Supplementary S1: Data & Method Description

Data Description

Data Description from Project Artefacts such as Carbon Collation tool are shown in Table S1 below:

Table S1: Data description

Element / data item	Description	Unit / representation	Key assumption / interpretation
Material inflow	Materials sourced externally and brought into the asset or intervention.	Tonnes (t) Conversion of volume units (e.g., m3, m2) to tonnes for Material Flow Analysis (MFA). ICE database[1] [48]	Represents gross material input associated with the intervention recorded in the Carbon Collation Tool (CCT).
Material flow	Movement of materials between inflow, asset, project/intervention and waste nodes in the Sankey model.	Tonnes (t); represented by flow width	Material categories retain the nomenclature used in the CCT.
Asset Node	Asset class associated with the material flow, e.g., culvert or flood gate.	Asset category	Asset classifications follow those used in the organisational carbon calculator/CCT.
Project / intervention node	Represents an intervention occurring during the 100-year	Intervention sequence (0, 1, 2, …)	Intervention 0 represents the current intervention. Subsequent interventions are generated according to asset

[1] See Embodied Carbon Footprint Database - Circular Ecology (https://circularecology.com/embodied-carbon-footprint-database.html)

Element / data item	Description	Unit / representation	Key assumption / interpretation
	assessment period, such as new-build, refurbishment or replacement.		design life and the intervention logic embedded in the CCT.
Assessment period	Period over which future intervention requirements are represented.	100 years	Used as a static organisational assessment boundary. Future interventions are estimated using the assumptions embedded in the CCT, rather than interpreted as precise forecasts.
Asset design life	Expected period before a subsequent intervention is required.	Years	Taken from the organisational carbon calculator. For example, a 35-year design life may lead to refurbishment after 35 years and a later replacement within the 100-year boundary.
Intervention sequence	Sequence through which an asset may progress over the assessment period.	New-build → refurbishment → replacement	The subsequent intervention depends on the current intervention, asset type, design life and whether refurbishment is considered feasible.
Minor refurbishment	Reduced material requirement relative to the reference/new-build quantity.	10% of reference quantity (organisation database)	Organisational assumption applied where minor refurbishment is selected.
Moderate refurbishment	Reduced material requirement relative to the reference/new-build quantity.	25% of reference quantity (organisation database)	Organisational assumption applied where moderate refurbishment is selected.
Major refurbishment	Reduced material requirement relative to the reference/new-build quantity.	50% of reference quantity (organisation database)	Organisational assumption applied where major refurbishment is selected.

Element / data item	Description	Unit / representation	Key assumption / interpretation
Replacement following refurbishment	Material requirement estimated from the refurbishment quantity where the original asset material weight is unavailable.	Tonnes (t)	The CCT assumes like-for-like materials for replacement. Where the underlying full asset weight is unavailable, the study applies a conservative estimate based on the available intervention information.
Future material uplift/downlift	Adjustment applied to material quantities for subsequent interventions.	Percentage / tonnes	Determined by the intervention type and organisational assumptions, as illustrated by the minor, moderate and major refurbishment cases.
Construction waste	Material wastage generated during a new-build or other intervention.	Tonnes (t)	Waste is assigned to the corresponding intervention in which it is generated.
Material composition	Material type associated with each Sankey flow.	CCT material categories	Material nomenclature is retained from the organisational CCT for consistency with the source data.
Sankey representation	Graphical representation linking materials, assets, interventions and waste over the assessment period.	Node and flow network	Nodes represent stocks/categories/interventions and flow widths represent material quantities. The model is static and does not dynamically simulate changes over time.
Modelling software	Software used to generate the Sankey diagrams.	R and PantaRhei	Used for graphical representation of the material-stock and flow relationships derived from the CCT data.

Carbon terminology definitions in the asset lifecycle context

Carbon is defined based on the asset lifecycle stage and the intervention. This research adopts the industry standard of PAS 2080 definitions for two reasons: (a) to align with

the practitioner's focus of the research, and (b) to prevent duplication of effort by reusing a well-established and widely understood concept. The core concepts used in this article to define the contextual boundaries are outlined below and are applied within the organisation's research setting.

Capital carbon

It is the carbon associated with constructing a "new build" asset, which includes the categories below.

Materials Carbon

Carbon associated with materials used for the project, including extraction, processing, manufacture and distribution to the supplier—this is also known as ***cradle-to-gate embodied carbon***.

Transportation carbon

Carbon associated with the transportation of resources—materials, personnel and plant and machinery.

Installation carbon

Carbon is linked to the construction process. Three subcategories are identified within this category: (a) Site establishment—fuel and energy use during construction, (b) Plant use—fuel consumption during construction, and (c) Waste—transportation off-site for disposal of excess materials and other waste generated during construction, such as that arising from the site.

Refurbishment carbon

Carbon is related to interventions at the end of an asset or sub-asset's useful life that prolong its lifespan.

Replacement carbon

Carbon associated with rebuilding an asset/sub-asset at the end of its useful (or, if refurbished, extended useful) life.

Demolition carbon

Carbon is linked to the demolition of expired assets or sub-assets. Three subcategories are evaluated: (a) Materials Waste—transportation of demolished materials off-site; (b) People—travel to and from the site; and (c) Plant—transportation to and from the site and fuel consumption.

Method: Top-Down analysis

Creating Baseline Data and Analysis—top-down approach

To develop a comprehensive and systematic database of assets along with their material and carbon attributes, the research used the following data sources: AIMS PD JSON files (publicly available), the Carbon Collation Tool (CCT), and the Carbon Modelling Tool (CMT), both provided by the organisation. ***Data Preparation*** involved ***three stages***, as outlined below.

Stage 1: Defining data entity and attributes

In AIMS PD, multiple data levels and details exist, such as an asset category, an asset subcategory, and an element. For analysis, the research defines the entity referred to as the "asset-sub category" in the AIMS PD[2] dataset as "asset", and their asset ID counts as "attributes". Further, the carbon data residing in CCT from 415 assets (entity) is identified to calculate the average emission per asset type (attribute) (see stage 3 below).

Stage 2 Data Processing

For asset-level analysis

From the Carbon Collation Tool (CCT) (Jan 2024), extensive data cleaning and mapping were necessary to align capital phase data from CCT with asset data from AIMS-PD, as they used different definitions for asset, sub-asset, asset class, and element, which caused inconsistencies in reporting outputs. Based on data stored in CCT from 164 projects, including 1,905 carbon data points on asset types, and after cleaning and transforming the data regarding units of measurement and preferred options, the research identified 415 records on different asset types as the final dataset for the top-down analysis. This file did not include material-level information.

For material-level analysis

Another version of the Carbon Collation Tool (June 2024) was obtained, containing capital material data on material inflows from 296 projects. Following data cleaning, the final sample used for analysis comprised 5,486 records of material inflows across 277 projects and 1,695 assets.

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[2] The data includes Asset ID counts from AIMS PD fetched on 07 Mar 2024 through the public API available on the website (API data link https://environment.data.gov.uk/asset-management/doc/reference). The rest of the data is from two versions of the Carbon Collation Tool (CCT): one from January 2024 (this file missed the material level and hence was used for asset-level analysis), and the June 2024 version of CCT, which contained material-level data. The June version of CCT covers projects from 2014 to 2024 and was used for material-level analysis.

Stage 3: Analysis and output

To report portfolio analysis output, three steps were performed on the processed data:

1. Gathering asset ID counts for various asset types managed by the organisation.
2. To develop an organisation-wide carbon distribution snapshot, map and extrapolate the average carbon per asset type (whole-life defined in CCT) cumulatively for all assets.
3. Mapping and generating a typical material mix per asset type cumulatively for assets to derive organisation-wide material estimates from actual consumption data from samples in CCT.

A portfolio's asset-level carbon distribution and material inflow distribution were generated to develop differentiated strategies for CE at the asset and material levels, as reported by the portfolio analysis. Each of these steps is explained below:

AIMS asset ID Counts and Average carbon per asset type.

Data on the count of assets was obtained from publicly held asset IDs in AIMS PD, with the count of asset types treated as representing unique assets. The reliability of the AIMS PD data was confirmed through consultation with the organisation, and the asset IDs were extracted on 07 March 2024.

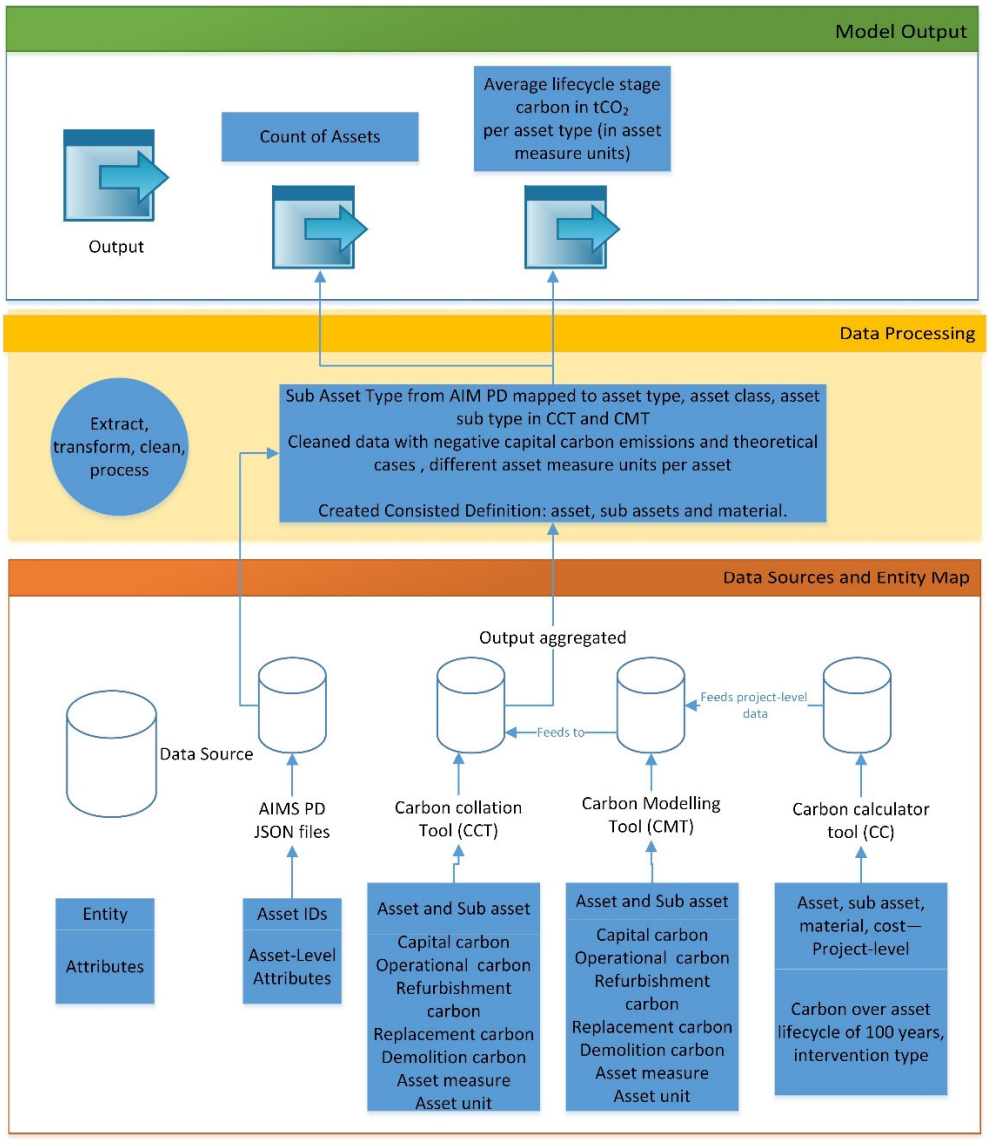


Figure S1: Data Model

Using data from the Carbon Collation Tool (CCT) covering 164 projects between 2014 and 2023, a total of 1,905 carbon data points related to asset types were compiled[3]. After cleaning and transforming the dataset to ensure consistency in units of measurement and selection of preferred options, a refined dataset of 415 records representing different asset types was produced for top-down analysis. This dataset included information on capital carbon, operational carbon, replacement carbon, refurbishment carbon, and demolition carbon. Based on this sample, average stage-wise carbon values were calculated for each asset type. Figure S1 describes in more detail the data extraction, data transformation and model output.

[3] It may be noted that the asset is identified within the carbon calculator with unique identifier at three levels, namely, material→asset→project; therefore, chances of duplication were highly unlikely. So, by using the code for an asset it is possible to track it both for the project and for the materials used within it. So, while aggregating this we ensured that duplication is highly unlikely.

Asset type from AIMS PD and Asset class for Carbon Calculator mapping for overall carbon profiling.

The AIMS PD database defines embankments as linear assets that should be segmented based on consistent ownership, design, or construction characteristics, or capped at a maximum length of 600 metres: "New linear assets should be limited to the minimum of continuous single ownership, common design or common construction length or 600m. Longer asset runs must be defined (chunked) as separate assets" [49]. Based on this definition, segmentation provides some consistency, but does not eliminate within-category variation.

Asset counts provide a consistent portfolio-scaling variable, but do not eliminate uncertainty arising from differences in asset segmentation, scale, material composition or complexity. The use of multiple retained observations within the available CCT sample reduces the influence of individual records in categories with adequate coverage, although it does not eliminate sampling bias, within-category variability or the influence of extreme observations.

A manual mapping exercise was conducted to align asset descriptions between the AIMS PD database and the Carbon Collation Tool (CCT) database. Following this alignment, it became possible to extrapolate carbon distribution across all assets and materials at the organisational level over a 100-year period. While this analysis does not constitute an accurate estimate (which is not the intention of the research design), it contributes to the development of an organisation-wide portfolio-level asset prioritisation strategy.

In this context, the primary objective is to establish a representative distribution of emissions, rather than to ensure absolute numerical precision. Further, the objective is to identify broad portfolio-level concentration patterns, rather than precise numerical estimates. Robustness was assessed through practitioner review of the resulting distributions and classifications.

The findings from the top-down analysis are presented in various graphs in the Findings section.

Sensitivity and robustness

A conventional sensitivity analysis has limited interpretive value for this study because the model is intended to identify order-of-magnitude patterns and classify portfolio-level hotspots, rather than generate precise asset-level carbon estimates. The outputs are used to distinguish relatively high- and low-priority lifecycle, asset and

material categories. Robustness was therefore assessed through iterative review with organisational subject-matter experts, who confirmed the plausibility of the broad distributions and classifications. The results should be interpreted as indicative portfolio-level screening signals, rather than precise numerical estimates.

Supplementary S2: Data Visualisation

The insights derived from Figure S2 and Figure S3 underscore the importance of visualising the Material–Project–Asset ***boundaries*** from a management perspective. This highlights that managing innovations at the materials level—specifically targeting high-volume, high-cost, and high-carbon materials—can significantly influence overall carbon and cost performance. Consequently, prioritising interventions at the material level is essential for achieving impactful results.

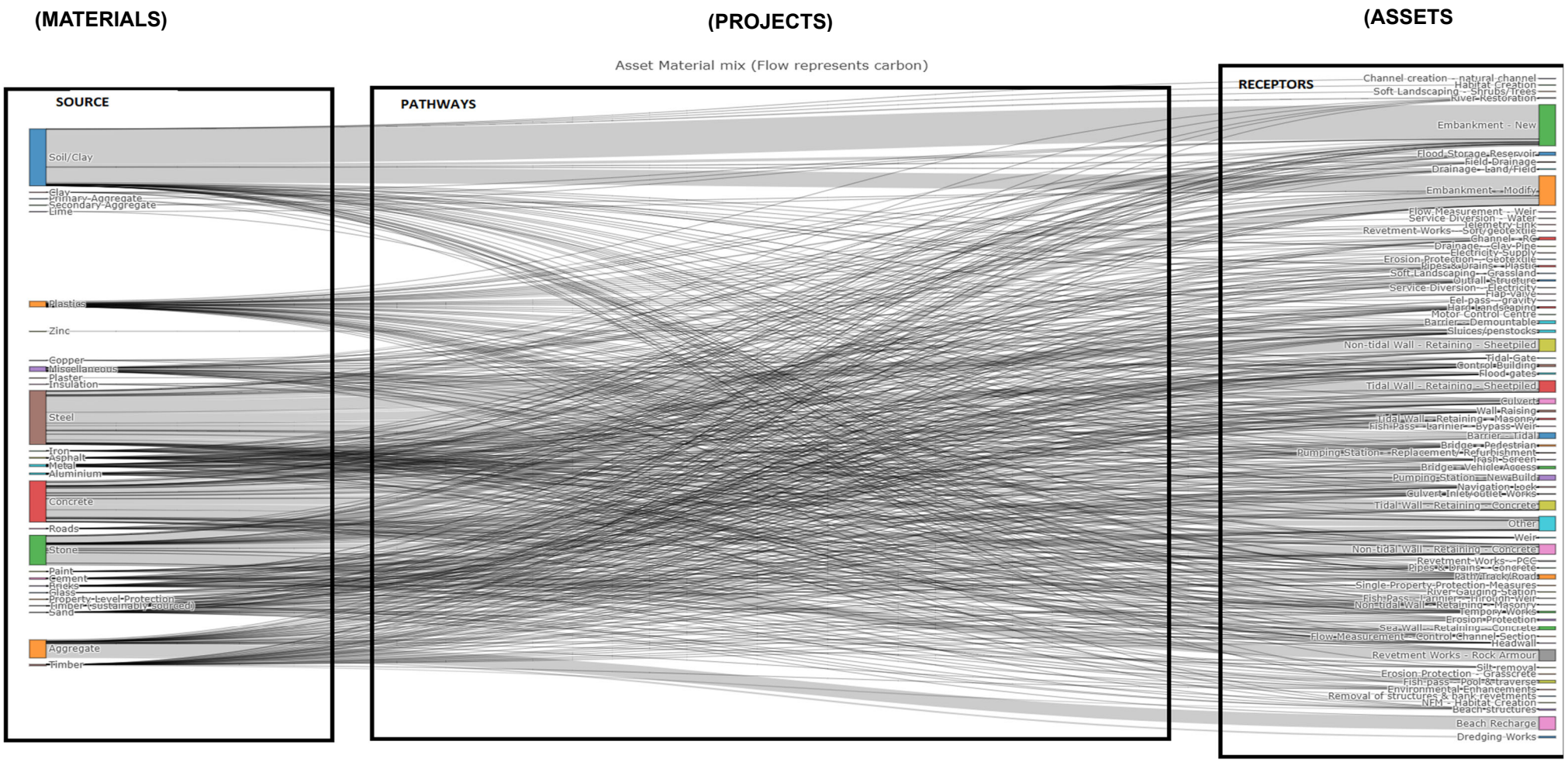


Figure S2: Material flow diagram—carbon emissions (company data source). (Author's own analysis.)

This Sankey diagram shows the relationship between materials, assets, and project types, where the flow width represents carbon contribution. It highlights that a small number of materials—especially soil/clay, concrete, steel, and aggregates—represent major carbon hotspots across a wide range of flood- and coastal-defence assets such as embankments, revetments, and retaining walls, indicating potential areas for subsequent carbon-reduction and circular-economy appraisal.

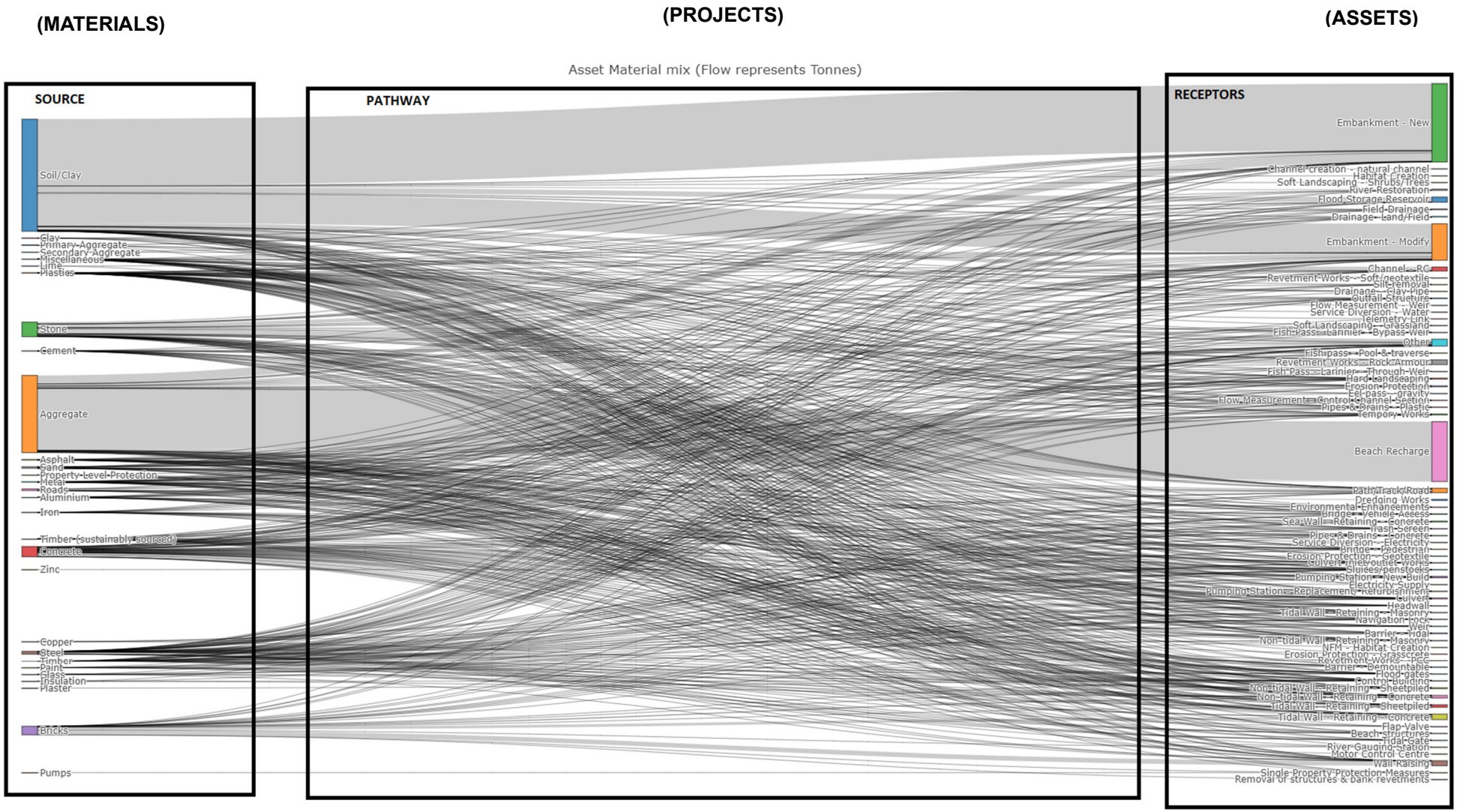


Figure S3 : Material flow diagram—mass flow in tonnes (company data source). (Authors own analysis.)

Sankey diagram illustrating the flow of materials from projects through assets, where line thickness represents the total material mass (tonnes), highlighting the dominant material–asset relationships and areas of high material intensity across the portfolio.

Supplementary S3: MFCI framework and strategy mapping

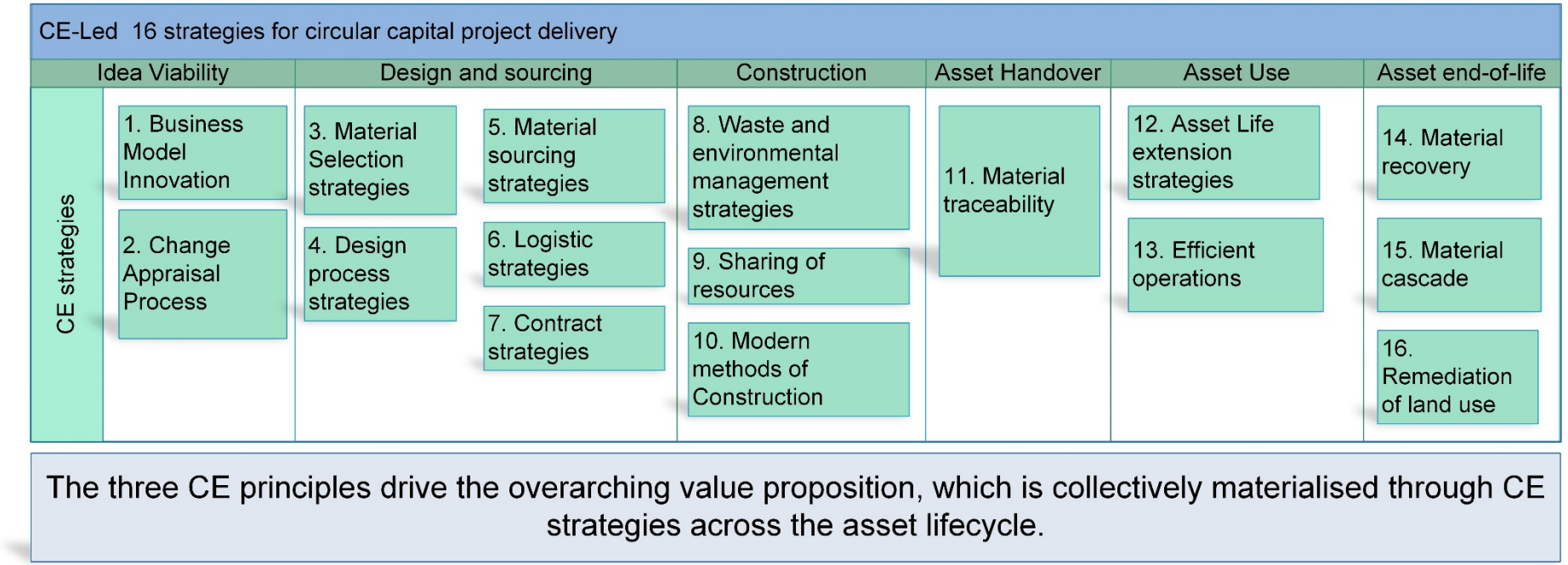


Figure S4: MFCI framework (adopted from Jain et al. [22])

The Material-Focused Circular Innovation (MFCI) framework provides a lifecycle-based set of circular-economy (CE) strategies that can be considered across infrastructure planning, delivery, use and end-of-life stages. In this study, the framework is used after portfolio-level hotspot identification to translate lifecycle, asset and material priorities into a potential action agenda for asset owners. The strategies are therefore not treated as prescribed project-level interventions. Instead, they indicate the types of CE actions that

may warrant more detailed engineering, financial, environmental and asset-specific appraisal once portfolio screening has identified where intervention is likely to have the greatest effect.

The linkage between MFCI strategies and the Asset Categorisation Matrix is summarised in Table S2. The categories refer to the relative lifecycle patterns identified through the portfolio analysis, rather than fixed engineering thresholds. Accordingly, the table should be interpreted as a strategic screening and prioritisation aid. It provides a structured bridge between portfolio hotspot identification and subsequent CE appraisal, while recognising that final decisions would also need to consider asset condition, residual life, hydraulic performance, service criticality, flood risk, technical feasibility and value for money.

Table S2. Translating portfolio asset categories into potential MFCI intervention strategies

MFCI lifecycle stage	CE strategy from MFCI	Intervention level	Relevant asset category	Illustrative action for further CE appraisal
Idea viability	1. Circular project appraisal and/or Natural Capital Accounting	Material–project–asset levels	Cat. 1, 2, 3	Consider existing asset retention, end-of-life recovery potential and associated whole-life cost and carbon benefits during appraisal. Natural Capital Accounting may, additionally, capture wider environmental and societal benefits.
Idea viability	2. Business model innovation	Asset level	Cat. 1, 2, 3	Explore service-based models for pumping and MEICA assets where performance-based ownership could incentivise longevity, maintenance, reuse and recovery.
Design and procurement	3. Material selection strategies	Material level	Cat. 2, 3	Assess material reuse, secondary materials and alternative material solutions, including unconventional recovered materials such as tyre bales, where technically appropriate.

Design and procurement	4. Design process strategies	Material–project–asset levels	Cat. 2, 3	Consider modular design, standardisation, lean engineering and design for recovery or reuse using components such as precast concrete sections, sheet piles and timber.
Design and procurement	5. Material sourcing strategies	Material level	All categories	Apply whole-life considerations to high-volume, high-cost or high-carbon materials and assess alternative sourcing, recovered-material and local-supply options.
Design and procurement	6. Logistics strategies	Material/project level	All categories	Examine opportunities to reduce transport requirements, improve local material balancing and coordinate the movement of recovered materials between projects.
Design and procurement	7. Contract strategies	Material/project level	All categories	Incorporate whole-life material considerations, recovery requirements, take-back arrangements and alternative material pathways within procurement and contracting strategies. For high-cost or high-carbon materials, such as rock revetment, procurement can also be used to test assumptions established during earlier appraisal stages.
Construction	8. Waste and environmental management strategies	Project level	Cat. 2, 3	Retain existing structures where feasible, reuse material stocks already available on site and minimise unnecessary excavation, disposal and replacement.
Construction	9. Sharing of resources	Project/portfolio level	Cat. 2, 3	Enable reclaimed materials to be transferred between projects, including surplus soil, precast sections and other recoverable components that might otherwise leave the organisational material system.

Construction	10. Modern methods of construction	Project level	Cat. 2, 3	Design standardised components with appropriate jointing, lifting and disassembly arrangements to facilitate future recovery and reuse. Examples include boxed culverts and precast concrete sections. Alternative fuels and energy-efficient construction practices may complement these material-focused interventions.
Asset handover	11. Documentation and technology for traceability	Project/asset level	All categories	Link capital-phase material information, design intent and as-built records with asset-management systems so that information required for future maintenance, refurbishment, replacement and recovery remains accessible during the asset-use phase.
Asset use	12. Asset-life extension strategies	Asset and material levels	Cat. 1, 2	Use condition-based monitoring, remote sensing, proactive maintenance and alternative ownership arrangements to extend useful life and reduce premature replacement and associated material demand.
Asset use	13. Efficient operations	Asset level	Cat. 1, 2	Reduce operational impacts and intervention frequency through proactive maintenance and, where appropriate, alternative energy sources generated on-site, such as solar or hydro power.
Asset end-of-life	14. Material recovery strategies	Asset and material levels	Cat. 2, 3	Assess whether assets, components or materials can be retained, recovered or directly reused, rather than automatically removed and disposed of on replacement.
Asset end-of-life	15. Material cascading	Material level	Cat. 2, 3	Where equivalent reuse is not technically feasible, identify lower-order applications that retain residual

				material value within the infrastructure system.For example, The potential value of retaining an existing outfall structure, rather than treating replacement automatically as a disposal event.
Asset end-of-life	16. Land-use strategies	Asset level	All categories	Examine opportunities to generate wider value from transitioned or decommissioned assets through recreation, habitat enhancement, biodiversity, air-quality, water-quality and health benefits.

The Table S2 demonstrates that CE intervention should not be applied uniformly across the asset portfolio. Assets characterised by relatively high capital and replacement impacts may warrant greater emphasis on design optimisation, material selection, procurement, reuse, recovery and replacement avoidance. Assets characterised by relatively high operational and refurbishment impacts may require greater attention to maintainability, operational efficiency, monitoring and life-extension strategies. Where both dimensions are significant, a wider combination of MFCI strategies may be appropriate. Conversely, assets representing relatively low portfolio-level impacts may require less immediate intervention, subject to subsequent asset-specific appraisal.

The resulting decision logic is therefore sequential. Portfolio-level analysis first identifies the dominant lifecycle, asset and material hotspots; the Asset Categorisation Matrix then differentiates assets according to their relative lifecycle burden; and the MFCI framework provides a structured repertoire of potential CE strategies for further consideration. In this way, MFCI is used as a strategy-selection layer following portfolio screening, rather than as a substitute for conventional engineering or investment appraisal. The approach consequently supports a transition from generic CE ambition towards differentiated, asset- and material-specific intervention priorities.