A New Circular Economy Framework for construction projects

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Abstract

Circular Economy (CE) is a holistic, viable solution to the linear model's 'take-make-dispose' system which enhances economic growth without threatening environmental and social value. Its principles are based on product optimisation, waste elimination, and regeneration of natural systems. In this paper, a pilot study evaluates the feasibility of implementing CE in construction projects, followed by the development of a new framework with strategies to alter current construction activities for greater circularity. To demonstrate the benefits of implementing a CE model, a critical assessment of its impacts in industry was made which considers costing, environmental impacts, and legislative action. A new comprehensive CE framework was developed which details a set of indicators, action plans and resources allocated to assess the performance of the strategy implementation, specifically designed for building cycles. To address the challenge of monitoring progress on the transition towards circularity, quantitative tools using a life cycle approach were developed in this study including an embodied carbon emissions calculator and databases for waste and circularity indexing of common construction materials. The framework, accompanied by these tools, were applied to a construction case study to verify its feasibility in combining scientific and policy making guidelines. Good practice recommendations were also offered, based on the qualitative research undertaken, to further enrich the study.

Author keywords Circular Economy, life cycle, construction project, waste and circularity indexing

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1. Introduction

Since the emergence of Circular Economics in the late 1970s, the pursuit of responsible and cyclical resource use has been received as a modern solution to tackle unsustainable human activities. Circular Economy (CE) policies seeks to replace the linear economic model, a system whereby value is generated through mass production, consumption, and permanent disposal of resources, into one that is "restorative and regenerative by intention and design" (EMF, 2013). This is achieved through decoupling economic profit from exhaustive consumption of finite resources to alleviate environmental burdens without economic compromise. With systems innovation at its core, CE solutions are most relevant within a product's life cycle - from conscientious production that reduces use of raw materials, to serving a function that maximises reuse of it and its components and finally closing the systems loop at end of life recovery.

Despite this business model's growing traction in modern policy making, its lacking formal, mutually agreed definition prevents establishing targets crucial to facilitating circular actions (Morseletto, 2020). This poses a significant research gap that must be overcome to ensure industries, particularly the built environment, are better prepared to adopt robust and new-found circularity practices and policies. Though one of the most encompassing definitions within the sustainability science scope defines CE as "a regenerative system in which resource input and waste, emission and energy leakage are minimised by slowing, closing, and narrowing material and energy loops" (Geissodoerfer et al, 2017).

Section 1 will introduce Circular Economics as a business model and its applicability to construction. Recurring themes of building cycles, environmental impacts, sustainable development, and value chains helps assert the broader relevance of CE in construction. Section 2 organises research into qualitative and quantitative methodologies. Qualitative research helps locate where circular solutions can be embedded into practice and mobilise uptake of the model whereas quantitative tools developed attempts to measure CE progress from a materials management perspective. Section 3 demonstrates use of these quantitative tools into a case study while substantiating the qualitative findings. Section 4 and 5 discusses the case study findings and conclusions observed.

The main research outcome is to establish a new framework that outlines implementation strategies across the whole building cycle, to be standardised for construction projects. This is approached by evaluating the solutions offered within a circular model and coordinating where it can potentially manifest along the construction value chain. The study aims to understand the challenges of replacing the linear model and the entrenched policies and practices of traditional construction, allowing discussion of the roles that cultural, market, regulatory and technological factors play in influencing change. Another objective is to develop methods of monitoring/measuring progress of CE transition against the framework. The study aims to contribute to the "need for specific methods to measure CE progress" (Moraga et al, 2019), one which supports the legitimacy of the proposed framework.

The Ellen MacArthur foundation (who pioneers the CE concept formulation) distinguishes the biological and technical material flow cycles through the 'Butterfly diagram'. For a CE, biological cycles focus on the natural recirculation of value within the biosphere whereas technical cycles promote value retention mechanisms such as reuse, repair, and recycle. Circularity is fulfilled if the products within these cycles are sustained at their highest utilities with minimal loss to negative externalities. Scales of implementation are classified into micro (product level), meso (eco-industrial parks) and macro scales (cities). For macro scale implementation, the complexity of the agenda overlaps to the redesigning of entire industrial, infrastructural, cultural, and social systems to achieve the ultimate vision of eco-cities (Ghisellini et al, 2016). Current circular practices, however, are limited to micro scale intervention strategies (e.g. promoting sustainable product design) while meso-macro scales of implementation remain vastly unexplored and inadequately managed (Levoso et al, 2020).

Circularity is highly applicable to the issues faced by the construction industry today. The industry is regarded as the largest consumers of materials globally (WEF, 2016) and largest producers of waste- with 66.2 million tonnes of construction and demolition waste generated in the UK in 2016 (Defra, 2020). These profound figures reveal material and energy inefficiency and poor waste management as the root causes of unsustainable linear activities.

For the built environment, a shift towards circularity will provide resilient infrastructure and communities against the topical issues of urban population growth, resource constraints and the climate crisis (Toyne, 2016). The dilemma of material productivity, which concerns 50% of the current resource challenge for construction, remains ever prevalent in the structural waste present in construction, operation, and end of life phases. Though the CE model is garnering acceptance in academia as a coherent strategy that responds to the resource challenge, the direction and change in practice remain insufficient for fear of industrial disruption.

To initiate the shift away from linearity and foster circular growth, significant contribution to completing the CE concept formulation is essential in preventing “divergent approaches within the field from hampering progress” (Kalmykova et al, 2018). The urgency for reformation stems from the notion that current anthropogenic impacts cannot be sustained without irreversible climate consequences, and that academics, governments and economic actors must advocate for a new economic structure to bridge prosperity across all dimensions of sustainability.

The following survey explores the initiatives available today designed to initiate transition towards circular construction as well as the limitations anticipated with replacing conventional, linear practice. The purpose of this qualitative survey is to contribute towards the development of the conceptual framework later introduced in Section 3.

Production

Acknowledging that design phases and production processes impacts sourcing, resource use and waste generation proves that the most significant opportunity to commit to circular construction practice exists right from the beginning (Foster15). The growing emphasis for project optimising strategies therefore recognises the importance of material flow and life cycles as being state-of-the-art analyses in studying circularity (Ghisellini et al, 2016). By identifying practical value retention schemes for production processes and proactively implementing these changes, the impacts down supply chains and consumers are better managed. Sustainable supply chain management presents great opportunities for circular ingenuity for management of material, information, capital flows and cooperation amongst companies- forming robust foundations for a CE (Seuring et al, 2008).

Other initiatives being developed to promote circularity in production processes include modular design, material passports and building for disassembly (material stocks). These emerging concepts, however, face challenges with policies and practice integration. For example, modular construction prefabricates building components and transports onsite for assembly and installation. Advantages include 50% reduced costs, improved productivity, time efficiency, less site-labour intensive, guaranteed quality control and reduced pollution (Kyrö et al, 2019; Mignacca et al, 2020; Munaro et al, 2020). Despite environmental and economic benefits, attitudinal, technical, financial, process, policy, and aesthetic concerns from various stakeholders continues to withhold the industry from investing in circular solutions such as this (Wuni et al, 2020). Material Passports (MP) is another example that enables the perception of buildings as material banks. Utilising MP, an inventory for recycling potential and environmental performances of materials, can serve as a powerful optimisation tool for improving present use, recyclability, and adaptable reuse of buildings (Honic et al, 2019).

Consumption/Operation

CE redefines the concept of ownership to be replaced with sharing platforms schemes, consumption of services instead of products, virtualisation, and the development of a collaborative economy (COM, 2015). A legislative example that encourages this is Green Public Procurement (GPP). This initiative takes advantage of the purchasing power from public authorities faced with an ever-increasing moral obligation to choose socially, ethically, and environmentally friendly goods, services and works (Sönnichsen et al, 2020). This incentivises governments and authorities to fund sustainable infrastructure projects with GPP in mind, thus setting standards founded under circular principles.

Some studies though, argue unsatisfactory public engagement with circular consumerism. Sharing platforms, leasing, and purchasing remanufactured goods have unpopular consumer acceptance due to poor awareness of circular programs, concerns of exploitation through sharing platforms and quality issues of remanufactured products (Kuah et al, 2020). These responses to circular consumerism stress the bigger dilemma of cultural and financial barriers. In the social, behavioural, and managerial context, cultural barriers prevalent in construction include lack of interest and engagement across the value chain and lack of collaboration between businesses (Hart et al, 2019).

Waste Management

The transformation away from a linear economy requires prioritising waste prevention as having the best environmental outcome under the waste management hierarchy. Construction waste management faces obstacles for site-level implementation for fear of programme delays and being a low priority project objective (Bakchan et al, 2019). Still, progress made with monitoring waste operations like recovery and recycling rates, incineration, and landfill has contributed to the Waste Framework Directive (Pires et al, 2019). The European Commission Directives for waste plays a key role in encouraging responsible waste collection, transport, disposal, and treatment while enforcing incentives for compliance or penalties (e.g. polluter pays and carbon constraints).

Recovery/Circularity

To better capture the fundamentals of circularity that promotes material optimisation, lifespan extension and useful end of life routes, a R0-R9 framework was studied to help develop the recovery criteria of the framework. The R0-R9 offers a hierarchy for recovery strategies that expands on the usual 3R's rubric: reduce, reuse, and recycle (developed by Potting et al, 2017). The hierarchy aligns with the principle of cascading (a notion derived from CE fundamentals) which is understood to be consecutive resource circulation that contribute towards higher resource efficiency (Campbell-Johnston et al, 2020).

From the survey, despite possessing the scientific and technological developments that offer solutions for circular construction practices, there are still weaknesses in its feasibility. Owing to prominent barriers hampering the effectiveness of implementation and the lack of supporting policies, it proves "public attitude and behaviour determine the extent to which policies are effective" (EASAC, 2016). Currently, there is no unified CE framework for engineers to use in the construction market. Therefore, this paper is to establish a new framework that collates and organises feasible circular solutions to be implemented across various points in the building cycle.

2. Methodology

2.1 Framework development

The objective of this study is to propose a new framework for CE implementation for construction (Figure 1). Through policy analysis, a unified assessment framework was developed which translates sustainability science research into legislation designed to implement and measure progress towards circularity (Turnheim et al, 2020; Momete, 2020). This study, which initially explored emerging circular and sustainability strategies, now sees it organised into five phases of the construction process acting as key intervention points (Production, Consumption/Operation, Waste Management, Recovery/Circularity, and Innovation). Under these intervention points, strategies and policies that are most impactful in delivering circular change are proposed (e.g. promoting modular design during production stage).

161 **Figure 1: Circular Economy Framework for construction developed in this study**

2.2 Developing quantitative tools with a life cycle approach

Transparent and accurate scientific study of the environmental and economic performances of products and services across the value chain and service lives can be performed through life cycle assessments and costing (LCA and LCC) (Boer et al, 2020). While both serve as modern cost management tools, LCA are concerned with the environmental impacts of processes and products (e.g. emissions activity during the product/service lives) whereas LCC accounts for expenses during the product/service lives (Atia et al, 2020; Honic et al, 2019). Quantitative tools proposed in this study use LCA and LCC for:

- Quantifying embodied carbon emissions of construction at production and manufacturing stage
- Cost estimations for processes of acquiring raw materials to its construction.
- Scoring waste impacts of various end of life routes and how this can indicate transition towards circularity for modern waste management.
- Scoring circularity potential of construction materials to measure implementation progress at micro level and across the material's life cycle.

2.3 Embodied carbon calculator

Embodied carbon (EC) is the emissions footprint from extracting, manufacturing, and transporting building materials onto site. Unlike operational carbon (the carbon load used to heat, power, and maintain buildings), EC is still yet to be formally regulated within building standards. Recent advances have prioritised the reduction of operational carbon through energy efficient and intelligent building design as well as schemes to decarbonise the energy grid but EC remains a major contributor to building emissions and currently accounts for 11% of all global GHG emissions (UN, 2017). Hence, EC becomes a necessary metric for measurement to facilitate better management of emissions in projects.

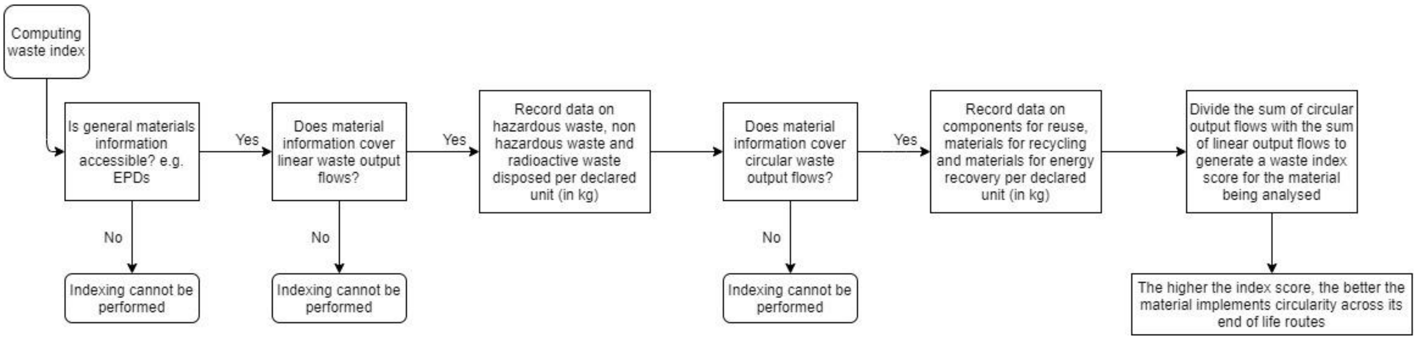
A register for raw materials and their associated carbon and energy load is an effective approach to quantifying environmental impacts of production processes, a boundary referred as cradle-gate. This study developed an EC calculator on Excel for common materials which sourced EC values from the Inventory of Carbon and Energy Database (Jones et al, 2019). The computation requires inputting material volumes used in construction which is multiplied with the material density and its corresponding EC value (tCO2e/tonne) to calculate total EC emissions (tCO2e). This analysis is valid in measuring circularity progress because it uses raw material parameters. Thus, materials with lower EC tend to implement circularity better due to reduced virgin feedstock use (Giama et al, 2020).

This calculator tool can also be purposed to simulate emissions count for circular-alternative designs, thus allowing comparisons of environmental impacts of the baseline (the client's initial specimen design) and a circular-alternative (to be proposed during conceptual design). Therefore, potential savings of materials, emissions, and feasibility assessments of adaptive designs that instead, tends towards sustainable and circular practices, can be exmined. Designers must undertake these obligations to attract clients towards more green, economic, and valued engineering options.

2.4 Waste indexing calculator

A database for indexing circular output flows against waste lost to negative externalities was developed in this study and applied to a catalogue of common construction materials. Since large waste operations are associated with construction, this indexing tool presents an opportunity to measure progress of the industry's implementation of the circular principle of eliminating waste. It achieves this by calculating the ratio of components recirculated at end-of-life against components linearly disposed for all construction materials in the database (Figure 2). The higher the calculated waste index value for a material, the better its end-of-life routes implements circularity since its rate of circular output flows is higher than linear disposal flows. If more materials used in construction can progress towards obtaining higher waste indexes, it suggests that the industry is also progressing towards implementing practices that dissociates from the linear waste concept and its conventional disposal routes. Material end-of-life data was collected from numerous Environmental Product Declaration (EPDs) forms which separates linear end-of-life waste routes from end-of-life routes in favour of circularity.

Figure 2: Flowchart on computing material waste index



2.5 Material circularity indexing calculator

A database for circularity indexing was developed to indicate how well materials implement circularity across their life cycles. This method explores the notion of inherent circularity (first introduced by Saidani et al, 2019) which is a measure of the proportion of recirculated material within a product. The database was formed using materials information collected from EPDs and materials database from CES software. All data covered in the index formulation include renewable primary energy (MJ), non-renewable primary energy (MJ), secondary material (kg) and suitability to end-of-life routes of reuse, upcycling, downcycling, incineration with energy recovery, landfill, and biodegradability. This study's proposed circularity index credits each operation with a +1 if the contribution to CE is positive and -1 if not. This crediting system is summarised in Table 1. Equation 1 presents the formula developed in this study to calculate circularity index.

Table 1: Crediting system summary for circularity index formula developed in this study

Criteria for positive circular credit (+1)	**Criteria for negative circular credit (-1)**
Higher use of renewable primary energy compared to non-renewable primary energy (RPE)	Higher use of non-renewable primary energy compared to renewable primary energy (NPE)
Reuse of secondary material (SM)	Incineration with energy recovery (IwE)
Reusable (R)	Landfill (L)
Upcycling (UC)	
Downcycling (DC)	
Biodegradable (B)	

$$Circularity\ index = \left[\frac{(RPE + SM + R + UC + DC + B) + (NPE + IwE + L)}{No.\ of\ operations\ covered}\right]$$

Equation 1: Formula developed in this study to calculate circularity index

3. Case study

To study the feasibility of the proposed new framework in a real construction project, a case study is applied against it.

3.1 Lambeth Bridge, London

The pilot case study is on the Lambeth Bridge, spanning 236.5m, with steel arches and piers and abutments of reinforced concrete. Bridge design was selected for exploration as it represents large scale infrastructure projects of long design lives, long economic investments, high material tonnages, high emissions and waste operation impacts, high reuse and recycling potential and finally, high demands for collaborative engagements from diverse stakeholders. The new framework was implemented in this case study at a reduced scale as specified in Figure 3. Criteria selected for the case study application involves quantification of EC emissions, costing analysis with a R0-R9 framework, waste and circularity indexing and further recommendations for innovation.

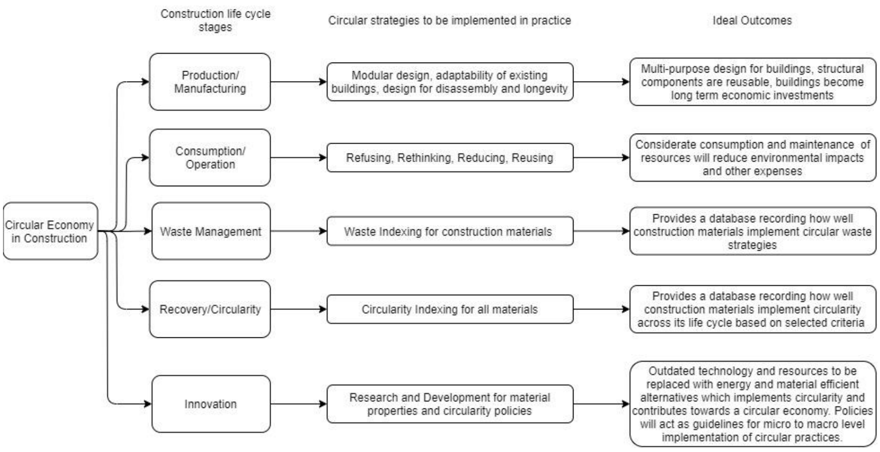


Figure 3: Proposed framework to be implemented in case study

The structural drawings of the existing bridge dating back from 1930s were accessed from the London Metropolitan Archives. The bridge design was analysed by manually extracting dimensions and materials information from general arrangement and section drawings. Cross-sectional areas of the bridge components (e.g. deck, piers, abutments) were measured and multiplied with its width to obtain volumes and materials were determined through the drawing's annotations. Table 2 provides a volumes summary for each bridge component and the materials used.

Table 2: Summary of material volumes from structural drawings

Bridge component	Material information	Material volume (m^3)
Bridge deck	Reinforced concrete deck	**1700**
	Asphalt road base	**318.6**
Pier 1	Reinforced concrete	**1019**
	Granite	**16.2**
Pier 1 foundation	Steel caisson	**13.5**
	Concrete	**931.5**
Pier 2	Reinforced concrete	**1486**
	Granite	**16.2**
Pier 2 foundation	Steel caisson	**13.5**
	Concrete	**931.5**
Pier 3	Reinforced concrete	**1486**
	Granite	**16.2**
Pier 3 foundation	Steel caisson	**13.5**
	Concrete	**931.5**
Pier 4	Reinforced concrete	**1019**
	Granite	**16.2**
Pier 4 foundation	Steel caisson	**13.5**
	Concrete	**931.5**
West abutment	Reinforced concrete	**3898**
	Sheet piles	**6.12**
	Granite	**7.4**
East abutment	Reinforced concrete	**4845**
	Sheet piles	**5.4**
	Granite	**6.2**
Steel arches	Steel sections	**2034**

Equation 2: Example calculation for composite concrete deck slab for bridge deck

$$\text{Dimensions: length} = 236\text{m; width} = 18\text{m; depth} = 0.4\text{m (measured from section drawings)}$$

$$\text{Total volume of reinforced concrete used for constructing bridge deck} = \text{length} \times \text{width} \times \text{depth}$$

$$\text{Concrete deck slab volume} = 236 \times 18 \times 0.4 = 1700\text{m}^3$$

3.2 Baseline and circular embodied carbon results

Baseline EC emissions of the case study were measured using the calculator. Material tonnage is calculated then multiplied with its corresponding EC value (sourced from the Inventory of Carbon and Energy Database) to generate a total emissions count. Table 3 summarises the baseline EC emissions from the case study. A similar method was followed for the circular scenario that instead uses low carbon alternatives. Table 4 details the materials substitution and projected emissions.

Table 3: Baseline embodied carbon emissions for a cradle-gate LCA boundary

Material	Volume (m^3)	Density (tonne/m^3)	Embodied carbon per unit (tCO2e/tonne)	Embodied carbon emission (tCO2e)
Concrete (CEM I)	19,179	2.4	0.161	7,410.8
Steel	2,099.5	7.7	1.27	20,531.0
Granite	78.4	2.7	0.70	148.2
Asphalt (4.5% binder)	318.6	1.7	0.00532	2.9
Total baseline embodied carbon emissions, tCO2e				**28,093**

Equation 3: Example calculation for total EC emissions from CEM I (RC 35/45) concrete

$$\text{EC emissions} = \text{Volume} \times \text{Density} \times \text{EC value} \qquad \text{EC emissions} = 19{,}179 \times 2.4 \times 0.161 = 7{,}410.8\ \text{tCO2e}$$

Table 4: Projections of circular-alternative embodied carbon emissions

Material	Volume (m^3)	Density (tonne/m^3)	Embodied carbon per unit (tCO2e/tonne)	Embodied carbon emission (tCO2e)
Concrete (25% GGBS replacement)	19,179	2.4	0.129	5,937.8
Steel	2,099.5	7.7	1.27	20,531.0
Granite replacement	78.4	2.7	0.09	19.1
Asphalt (3% binder)	318.6	1.7	0.00501	2.7
Total circular embodied carbon emissions, tCO2e				**26,490.6**

Equation 4: Example calculation for total EC emissions from 25% GGBS (RC 35/45) concrete

$$\text{EC emissions} = \text{Volume} \times \text{Density} \times \text{EC value} \qquad \text{EC emissions} = 19179 \times 2.4 \times 0.129 = 5{,}937.8\ \text{tCO2e}$$

3.3 Baseline and circular cost analysis outputs

Baseline costing was computed by multiplying material volumes with unit cost (sourced from CES materials database) to obtain the actual cost in GBP (Table 5). The same approach was completed for the circular scenario costing, but the rates were sourced for material substitutes with greater recycled/replacement content. Table 6 details costing for alternative materials.

Table 5: Baseline costing through material substitution

Material	Volume (m^3)	Cost per unit (£/m^3)	Cost (£)
Concrete (CEM I)	1,9179	66.8	1,281,157.2
Steel	2,099.5	1,598	3,355,001
Granite	78.4	1,080	84,672
Asphalt	318.6	33.4	10,641.24
TOTAL COST, £			**4,731,471.44**

Equation 5: Example costing for total EC emissions from CEM I (RC 35/45) concrete

$$\text{GBP value} = \text{Volume} \times \text{Unit material cost} \qquad \text{GBP value} = 19{,}179 \times 66.8 = 1{,}281{,}157.2\ \text{GBP}$$

Table 6: Circular-alternative costing

Material	Volume (m^3)	Cost per unit (£/m^3)	Cost (£)
Concrete (30% GGBS replacement)	1,9179	38.42	736,857.2
Steel	2,099.5	Average scrap steel price per tonnage was used (£130/tonne)	2,101,599
Replace granite for limestone	78.4	1,080	84672
Asphalt	318.6	33.4	10,641.24
TOTAL COST, £			**2,933,770**

Equation 6: Example costing for total EC emissions from 25% GGBS (RC 35/45) concrete

$$\text{GBP value} = \text{Volume} \times \text{Unit material cost} \qquad \text{GBP value} = 1{,}9179 \times 38.42 = 736{,}857.2\ \text{G}BP$$

4. Discussion of case study results

The results of the case study will be explored in this section.

4.1 Embodied Carbon saving through the framework

An environmental impacts assessment of the case study was completed with the implementation of the framework's production criteria of 'Quantifying Embodied Carbon'. Comparison of the case study's baseline and circular emissions proves that implementing circularity in construction offers opportunities for carbon savings and data obtained from this quantitative tool demonstrates this (see Figure 4).

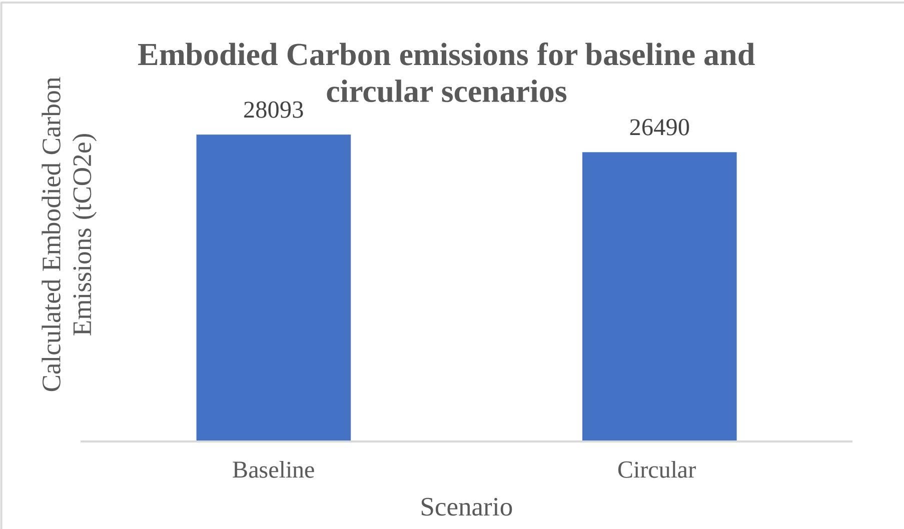


Figure 4: Summary of Embodied Carbon emissions for baseline and circular scenarios

The case study's baseline EC emissions totalled to 28,093 tCO2e. Measuring EC footprints of existing infrastructure captures the prerequisite of improving data collection of quantified environmental impacts and monitoring which buildings/infrastructure are accountable for the greatest impacts. This assessment allows designers to understand which factors (e.g. material type, material tonnage, material properties) contribute most to increasing emissions footprint, and how this can be pre-empted by considering substitutes. The proposed circular-alternative design was calculated to emit 26,490 tCO2e which offers emissions savings of 1,603 tCO2e or a 6% reduction from the baseline.

Although the percentage savings can be criticised as insignificant, it is noted there were no EC value representative of recycled steel so the baseline values were reused. Virgin steel is responsible for significant emissions and the lack of EC value data for low-carbon steel withheld the circular scenario from obtaining higher carbon savings. For concrete, there was a 20% reduction in EC emissions by substituting CEM I concrete with 25% GGBS replacement. Production of Portland clinker is estimated to be responsible for 50% of CO2 emitted by the cement sector. Nevertheless, any net reductions of EC emissions is an encouraged step and deserving of commendation for implementing circularity to reduce environmental impacts.

4.2 Material Consumption saving through the framework

Comparison of the case study's baseline and circular costing proves that implementing a R0-R9 framework that is aligned with circularity has potential for both environmental and economic savings (see Figure 5).

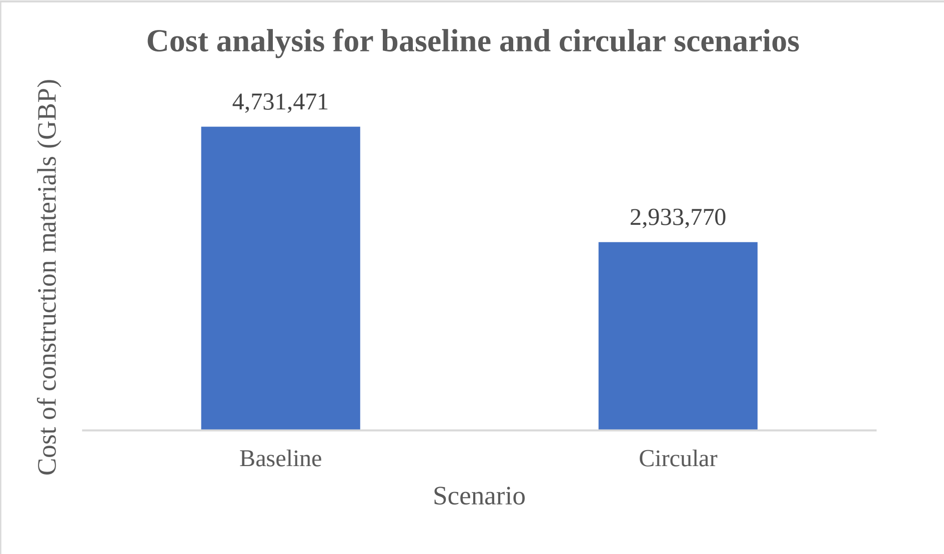


Figure 5: Summary of costings for baseline and circular scenarios

The case study's baseline costing totalled £4,731,471. The actual project value is unknown but the equivalent cost of constructing this bridge in the 1930s would be £3,218,710 today. The discrepancy worth £1,512,761 could be due to overestimations of the bridge dimensions, considering data was manually extracted from structural drawings alone, which would affect the tonnage of material calculated and therefore the final pricing.

Alternatively, the circular design estimates a budget of £2,933,770 which totals economic savings of £1,797,701- a 38% reduction from the baseline price. Without changes to the project's structural dimensions, cost savings were made possible through material reconsideration. This was achieved by specifying for concrete with 30% GGBS replacement, which was also cheaper priced and replacing granite finishes with limestone that is cheaper to supply and does not detract from desired aesthetics.

Conducting a costing analysis with a project that employed conventional, linear construction and comparing it with a modelled circular design, allows the inference that adopting circularity in construction projects can result in profound cost savings.

4.3 Waste management through implementing waste indexing

Waste indexing was implemented under the framework's waste management criteria. To interpret the index scores for each material, the higher the value, the better the material implements circularity since its circular output flows are higher than its linear waste outputs (see Table 7). Applying this to the case study indicates on how well circularity strategies are implemented in its waste management processes.

Table 7: Waste index scores for materials used in the case study

Material	Linear output flows (kg)			Circular output flows (kg)			Waste index
Declared unit: 1tonne	Hazardous waste	Non-hazardous waste	Radioactive waste	Components for reuse	Materials for recycling	Materials for recovery	
Concrete	0.03	136.24	0.023	0.00	903.95	0.00	6.63
Steel	0.00	127.00	0.00	0.00	890.00	0.00	7.01
Granite	0.50	115.00	0.00	-	-	-	0.00
Asphalt	0.001	24.31	0.003	0.00	960.00	0.00	39.5

The case study's index scores for concrete, steel, and asphalt suggests good potential for circular waste management since material recycling is the more popular end-of-life route. For a declared unit tonne of material, asphalt scores highest owing to being the most recyclable material with minimal loss to externalities. This information is key in projecting waste operations of construction projects at the end of its design life.

It shows good recycling potential for concrete, steel, and asphalt but to improve its implementation of circular waste management, its end-of-life routes should be more inclusive to reuse and recovery pathways. Reductions in the linear waste disposal also helps to improve materials waste index scores.

4.4 Recovery/Circularity: Implementing circularity indexing

To interpret the circularity indexing under the framework's recovery/circularity criteria, positive values favours circularity and negative values otherwise. This is applied to the case study to determine effectiveness of circularity strategies across the materials' lifecycles. Table 8 summarises the circularity index scores for the case study's construction materials and the coefficients inputted in the formula for calculation.

Although the scores are positive to suggest some degree of circularity, strong favour towards circularity in material LCAs is not evident. It verifies that more circular progress in materials lifecycles are needed to accelerate a shift towards circularity and improve scores. Nevertheless, the indicators applied covers a range of circularity factors from types of energy sources used during production to secondary materials and end-of-life routes, positioning its validity in measuring materials circularity on a micro-scale using a lifecycle approach. The intention of this circularity indexing tool is to holistically cover aspects of secondary market formation, collaboration between manufacturers and recyclers as well as implementing value retention techniques across material lifecycles (Rahman et al, 2020). The information obtained from these results emphasises that more effort is needed to improve circularity at larger and stronger scales from a materials performance perspective.

352 **Table 8: Circularity index scores summary for case study**

Material	Renewable energy resources	Non-renewable energy resources	Secondary materials	Reuse	Upcycle	Downcycle	Incineration with energy recovery	Landfill	Biodegrade	No. of operations covered	Circularity index
Concrete	0	-1	1	1	1	1	-1	-1	0	9	**0.11**
Steel	0	-1	1	1	1	1	-1	-1	0	9	**0.11**
Granite	0	-1	1	1	0	1	-1	-1	0	9	**0.00**
Asphalt	1	0	0	1	1	1	-1	-1	0	8	**0.25**

5. Recommendations

Based on the qualitative survey research and case study conducted, the following are recommendations on how to improve circular performance in construction.

5.1 Adaptive reuse of buildings

Renovation, refurbishment, retrofitting, and reuse projects reap the benefits of saving up to 70% of EC emissions, instead of building new (AIA, 2017). The potential to extend useful lifespans, remediate brownfields and restoring value to poor-performing infrastructure yields enormous benefits of preserving emissions and materials, improving land use management, reflecting the changing needs of communities, revitalising cities and so forth (Foster, 2020).

5.2 Conscientious selection of materials

As in the report's findings, specifying concrete mixes with lower carbon impacts and higher cement replacements (e.g. fly ash or blast-furnace slag) can significantly reduce EC emissions. Other forms of cement content savings can be achieved through use of higher-quality aggregates and reducing water content (CCC, 2018). Organisations must strive to comply with BES 6001 in responsible sourcing of concrete by opting for low carbon footprint specifications, local suppliers, and shorter supply chains (Concrete Centre). Using materials with higher recycled content reduces demand for virgin resource extraction, promotes material value retention within its system and reduces EC emissions.

5.3 Innovation: Using automated tools to aid circular implementation

The construction sector's slow adoption of the fast-evolving technological advances within its field risks regression of opportunities that drives circular transition. BIM has vast capacity to perform analyses to optimise building systems yet remains an underutilised tool. Two suggestions of other uses that aid circular progress include a Whole-life Performance Estimator (BWPE) and as a Construction Waste (CW) Estimator. A study from Akanbi et al. (2018) developed BWPE to appraise the salvage potential of structural components from design stages to influence initial decisions making from designers and final decisions making from consultants when generating pre-demolition audits. Applying BIM as a CW estimator allows information on building systems to scope CW disposal scheduling, cost estimation, onsite reuse, and waste streams sorting (Bakchan et al, 2019). This tool can help oversee opportunities for cost savings from reuse and recycling processes and identifying percentage errors between estimated and actual waste quantities. Both schemes guide the decisions making of construction practitioners for better CWM and resourcefulness.

6. Conclusions

This study developed a new CE framework that outlines actions plans to be implemented across all stages of a building cycle. This was supported by a feasibility study of integrating a CE framework in a real construction project. It identified the challenges of replacing conventional, linear practices and raised awareness of its potential to bridge all dimensions of sustainability. The CE model demands an accelerated transition in order to mitigate the climate emergency and other prominent issues on resource and energy security, aging infrastructures, pollution, and the increasing development gap. Regardless of technological advances, the success of adopting a CE model is largely dependent on supporting policies and the cooperation of stakeholders involved. Without these enabling conditions, the identified barriers will only continue to hurt progress towards circularity. A thorough qualitative assessment was achieved by exploring factors that influence the extent to which CE policies are implementable. The outcome ultimately favours the argument that the positive impacts of circularity outweigh its challenges. Applying the framework to a real construction project allowed for the following to be ascertained:

(1) It evidenced the applicability of circularity practices within industry.

(2) It demonstrated the functions of the quantitative tools developed where its outputs measured circularity progress and allowed for monitoring the status of CE implementation.

(3) The outcome of the results suggests that while there is some implementation of circularity in practice (mainly recycling schemes), there is still a major lack of circular initiative in areas proven to have abundant potential for environmental and economic savings.

To conclude, the policies and recommendations offered and the development of a CE framework most fitting for industry purpose helped to form a concerted effort in guiding the direction of change needed for improving implementation policies. The findings reclaim the confidence in circular economics being the viable and holistic solution to unsustainable linearity.

7. Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request

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