 120 years for aggregate used in general applications, although this can be more;
    - 20 years for aggregate used in filter drains with subsequent recycling for use in drainage materials or other suitable purposes;
    - 10-20 years for asphalt used in the surface course with replacement during planned maintenance; and
    - >100 years for asphalt used in the underlying base and binder. On heavily trafficked roads the binder course may need to be replaced after 30-40 years. Asphalt can be 100% recycled until such a time as it hardens beyond the point where it prevents recycling, this will depend upon climate and conditions of use.
- Average number of vehicles/day data is readily available for UK roads (Department for Transport., 2024), with scheme-specific projections also potentially available for larger schemes from the EIA. It is however, acknowledged that the volume of traffic flow used in the calculation was a 'design input value', rather than 'actual use' data. Traffic flow is likely to change as a result of the scheme as well as over the operational life of the road.
    - Traffic flow for the M5 = 93,000 vehicles/day; and
    - Average traffic flow for major roads and motorways = 82,000 vehicles/day.

The Utility factor for calculation of the MCI was derived from intensity of use, quantified on the basis of 'daily traffic flow', because:

i. Although variables affecting a road's service life, such as climate, traffic and maintenance are considered during design, a road's service life can significantly differ from its design life and planned service intervals.
ii. At DF4, pavement structure design was insufficiently developed to allow quantification of asset or component / material lifetime beyond 'industry average' hence, the lifetime element of the utility factor, (L/Lav) would equal one.
iii. Average daily traffic is linked to road category, which correlates with asphalt layer thickness and hence the mass of material used (M) and road material intensity factors (kg/m^2 of road) reflecting design guidelines and technical requirements (Grossegger *et al* 2024).

Whilst the utility factor was derived from intensity of use, it is recognised that it may generally be preferable to use durability. Intensity of use (vehicles per day) may be a 'fixed' design input value, whereas durability can be enhanced through design and specification. Hence, use of a utility factor based upon durability has the potential to recognise and thereby encourage progress in this aspect of design.

6.1.4. Input Data Sensitivity Analysis Recycling and reuse of road materials are well established in the UK (Anon, 2021), however, the values of E_C and E_F are material and recycling process specific. Previous authors have noted the lack of accurate information on asphalt recycling efficiency, with a recent publication suggesting a Dutch collection rate (C_R) of 100% and recycling rate (E_R) of 98% (Mantalovas and Di Mino, 2020, Liu et al, 2025). The combined effect of E_F and E_c (modelled at 95% or 100%) and C_R (modelled at 90% or 98%) on %MCI is ±2.5%, as shown in Fig. 5.

The UK Department of Transport (2024) report 2023 average daily motor vehicle traffic flow for major road sections and motorways of between 37,000 vehicles/day and 170,000 vehicles/day. The M5, with an average of 93,000 vehicles/day was slightly above the average 82,000 vehicles/day for major roads and motorways. Use of UK major road section traffic flow data to derive the utility factor would give utility factors (X) of 0.45-2.07, with the M5 having an intermediate value of 1.13. Hence, this approach to quantifying intensity of use can have a significant impact upon the %MCI value obtained – potentially more significant than derivation of utility factor by product durability. This result highlights the need for a consistent approach to derivation of the utility factor before it is possible to compare %MCI values between different road schemes.

6.2. Interpretation of M5 Junction 10 Improvements Scheme Materiality Circularity Indicator

6.2.1. DF3 Baseline Design Derivation of the DF3 Baseline design MCI demonstrated calculation of the metric using scheme data (Table 1a) and established baseline values (Table 2) against which future potential design options were assessed.

The DF3 scheme design had a LFI of 0.5269, reflecting predominantly linear material flow with %MCI of 53.42%. Material-level analysis reflects variance in circularity, with LFI of 0.5433 for key materials, except for soil which has more circular flow (LFI = 0.4421), due to the modelled reuse of waste soil generated during site preparation in construction and reuse of 10% of soil, in addition to 'end of life' recycling as modelled for other materials.

Scheme circular economy metrics are dominated by the flow of aggregate (general applications) which accounts for >77% of the mass of the four materials considered, with other components making proportionally smaller contributions. Aggregate is primarily used as imported fill for embankments, within structures, as capping and as sub-base for pavement, with smaller quantities used in applications such scour protection.

6.2.2. DF4 Design Options The key design approaches to reduce linearity / increase circularity in road scheme design are to use less material, to use material from sustainably sourced, reused and / or recycled sources, to use resources more intensively and to retain material value at end of life.

Refinement of the scheme's vertical alignment (Option 1) and replacement of flood culverts with a flood plain / use of integral viaduct (Option 2) reduce the mass of material required for construction, without changing other aspects of material flow relative to the DF3 Baseline.

Option 1, scheme LFI (0.5244) is improved slightly as soil (with more circular resource flow / lower LFI than aggregate) makes a greater contribution to scheme's overall mass. Option 2, scheme LFI (0.5269) is unchanged, with %MCI improved to 53.42%.

Increased reuse of excavated soil (Option 4) and increased recycled content (Options 3 and 5) resulted in more circular resource use during construction, but no change to the quantity of material required or its subsequent management, resulting in improved (lower) LFI and (higher) MCI.

The collective impact of the five design options considered was to improve scheme LFI to 0.4382 and the %MCI to 61.29%.

6.2.3. Correlation Between Carbon and the %MCI Whilst it is acknowledged that the %MCI and potential A1-A3 carbon savings (tCO_2e) associated with the DF4 opportunities modelled for options appraisal reported in Table 3 and shown in Fig.5 address different lifecycle stages, it is clear that they do not correlate closely.

This finding is no surprise as the potential carbon saving associated with design options is the product of the type and quantity (tonnes) of material used and its carbon intensity (tonnes CO_2e/tonne of material), whereas MCI is the product of the type and quantity (tonnes) of material used, its source, utility and management at end of life. Although material source can influence carbon intensity, for example, recycled materials frequently have lower carbon intensity than primary materials, the carbon intensity of the materials used in road construction vary significantly (e.g. general aggregate (0.007 tCOe/tonne) and ready mix concrete C40/50 mpa (0.159 tCO_2e/tonne) (Circularecology, 2025), consequently, the two metrics diverge. The significance of the lack of correlation lies in demonstrating that carbon emissions, which are currently routinely monitored in major UK road scheme design, cannot act as a 'proxy metric' for material circularity, underscoring the need for a dedicated circularity metric.

6.2.4. General Observations The design option examples considered demonstrate the application of the MCI to 'real world' design changes that had initially been developed primarily through value engineering and to reduce scheme greenhouse gas emissions. Calculation of the LFI and MCI during the scheme's detailed design supported consideration of material flow, including the comparison of design options, but did not formally inform the design.

Focussing analysis on the four key materials used, helped to simplify data requirements and interpretation of results. The MCI of several other DF4 design options e.g., roadside barrier reduction, refinement of the lighting strategy and a replacement transmission station that provide whole life carbon benefits (unpublished) were not modelled as the opportunities involve relatively small quantities of materials that were outside of the scope of the current calculations. It is however, recognised that these design options could also be assessed using the MCI comprehensive approach.

As no significant quantities of biological materials are used within the scheme's design, calculations focussed on the flow of materials through the circular economy's technical cycle. If design elements incorporating renewable materials were incorporated into a scheme's design, the associated flow of resources through the biological cycle could be assessed through component or material level calculations.

Changes to LFI and MCI associated with the design options are more significant at component / material level than when calculated for the scheme as a whole, reflecting the weighted contributions of the individual materials to the scheme and the dominant contribution of aggregate to the scheme's total mass. MCI calculation at component level is more sensitive than analysis at scheme level and hence could be used to assess potential design revisions where the LFI benefit may be insignificant at scheme level.

The MCI provides a way of measuring how restorative and regenerative the material flows of an asset are and can be used to assess and compare the circularity of alternative designs supporting design stage decision-making. The MCI complements existing scheme resource management metrics which may be focussed on aspects such as material recovery, recycling and re-use, including specification of minimum levels of recycled content (Emery *et al*, 2007) or diversion of waste from landfill.

Comparing %MCI values is not meaningful without standardising the scope and approach to calculation, including derivation of the utility factor. However, if the utility factor is calculated on the basis of durability and 'industry average' durability is assumed for all materials at DF4, then the LFI of 0.4382 corresponds to a %MCI of 56%. This value is at the lower end of the range reported for asphalt product EPDs (Higgins Asphalt, 2023). It is important to recognise that DF4 MCI reflects an ‘interim result’ with potential for further improvement during procurement and construction, rather than a fully optimised scheme in terms of material circularity and may differ from the ‘as-built' MCI.

Existing road scheme ambitions and targets create the requirement for on-going monitoring of scheme carbon performance throughout construction. The use of common scheme data and wider scheme knowledge for both carbon and circular economy modelling helps overcome potential constraints associated with access to data and creates a practical driver for co-consideration within the design team facilitating further refinement of the circular economy metrics and scheme performance as more scheme specific information becomes available.

The project level experience reported support the view that the MCI is well suited to application as a road schemes design stage indicator as:

- Major road schemes are subject to regulation (e.g. environmental impact assessment) and management (e.g. National Highways Benefits Realisation Management) creating a monitoring framework of complimentary indicators;
- The requisite data for calculation is collected and collated during scheme design and construction for reporting carbon impact;
- Road schemes incorporate a range of materials; however, MCI calculation can be simplified as the total mass of materials used is dominated by relatively few materials; and
- The metric demonstrated sensitivity to design stage improvement in material circularity for the design options considered.

7. Conclusions

This paper reports the calculation of the Ellen MacArthur Foundation’s Material Circularity Indicator during road scheme design. The MCI, expressed as the %MCI, was derived from pre-existing design data using a limited number of supporting assumptions.

Calculation of the MCI helped to encourage and support consideration of material flows, including the assessment of circularity across alternative design options and quantified progress in this aspect of the design.

Despite carbon management, including the application of the carbon reduction hierarchy, being a key drivers for considering circular economy approaches during design, evaluation of design options shows that A1–A3 Product Stage carbon emissions / savings cannot serve as a proxy indicator for material circularity as measured by %MCI. This highlights the need for a dedicated circularity metric.

Further research is required to:

- Establish a standardised approach to the calculation of the MCI, to enable comparison of results across different road schemes;
- Establish key sensitivities and representative road scheme %MCI values in order to identify opportunities to improve the %MCI and assess the potential to benchmark this aspect of road scheme design;
- Investigate the relationship between %MCI values derived at preliminary and detailed design stages and those achieved post-construction; and
- Refine the methodology to align with emerging best practice.

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Declarations

Competing Interests The authors declare no competing interests.

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