From Linear to Circular: Implementing Digital Product Passports to Enable Data-Driven Circular Lifecycle Transitions in the Built Environment

Alireza Moghayedi, UK and Bankole Awuzie, South Africa

ABSTRACT

The built environment remains a major contributor to global carbon emissions and construction and demolition (C&D) waste, largely due to the dominance of linear lifecycle models and static assessment methods such as cradle-to-grave Life Cycle Assessment (LCA). This paper proposes a comprehensive framework to support the transition toward a circular, cradle-to-cradle lifecycle in built environment projects, centred on the use of Digital Product Passports (DPPs). By analysing the full lifecycle, from raw material extraction to end-of-life and beyond, the study maps critical data flows, identifies purpose-driven data types, and classifies the digital tools required for data collection, processing, storage, and sharing. A novel contribution of this work is the integration of emerging technologies, including BIM, IoT, AI, digital twins, robotics, XR, and blockchain, linked to stakeholder roles and lifecycle stages. The resulting framework establishes a closed-loop information system that enables forward and backward feedback loops, enhancing decision-making, traceability, reuse, and circularity. This conceptual study lays the groundwork for implementing DPPs in practice and highlights their potential to engender sustainability outcomes across the built environment.

Keywords: Circular Economy, Digital Product Passports, Built Environment, Lifecycle Data Management, Sustainable Construction

1. INTRODUCTION

The built environment significantly contributes to climate change, resource depletion, and waste generation, accounting for nearly 39% of global energy-related carbon emissions (Moghayedi & Awuzie, 2025). Approximately one-quarter of these emissions are attributed to embodied carbon from materials and construction processes (WGBC, 2021). In the UK, embodied carbon alone represents roughly 20% of the built environment's total emissions (UKGBC, 2023). Alongside this, the sector is a leading source of waste: in 2020, the UK generated approximately 59.4 million tonnes of non-hazardous C&D waste, of which several million tonnes still ended up in landfill despite reported recovery rates exceeding 92% (DEFRA, 2022).

Conventional cradle-to-grave Life Cycle Assessment (LCA) models support the linear approach dominating the built environment, resource extraction, use, and disposal, often relying on averaged, static data that fails to account for reuse, refurbishment, or degradation across time (Samani, 2023; Incelli et al., 2023; Pristerà, et al., 2025). This leads to systemic inefficiencies, including single-use treatment of materials, weak feedback loops, and limited CE-oriented decision-making support across lifecycle stages. These limitations severely constrain the ability

to optimise carbon neutrality performance, reduce waste, and extend the lifecycle of materials. In response, the shift from cradle-to-grave to cradle-to-cradle models is gaining momentum. CE strategies emphasise closing material loops, maximising resource value, and designing for adaptability, reuse, and regeneration. Implementing such strategies in the built environment requires continuous and interoperable data flows across lifecycle stages, enabled by digital tools that can track materials, monitor conditions, and inform second-life decisions in real time. A critical enabler of this paradigm is the Digital Product Passport (DPP), a structured digital repository that stores and updates essential information about a product's composition, provenance, performance, and sustainability credentials throughout its lifecycle.
To address these challenges and opportunities, this study proposes a comprehensive process framework to support the transition from linear to circular lifecycle practices in the built environment, centred on the operationalisation of DPPs. The specific objectives of this paper are to:

- Identify critical data and information flows across all lifecycle stages to support circularity.
- Define key data types and purposes for each stage and activity.
- Map enabling digital tools for data collection, processing, storage, and sharing.
- Develop an integrated lifecycle framework to operationalise DPPs and feedback loops.
- Align stakeholder roles with their data needs and supporting digital technologies.

This paper offers a distinct contribution by proposing an integrated, dynamic, and stakeholder-informed approach to lifecycle management in the built environment. It advances the discourse beyond traditional carbon-centric or end-of-life focused studies by introducing a data-purpose-tool triad that spans all lifecycle stages, including post-demolition recovery and second-life planning. By incorporating emerging and underutilised technologies, the framework operationalises DPPs not as static checklists but as interactive, evolving platforms. This positions DPPs as enablers of circular value creation, supporting decisions that are grounded in real-time data, interoperable systems, and long-term lifecycle intelligence.

2. LITERATURE REVIEW

2.1 Data-Driven Circular Economy Transitions in the Built Environment

The transition from linear to circular economy (CE) models in the built environment is widely recognised as critical for achieving net-zero targets, conserving resources, and reducing construction and demolition (C&D) waste. Unlike the traditional "take–make–dispose" paradigm, CE promotes material retention through strategies such as reuse, remanufacturing, and high-value recycling (Ho et al., 2024). This shift demands systemic changes in how buildings are designed, constructed, operated, and deconstructed, reimagining them as material banks rather than waste sources (Pomponi & Moncaster, 2017).
Circular construction practices, including design for disassembly, modularity, and material passports, have been shown to significantly reduce environmental impacts. For instance, the reuse of structural materials can lower embodied carbon by 20–30% across European contexts (Thakuri et al., 2025). However, despite supportive policies like the EU Circular Economy

Action Plan (European Commission, 2020), implementation remains fragmented, particularly at end-of-life stages.

Effective information management has emerged as a critical enabler of circularity (Al-Qazzaz, 2025). Beyond technical innovations, circular strategies depend on timely, accurate, and accessible data across lifecycle stages. Studies emphasise the need to move beyond static LCAs and adopt dynamic, performance-based data models that account for material degradation, repair history, and reuse potential (Moghayedi et al., 2025).

To support this, scholars propose reconceptualising data flows across the building lifecycle, from early design and procurement to reuse and recovery. Key data types include:

- Material provenance: Information on composition, source, and certifications, crucial for reuse and compliance (Ho et al., 2024);
- Durability and performance: Data on service life, maintenance, and degradation to support lifecycle costing (Balasbaneh et al., 2025);
- End-of-life data: Details on disassembly, component condition, and recovery logistics (Moghayedi & Awuzie, 2023);
- Environmental metrics: Carbon, water, and toxicity data tracked beyond manufacturing stages (Thakuri et al., 2025).

These data types serve multiple CE functions, enabling carbon accounting, early-stage design decisions, reuse forecasting, regulatory compliance, and stakeholder coordination.

However, achieving such integration requires bidirectional data flows, where information from demolition or in-use monitoring feeds back into design, procurement, and policy (Ma et al., 2022). Current digital tools often lack this feedback functionality, creating fragmented knowledge systems and missed learning opportunities.

In response, the literature has increasingly pointed to DPPs and associated digital technologies (e.g., BIM, IoT, digital twins) as mechanisms for enabling continuous, verifiable, and standardised data flows across stakeholders and stages. These tools can act as lifecycle "backbones," linking actors and decision points via shared, structured information systems (Thakuri et al., 2025). The transition to circularity in the built environment is inseparable from the evolution of data practices. Unlocking circular value requires not only design and material innovation but also a robust infrastructure for tracking, analysing, and sharing data throughout and beyond the building lifecycle. A comprehensive understanding of what information is needed, when, by whom, and for what purpose, is fundamental to this transformation, and forms the basis for the operationalisation of DPPs and digital lifecycle management frameworks discussed in subsequent sections.

2.2 Digital Product Passports: Enabling Transparency and Circularity Across the Building Lifecycle

As the construction sector transitions toward CE principles, the need for transparent, dynamic, and interoperable information systems has become increasingly evident. Among the emerging tools designed to support this transition, DPPs are structured, evolving digital records that track key information like material composition, carbon footprint, and reuse potential, throughout a component's lifecycle. Unlike static tools like Environmental Product Declarations (EPDs), DPPs enable real-time feedback loops that inform design, construction, and deconstruction decisions (Kebede et al., 2024).. This dynamic nature enables DPPs to serve not only as documentation tools but as enablers of feedback loops, fostering more informed design, construction, and deconstruction decisions.

From a regulatory standpoint, DPPs are being actively integrated into European Union policy frameworks. The Ecodesign for Sustainable Products Regulation (ESPR) and the revised Construction Products Regulation (CPR) both promote the use of DPPs to support compliance with sustainability, recyclability, and embodied carbon standards. These policies form part of the broader EU Green Deal and Circular Economy Action Plan, which aim to embed circularity into product design, construction practices, and supply chains (European Commission, 2020). In line with these goals, several EU-backed initiatives such as CIRPASS and the Buildings as Material Banks (BAMB) project, have developed pilot DPPs that connect physical components to their digital identities using QR codes, RFID tags, or blockchain-based identifiers. These pilots test real-world integration into Building Information Modelling (BIM), supply chain platforms, and facility management systems within the built environment context (European Commission, 2020; European Commission, 2023). Use cases include automated compliance verification, lifecycle impact tracking, and support for reuse planning during renovations or demolitions. In addition to formal DPPs, material passport systems such as Madaster and Concular offer complementary approaches, digitising building inventories to enable more sustainable asset management. These platforms focus on component-level documentation, such as geometry, material type, condition, and disassembly potential, essential for high-value recovery in retrofit or adaptive reuse projects (Kebede et al., 2024). While these systems vary in scope and structure, they collectively highlight the growing ecosystem of digital tools aimed at advancing circular construction practice.

Despite growing momentum, however, the widespread adoption of DPPs still faces significant technical and institutional challenges:

- Data Standardisation and Interoperability: Many DPP initiatives operate with varying data models, terminologies, and structures, which limit their interoperability across platforms and lifecycle stages. Without harmonised data schemas and protocols, the risk of fragmentation increases, undermining the core objective of lifecycle integration (Kebede et al., 2024).
- Data Availability and Maintenance: Effective DPPs require continuous updates as products evolve through use, repair, or disassembly. However, maintaining high-quality, real-time data across multiple actors and over extended timescales remain technically and operationally demanding, particularly for second-life components, where performance and condition data may be incomplete or unreliable (European Commission, 2020).
- Implementation Complexity and Cost: While regulations are advancing, many firms lack clear guidance on how to embed DPPs into existing workflows. Integration with BIM, IoT, and enterprise resource planning (ERP) systems requires new technical capacities, while concerns over data security and commercial confidentiality present further barriers (European Commission, 2023; Ma et al., 2024).
- Stakeholder Engagement and Trust: For DPPs to be effective, all actors across the value chain, from material producers to demolition contractors, must participate in data

sharing and stewardship. However, current business models rarely incentivise such collaboration. Emerging frameworks suggest the need for verifiable credentials, decentralised identity systems, and shared governance models to build trust and ensure equitable data ownership (Kebede et al., 2024).

These challenges point to the need for a robust, multi-actor, and system-integrated framework for DPP deployment in the built environment. Such a framework must align technical requirements with regulatory mandates, provide incentives for data stewardship, and promote interoperability with other digital tools. In doing so, DPPs can evolve from isolated pilots to central enablers of intelligent, circular lifecycle management, transforming how buildings are designed, constructed, used, and reused.

2.3 Digital Technologies as Enablers of Circular Lifecycle Integration

The transition to circularity in the built environment is deeply dependent on digital technologies that support the continuous collection, processing, and sharing of data throughout the building lifecycle. These tools underpin Digital Product Passports (DPPs), enabling real-time traceability, feedback loops, and cross-stakeholder coordination essential for circular construction. While no single technology is sufficient on its own, an integrated system of digital solutions is required, each contributing to sensing, modelling, automation, intelligence, governance, or interaction (European Commission, 2023).

Core Digital Infrastructures: BIM, IoT, and Digital Twins

Building Information Modelling (BIM). This remains foundational, offering object-based digital representations of built assets embedded with material, cost, and performance data. When integrated with Digital Twins, these static models evolve into dynamic, real-time systems, synchronised with physical environments through IoT sensors and other monitoring tools. Together, these technologies allow for scenario simulation, predictive maintenance, and residual value assessment, crucial for lifecycle extension and circular decision-making (Thakuri et al., 2024).

Digital Product Passports (DPPs): These act as central repositories within this system. By linking physical components to structured digital records, DPPs connect stakeholders, track materials, and support compliance with carbon and circularity standards (Kebede et al., 2024). Their effectiveness depends on integration with BIM, IoT, and supply chain platforms.

Supporting Technologies: Tracking, Automation, and Analytics

Sensing and automation technologies such as RFID, GPS, and smart meters collect data on component condition, energy use, and environmental performance. These tools are increasingly used in construction, renovation, and demolition to feed DPPs and digital twins with real-time data. Additionally, robotics and automation, including modular manufacturing, robotic demolition, and automated sorting, enhance precision and recovery rates while reducing waste (Moghayedi & Awuzie, 2023).

Advanced analytics, including AI and machine learning, further optimise decision-making. These tools process complex datasets to predict material degradation, optimise energy use, and forecast carbon impacts. For instance, AI-enabled tools can recommend reuse pathways based on historical repair data and condition assessments (Moghayedi et al., 2025).

Data Governance and Interoperability

Secure and transparent data governance is essential for scaling circular digital systems. Blockchain and distributed ledger technologies (DLTs) can verify material provenance, ensure auditability, and support decentralised access control. Cloud platforms and enterprise resource planning (ERP) systems provide shared environments for data storage and integration, while QR codes, RFID, and geospatial tags ensure the link between physical assets and their digital identities (European Commission, 2023).

Nevertheless, challenges persist. Non-standardised data formats, fragmented platforms, and siloed information flows continue to hinder interoperability. Addressing these requires unified data schemas, shared ontologies, and regulatory alignment across actors and systems.

<u>Complementary and Emerging Tools</u>

Technologies such as Geographic Information Systems (GIS), 3D scanning, and UAVs offer spatial intelligence that supports site analysis, logistics, and lifecycle tracking. Meanwhile, Extended Reality (XR) tools like Augmented Reality (AR) and Virtual Reality (VR), enhance stakeholder engagement, visualising material flows and disassembly processes in immersive ways (De Wolf et al., 2024). While valuable, these tools currently play a supplementary role and are limited in adoption across lifecycle stages.

<u>Addressing Lifecycle Integration Gaps</u>

Despite technological progress, implementation across all lifecycle stages remains uneven. Tools like BIM and IoT are well-established in design and construction, but adoption of robotics, XR, additive manufacturing, and blockchain remains limited in end-of-life and reuse contexts. Unlocking the full potential of digital technologies for circular construction will require coordinated efforts to improve integration, develop shared data standards, and strengthen capacity across the value chain.

3. METHODOLOGY

This study adopts a conceptual research design, aiming to synthesise existing knowledge and frameworks to propose a comprehensive DPP implementation framework for the built environment. The methodology is grounded in a systematic literature review, technology mapping, and theoretical integration. It combines academic literature with policy documents and pilot project evidence using a structured, multi-phase process. This approach is particularly suitable for addressing complex, multi-stakeholder problems such as transitioning from linear to CE lifecycle practices in construction, where knowledge is fragmented across disciplines, tools, and lifecycle stages (de Alcantara and Martens, 2019).

3.1 Conceptual Framework Development

The methodology followed a structured multi-phase process:

a. <u>Systematic Literature Review and Policy Selection</u>

A targeted literature search was conducted between March and June 2025 using Scopus, Web of Science, and ScienceDirect. Search strings included combinations of terms such as "circular economy," "material/product passport," "building lifecycle," "whole-life carbon," "innovative technologies*"and "construction digitalisation." Filters were applied to limit results to peer-reviewed journal articles (preferably Q1) from 2010 to 2025 in the fields of

sustainable construction, architecture, environmental engineering, and digital built environment. 124 initial records were screened, resulting in 32 academic articles included in the final review after considering the whole papers evaluation.
In addition, grey literature and EU policy documents were reviewed. 11 key documents included the Ecodesign for Sustainable Products Regulation (ESPR), Circular Economy Action Plan, Construction Products Regulation (CPR), Green Deal, and CIRPASS reports. These were selected based on citation frequency in pilot projects and relevance to DPP implementation.

a. Lifecycle System Mapping

The first phase involved the redefinition of the conventional linear building lifecycle (cradle-to-grave) into a CE lifecycle model. This included mapping stages A1–A5 (product stage), B1–B8 (use stage), C1–C4 (end-of-life), and D (beyond life) in alignment with ISO 14040 and EN 15978 lifecycle assessment standards. This step explicitly incorporated CE principles, second-life pathways, and whole-life carbon (WLCA) considerations, allowing materials and products to re-enter new lifecycle loops rather than being treated as terminal waste. The transition was illustrated visually through updated lifecycle Figures 1 and 2.

b. Data Flow and Information Purpose Analysis

Each activity within the lifecycle was then systematically analysed to identify what data is required, for what purpose, and at which stage to enable CE practices., including material provenance, embodied and operational carbon, reuse potential, social compliance, and environmental impact. This analysis was structured around four key data processes: data collection, data processing and analysis, data storage, and data sharing. The identification of data purposes (e.g. carbon accounting, reuse planning, regulatory compliance, stakeholder transparency) was informed by recurring themes and requirements identified across the reviewed CE, WLCA, and DPP literature. The outputs of this phase informed the development of Table 1, which links lifecycle stages, activities, and data purposes.

c. Technology Identification and Classification

Using a systematic screening of academic literature, EU policy documents, and major pilot initiatives, the study identified digital technologies capable of supporting the four data processes across lifecycle stages. Only peer-reviewed Q1 journal articles, international standards, and authoritative EU policy and pilot programme documents were considered to ensure robustness and relevance (Boell & Cecez-Kecmanovic, 2015).
Identified technologies were then classified into six functional technology categories based on their primary role in the data lifecycle: sensing and tracking technologies; digital modelling

and simulation tools; automation and fabrication technologies; intelligence and analytics systems; data management and governance platforms; and visualisation and interaction tools. This classification directly informed Table 2, which maps each technology type to relevant lifecycle stages and associated data processes.

d. Synthesis of Circular Lifecycle DPP Framework

The final phase involved integrating lifecycle stages, data purposes, stakeholder roles, and enabling technologies into a coherent DPP-enabled circular lifecycle framework. The framework explicitly illustrates forward and backward data flows, stakeholder interactions, and feedback loops required for circular decision-making. Visual artefacts, including lifecycle diagrams, technology symbols, and stakeholder–data–tool mappings (Table 3), were developed to enhance conceptual clarity and practical applicability. .

3.2 Literature Base and Review Scope

The conceptual framework developed in this study is underpinned by a broad-based review of interdisciplinary literature, encompassing theoretical, technical, and policy-oriented sources. The literature review served two explicit purposes:

- to identify recurring concepts, data requirements, and lifecycle challenges related to circular construction; and
- to extract evidence on how digital technologies are being used (or proposed) to support lifecycle data management.

Sources were selected based on relevance to:

- lifecycle-based circularity in the built environment,
- data and information flows across building stages,
- digital technologies enabling lifecycle management, and
- policy and regulatory developments related to DPPs.

As outlined above, the review included 93 academic sources and 11 major policy/technical reports where these provided insights into implementation pathways. Rather than quantifying the number of studies, the review adopted a thematic synthesis approach, focusing on conceptual convergence across sources to inform framework development (Thomas & Harden, 2008).

This inclusive review approach enabled the integration of fragmented knowledge from both scholarly and practice-based domains to identify key data requirements, CE lifecycle considerations, and relevant enabling technologies. The review process was guided by the PRISMA principles for transparency and reproducibility in evidence synthesis. Emphasis was placed on ensuring that the framework reflects not only theoretical robustness but also practical feasibility across the lifecycle stages and stakeholder groups involved in built environment projects.

4. PRESENTATION AND DISCUSSION OF FINDINGS

4.1 Rethinking Lifecycle Logics: From Cradle-to-Grave to Cradle-to-Cradle in the Built Environment

The dominant paradigm in built environment project delivery has long followed a cradle-to-grave lifecycle model, where building materials are extracted, processed, used, and then discarded, often with limited attention to resource recovery or reuse. This linear model, illustrated in Figure 1, contributes substantially to global environmental burdens.

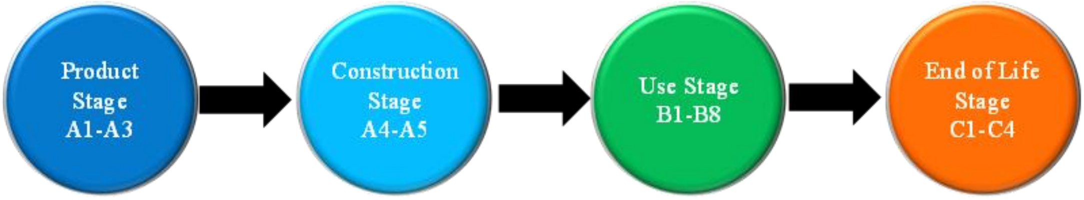

Figure 1: Linear lifecycle

As previously highlighted, buildings and construction account for a substantial share of global carbon emissions and material waste, with embodied carbon and C&D waste posing persistent challenges (WGBC, 2021; UKGBC, 2023; DEFRA, 2022). These data highlight a systemic issue: the linear model is poorly equipped to support long-term sustainability, material retention, or CE outcomes. This underscores the urgency of transitioning toward circular lifecycle practices that prioritise reuse, recovery, and emissions reduction, particularly at the material and end-of-life stages, where interventions remain limited. Even with growing adoption of LCA and WLCA, many current practices remain limited to static, one-time analyses focused on cradle-to-gate or cradle-to-site stages. As research shows, such approaches rarely account for material durability, repair cycles, or second-life applications, leading to missed opportunities for carbon savings and resource recovery (Kebede et al., 2024).

To address these limitations, this study proposes a reconceptualised CEBE (Circular Economy Built Environment) lifecycle framework, visualised in Figure 2, that redefines the building project as a dynamic and regenerative process. Informed by CE principles, this framework introduces a fourth stage (Stage D: Beyond Life Cycle) to explicitly account for reuse, repurposing, and secondary markets, concepts often excluded in conventional LCAs. The CE lifecycle framework proposed in this study is organised around four interlinked stages that together enable a cradle-to-cradle approach. Stage A represents the upfront phase, encompassing all activities from raw material extraction and transportation to manufacturing and on-site construction (A1 to A5). Stage B covers the use phase (B1 to B8), addressing aspects such as occupancy, operational performance, maintenance, repair, replacement, refurbishment, and user interaction. Stage C refers to the end-of-life phase, where deconstruction, waste processing, and disposal activities (C1 to C4) take place. Finally, Stage D, termed the beyond lifecycle phase, captures material and product reuse, repurposing, and reintegration into new construction cycles, an essential pillar of CE strategies.

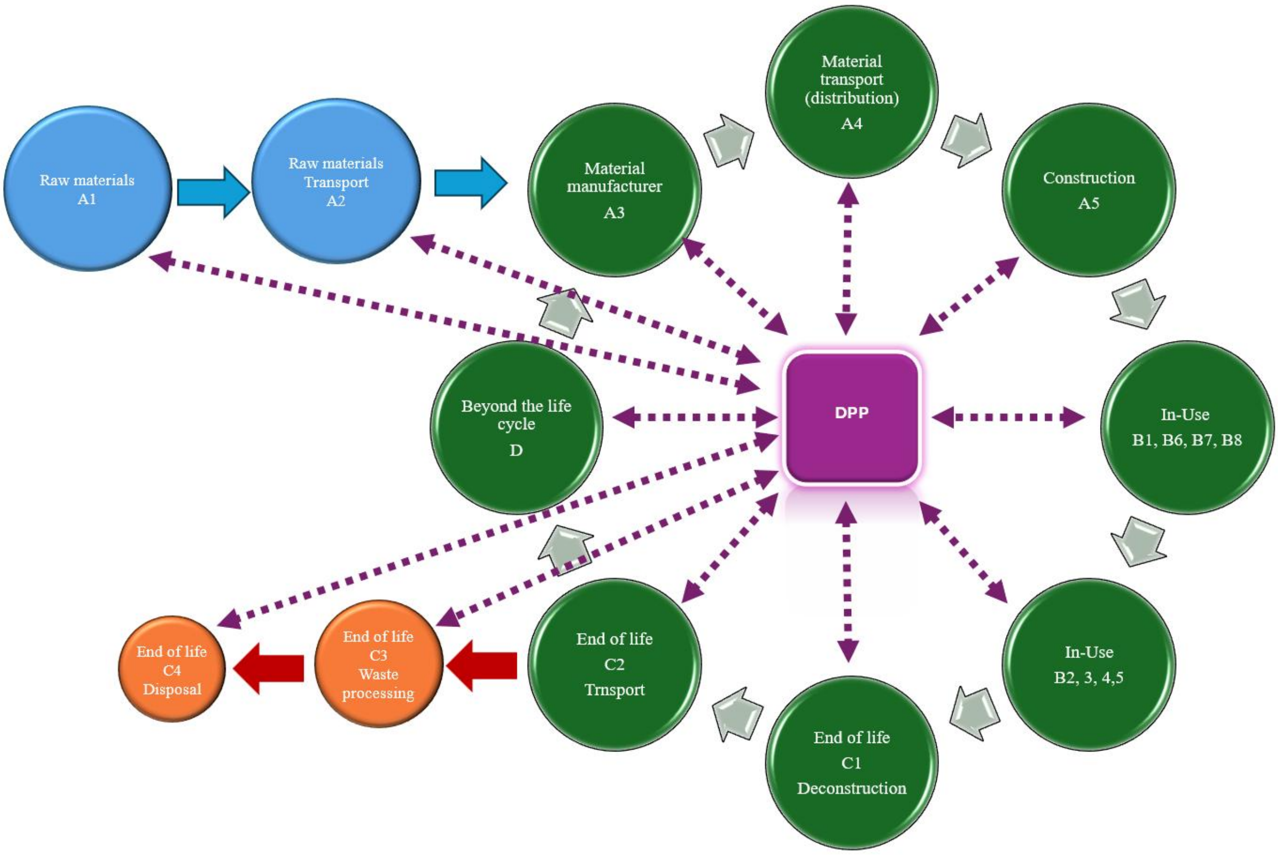

Figure 2. CEBE lifecycle framework integrating CE principles and Digital Product Passport

Unlike the linear model, the CEBE lifecycle framework introduces feedback loops where data and insights from Stage C (e.g., component condition, recovery rates) and Stage B (e.g., performance and maintenance records) inform future decisions in Stage A. This aligns with contemporary literature advocating for cradle-to-cradle lifecycle thinking that includes reversibility, reuse potential, and future material value (Moghayedi and Awuzie, 2025; Ma et al., 2022). Moreover, the CEBE framework embeds DPPs as core enablers of traceability, performance tracking, and decision support across all lifecycle phases. As supported by emerging EU policy frameworks (e.g., ESPR and CPR revisions), DPPs can facilitate data continuity beyond construction completion, offering a living repository for technical, environmental, and circularity-related attributes of materials and products (European Commission, 2023).

This reframing reflects a broader shift seen in the literature toward dynamic lifecycle governance and performance-based sustainability, where decision-making is informed not only by upfront data but also by real-time feedback during use and deconstruction stages (Thakuri et al., 2025; Samani, 2023). In this framework, value is not merely extracted and disposed of but retained, regenerated, and re-integrated into future projects, offering a systemic response to the sector's carbon and waste challenges.

4.2 Mapping Data Flows and Enabling Technologies Across the Circular Building Lifecycle

A successful transition from linear to CE practices in the built environment hinges on the ability to collect, process, store, and share data in ways that support informed decision-making at every stage of the building lifecycle. Each activity, from raw material sourcing to end-of-life and beyond, generates or requires specific types of information that are critical for enabling carbon reduction, circularity, and regulatory compliance (Ho et al., 2024).

As established in Figure 2 and detailed in Table 1, lifecycle stages (A–D) encompass distinct data purposes that must be addressed systematically. The shift from static, one-time assessments toward dynamic, continuous data flows necessitates a broader and more integrated approach to information management. While traditional LCAs often focus primarily on environmental indicators such as embodied carbon and operational energy, CEBE lifecycle framework require more granular, longitudinal data about material provenance, durability, performance, and reusability (Kebede et al., 2024).

In this context, geospatial data infrastructures (GDIs), surveying technologies (e.g., GNSS, LiDAR), and spatial standards (e.g., ISO 19115, OGC CityGML) are increasingly essential for capturing, integrating, and visualising location-specific asset information. These tools enable spatial referencing of building components, facilitate integration with cadastral and infrastructure registries, and support the traceability of materials across sites and lifecycles. Their inclusion ensures that DPPs not only function as static digital records but as spatially-aware, interoperable data carriers aligned with FIG-relevant domains.

Table 1. Data and digital technologies across building lifecycle stages to support circularity-oriented decision-making.

Lifecycle Stage			Collection	Processing	Storage	Sharing
Stage A:	A1: Raw Materials	Material traceability, certifications, social compliance	IoT Sensors, QR Codes, Blockchain	AI Analytics, LCA Tools, BIM	Blockchain, Cloud BIM, Material Passports	DPP Platforms, Blockchain, BIM Viewer
	A2: Transport	Transport emissions and energy tracking	GPS, IoT Devices, Vehicle Sensors	GIS, Carbon Tracking Tools, AI	Cloud Databases, Transport Logs	Open Transport Logs, Supply Chain Sharing

	A3: Manufacturing	Manufacturing impacts, health/safety, specs	Robotics, IoT, Environmental Sensors	AI, Digital Twins, Lifecycle Modelling	Digital Twins, Manufacturing DBs	Digital Twins, Compliance Dashboards
	A4: Distribution	Carbon footprint, packaging, logistics data	IoT, QR Codes, GPS Trackers	Supply Chain Platforms, Blockchain Analysis	QR Tag DBs, Supply Chain Repositories	QR-Based Product Info, Cloud Sharing
	A5: Construction	Construction energy, waste, H&S compliance	Robotics, XR Devices, UAVs, Smart Sensors	BIM, AI, Construction Simulation	Common Data Environments, BIM Cloud	BIM Collaboration Tools, XR Interfaces
Stage B: In-Use	B1: Use	Usage trends, occupancy rates, indoor environment	Smart Meters, Occupancy Sensors	Digital Twins, Building Analytics	Cloud Platforms, IoT Hubs	Real-Time Dashboards, Smart Displays
	B2: Maintenance	Maintenance schedules, costs, resource use	Robotics, IoT, CMMS, Maintenance Logs	CMMS Software, Predictive AI	Maintenance Systems, DPP Portals	Maintenance Reports, DPP Sync
	B3: Repair	Repair frequency, emissions, resource use	Robotics, Condition Monitoring IoT, User Logs	AI, Repair Forecasting Models	Repair Logs, Cloud Platforms	Repair Histories, Shared Logs
	B4: Replacement	Replacement rates, circular options, impact	Robotics, IoT, DPP Feedback Forms	Lifecycle Assessment Tools, AI	Asset Registers, BIM Repositories	Replacement Guidelines, DPP Portals
	B5: Refurbishment	Refurbishment scope, reuse feasibility	3D Scanners, Condition Surveys	BIM, Cost-Benefit Analysis, AI	Digital Logs, Refurbishment Platforms	Stakeholder Reports, Cloud Collaboration
	B6: Operational Energy	System performance, efficiency, peak loads	Smart Meters, IoT, BEMS	BEMS, Energy Dashboards, AI	Energy Platforms, Smart Grid Data Hubs	Energy Reports, Smart Grid Interfaces
	B7: Operational Water	Water usage, efficiency, leakage	Water Flow Meters, Leak Detection Sensors	Water Management Software, AI	Cloud Water Systems, BIM Integration	Efficiency Reports, Public Dashboards
	B8: User Activities	User behaviour, feedback, health indicators	User Apps, Feedback Surveys, IoT	Behaviour Analysis, AI Tools	User Platforms, Occupant Feedback DBs	User Portals, Feedback Sharing Tools
Stage C: End-of-Life	C1: Deconstruction	Disassembly method, material condition	Robotics, UAVs, Cameras, IoT Tags	Digital Twins, Deconstruction Models	Deconstruction Repositories, Cloud Twins	Circularity Platforms, BIM Views
	C2: End-of-Life Transport	Transport method, emissions, packaging	GPS, QR Codes, Transport Trackers	Logistics Analytics, Route Optimisation AI	Transport Logs, QR Databases	Transport Data Links, Compliance Sharing
	C3: Waste Processing	Recycling method, recovery, by-products	Smart Waste Bins, Material Trackers	Recovery Rate Analytics, AI	Waste Portals, Blockchain Storage	Recovery Dashboards, LCA Data Sharing
	C4: Disposal	Disposal method, toxicity, leachability	Disposal Reports, Compliance Logs	Toxicity Analysis Tools, LCA Databases	Disposal Registers, Compliance DBs	Compliance Tools, Public Disclosure Platforms
Stage D: Beyond Lifecycle		Reuse/repurposing, secondary markets, innovation	Material Banks, Product Registries	Circularity Analytics, Market AI	Circular Platforms, Material Banks	Reuse Marketplaces, Innovation Hubs

Stage A (Upfront): In this phase, activities such as raw material extraction and manufacturing (A1–A3) require information on material composition, geographic source, energy consumption, social compliance, and environmental certifications. These data support early decisions related to low-carbon procurement, ethical sourcing, and material circularity potential. Integration of spatial technologies is especially critical in this phase. Survey-grade GNSS systems and GIS-based material traceability platforms enable spatial tagging of raw materials and transport routes. Geospatial metadata standards (e.g., ISO 19115) ensure location-based provenance can be linked to environmental assessments and asset documentation. Digital tools reinforce these purposes: IoT sensors, QR codes, and blockchain capture provenance and certification (A1); GPS and IoT monitor transport emissions (A2); robotics, environmental sensors, and IoT record manufacturing impacts (A3); and AI-powered LCA tools, BIM simulations, and GIS and spatial data infrastructures process these data into actionable insights. Storage is ensured through blockchain-secured DPP repositories and cloud-based BIM, while sharing is facilitated by DPP platforms, BIM viewers, QR-enabled access and spatial databases aligned with open geospatial standards.

Stage B (Use Phase): In this phase, data collection expands to operational performance, maintenance records, repair history, and occupant behaviour. Maintenance data (B2) and energy consumption metrics (B6) inform decisions on refurbishment or circular retrofit options (Kebede et al., 2024). Smart meters, occupancy sensors, and CMMS tools automate acquisition of operational and maintenance data. Surveying tools such as laser scanning, LiDAR, and geotagged condition assessments provide spatially-anchored data about component degradation and performance. These are essential for location-specific maintenance prioritisation and integration with municipal asset registries. Predictive AI models, digital twins, and analytics dashboards support analysis for system performance monitoring and refurbishment forecasting. Data are stored in CMMS databases and building performance platforms, and shared through dashboards, user apps, and DPP synchronization, ensuring accessibility to managers, occupants, and service providers.

Stage C (End-of-Life): As buildings reach this phase, the value of backward data flows becomes evident. Deconstruction data (C1), including component condition, disassembly techniques, and recovery rates, inform reuse or recycling decisions. Yet, such data are rarely collected systematically, and when collected, they often fail to inform upstream decisions due to lack of integration or feedback loops (Ma et al., 2022). Geospatial asset tagging (e.g., with GNSS identifiers), LiDAR scans of demolition sites, and integration with cadastral asset registers are essential for spatially indexing components during deconstruction and reuse. Tools such as CityGML and IFC-GeoLink enable semantic and geometric harmonisation of DPP data with urban models and land management systems. UAVs, 3D scanners, and IoT tagging systems facilitate condition documentation and material identification, while GPS and RFID monitor transport (C2). Smart waste bins, AI recovery analysis, and LCA databases support waste processing (C3) and disposal assessments (C4). Storage platforms include waste tracking portals and compliance registries, with sharing enabled through public dashboards, DPP updates, spatial interfaces, and regulatory disclosure systems.

Stage D (Beyond Lifecycle): This phase represents the most transformative element of the circular model, formalizing reuse, repurposing, and secondary markets. To operationalize this stage, accurate and trusted data on material history, prior performance, and environmental impact are essential. Sensor-based condition assessments, AI-driven reuse potential scoring, and circularity analytics platforms support decision-making. The integration of spatial datasets into circularity platforms, such as those used in national material banks, urban mining maps, or cadastral reuse registries, enables location-specific secondary market visibility and supports spatial planning for reuse-oriented projects. Material banks, exchange platforms, and DPP-enhanced registries ensure secure storage and facilitate sharing via marketplaces, policy channels, and innovation hubs (European Commission, 2023; Kebede et al., 2024).

Across all stages, the multi-purpose nature of data in supporting carbon accounting, ESG reporting, design optimisation, refurbishment forecasting, waste minimisation, and stakeholder coordination becomes evident. However, persistent gaps in cross-stakeholder data exchange remain a key challenge. Tools such as BIM, LCA software, and supply chain platforms often operate in silos, limiting interoperability and feedback loops (De Wolf et al., 2024).

Crucially, the limited integration of geospatial data infrastructures, surveying technologies, and spatial asset registries constrain the ability to link Digital Product Passports (DPPs) with broader land administration systems, such as cadastral databases and infrastructure management platforms. Bridging this gap requires the adoption of open spatial standards, harmonised geospatial metadata practices, and coordinated engagement with FIG-relevant professionals, including land surveyors, geospatial data managers, and spatial planners.

The integration of digital technologies across the building lifecycle, particularly through the DPP-enabled CEBE framework, offers a structured pathway to embed these spatial dimensions. In doing so, DPPs can function not only as material trackers but also as geospatially enabled records that support dynamic, transparent, and circular flows of both materials and spatial information.

4.3 Operationalising Lifecycle Feedback Loops and Stakeholder Engagement via Digital Tools

A core feature of circular built environment transitions is the integration of feedback loops, not only across lifecycle stages but also between different stakeholders and their associated digital tools (Charef, 2022). These loops enable the forward flow of data from design to end-of-life and the backward flow of insights from real-world performance, deconstruction, and reuse outcomes to inform earlier stages like design, procurement, and construction. This section synthesizes how stakeholders interact with data processes (collection, analysis, storage, and sharing) using stage-specific tools, reinforcing the operationalisation of DPPs.

Building on the lifecycle-wide flow illustrated in Figure 2, Table 2 maps key stakeholders to their data needs, digital tools, and the purposes these technologies serve. This highlights how data collection, analysis, storage, and sharing are distributed across lifecycle phases and the roles of various stakeholders therein, forming the basis for DPP-driven decision-making.

Table 2. Mapping of stakeholders to lifecycle stages, data needs, digital tools, and intended purposes to support circular built environment practices.

Stakeholder	Lifecycle Stage	Primary Data Needs	Key Technologies Used	Purpose
Architects & Designers	Stage A: Upfront	Material specs, certifications, carbon data	BIM, LCA tools, DPPs, MPs, AI	Low-impact design, certification alignment
Construction Contractors	Stage A-C	Construction methods, logistics, energy use	IoT, Robotics, XR, Blockchain	Efficient, traceable construction

Facility Managers	Stage B: Use	Maintenance, durability, operational carbon	CMMS, IoT, Digital Twins, AI	Monitoring, repair planning
Demolition Contractors	Stage C: End-of-Life	Deconstruction methods, component condition	UAVs, RFID, Blockchain, DPPs	Selective recovery, documentation
Recyclers	Stage D: Beyond Life	Material origin, residual value, compliance	MPs, DPPs, Digital Platforms	Maximise reuse, market value
Policymakers & Regulators	All Stages	Carbon reporting, compliance, reuse statistics	BDA, Blockchain, DPPs	Policy updates, system-level insight
Building Owners/Clients	All Stages	Performance, cost, ESG metrics	DPPs, BDA, ESG Dashboards	Strategic decision-making, circular investment
Surveyors, Geospatial Specialists & Land Administrators	All Stages	Asset geolocation, cadastral data, spatial standards compliance	GIS, GNSS, LiDAR, CityGML, ISO 19115, OGC Tools	Spatial integration of DPPs, asset traceability, interoperability

Across all lifecycle stages, stakeholders interact with various technologies to produce and apply data that supports circularity. For example, manufacturers and suppliers provide critical material-level data in Stage A using QR codes, GIS, and IoT sensors to document provenance, composition, and certifications. Designers and engineers use BIM, LCA, and AI tools to inform low-impact material choices and simulate environmental performance and increasingly rely on feedback from later stages to improve design decisions.

Construction teams deploy UAVs, robotics, and on-site IoT systems to monitor construction quality, safety, and emissions. In Stage B, facility managers and building users apply CMMS tools, digital twins, and smart meters to track occupancy, maintenance cycles, and operational carbon performance. These data sets are essential for planning component reuse or refurbishment in later stages.

During Stage C, demolition contractors and recovery specialists gather reverse-stage data using AI-enabled image recognition, RFID, and robotics. This information includes material recovery rates and component condition, which support reuse in Stage D. Regulators and policymakers depend on transparent and traceable data across all stages to ensure compliance with carbon reporting and circularity standards. DPPs supported by blockchain and cloud-based systems help meet these requirements.

Surveyors, geospatial professionals, and land administrators provide a foundation for spatial accuracy and traceability. Their tools, including LiDAR, GNSS, and GIS platforms, ensure components are spatially referenced and linked to broader cadastral and land management systems. This enables interoperability between DPPs and national registries or city-scale asset databases, enhancing visibility and planning.

This collaborative data ecosystem fosters continuous lifecycle learning, where data from one stage can improve practices across the entire building lifecycle. Making these relationships explicit through tools such as DPPs, BIM, and IoT, and aligning them with spatial data infrastructures, helps transform static documentation into dynamic circular workflows.

However, successful feedback loops also depend on maintaining interoperability across technologies and stakeholder transitions. When buildings change ownership, new users may lack the systems or skills needed to maintain data continuity. This disrupts long-term lifecycle intelligence and reduces the value of DPPs. To address this, DPP implementation should be based on open, standardised data formats and user-friendly platforms. Public registries, national frameworks, and simplified interfaces can ensure accessibility and long-term participation across the sector.

4.4 Illustrative Scenario: Applying the Framework to a Modular Housing Retrofit Project

To demonstrate the practical application of the proposed DPP-enabled CEBE lifecycle framework, this section presents an illustrative scenario involving a modular housing retrofit project. Modular retrofits are increasingly adopted across Europe for accelerating decarbonisation of the ageing building stock, particularly in social housing contexts where time, cost, and occupant disruption are critical concerns (Ma et al., 2022; Qualisflow, 2023). This scenario aligns with recent EU pilot initiatives and helps illustrate how lifecycle stages, digital tools, stakeholder engagement, and data flows intersect to deliver circular and low-carbon outcomes.

Stage A – Upfront Phase: In this retrofit project, manufacturers provide prefabricated insulation modules, cladding, and renewable energy components (e.g., PV-integrated façades), each tagged with a DPP containing information on material origin, embodied carbon, certification status, and design-for-disassembly attributes. Architects and retrofit designers access this DPP data through integrated BIM environments, enabling low-impact design optimisation and compliance with lifecycle carbon targets. Transportation emissions and construction logistics are tracked using GPS-enabled IoT sensors, with data fed into supply chain dashboards and carbon accounting platforms to support Stage A reporting.

Stage B – Use Phase: During and post-retrofit, smart meters, IoT sensors, and building management systems monitor indoor environmental quality, operational energy and water use, and user comfort. Maintenance activities, including window seal replacement, filter cleaning, and façade inspection, are logged through CMMS platforms synced with the building's DPP. These data enable facility managers to identify performance anomalies and plan predictive maintenance. Moreover, occupant feedback is collected via digital interfaces, contributing to performance evaluations and feeding into the DPP for future Stage C and D decisions.

Stage C – End-of-Life Phase: At the end of the modular components' service life, robotic deconstruction equipment and condition-monitoring UAVs collect data on material integrity, contamination, and potential for reuse. This information is uploaded to the DPP and shared with recyclers, policymakers, and new designers. Material sorting, disassembly, and logistics are guided by DPP-stored metadata, which includes disassembly instructions, hazardous material alerts, and prior repair history.

Stage D – Beyond Lifecycle Phase: Based on real-time and historic performance data, eligible components are listed on digital material banks and secondary markets. Recyclers and designers access the DPP to assess reuse potential, verify compliance with circular procurement criteria, and calculate residual environmental impact. AI-powered analytics suggest optimal second-life applications (e.g., new modular wall systems), and data exchange occurs via DPP-integrated innovation hubs.

This scenario demonstrates how DPPs serve as a digital backbone that connects stakeholders across lifecycle stages, enabling not just data collection but also actionable insights and feedback loops. The modular housing retrofit case illustrates how digital traceability, real-time monitoring, and cross-stage data sharing can enhance the circularity, transparency, and adaptability of built environment projects, bridging the gap between conceptual frameworks and operational reality.

5. CONCLUSIONS AND RECOMMENDATIONS

The transition to a circular built environment demands more than design innovation or material substitution. It requires a systemic shift in how information is created, shared, and used across all phases of a building's lifecycle. This study has addressed this need by proposing a comprehensive, data-centred framework, the CEBE lifecycle framework, for circular built environment lifecycle management, with Digital Product Passports (DPPs) serving as a core mechanism for operationalising circularity in practice.

The framework contributes to the existing discourse by integrating material traceability, stakeholder coordination, and feedback loops into a single cohesive structure. It identifies key data types and aligns them with specific circular economy objectives such as carbon accounting, reuse planning, and regulatory compliance. These data needs are linked to enabling technologies, including BIM, IoT, digital twins, and distributed ledgers, which together form the foundation for informed, cradle-to-cradle decision-making.

By expanding the lifecycle to include post-demolition processes in Stage D, the framework captures circular pathways that are often excluded from conventional lifecycle assessments. This approach helps bridge the gap between design intentions and end-of-life outcomes, enabling continuous value retention and informed material reuse.

However, the success of this framework depends on addressing critical implementation challenges, including data standardisation, tool interoperability, and trust among stakeholders. Achieving these goals requires coordinated action to harmonise data models, incentivise participation throughout the value chain, and embed circular principles within regulatory and institutional structures.

Future research should prioritise piloting this framework across diverse project types, refining DPP content standards, and developing governance models that support secure and equitable data sharing. Further exploration of connections between DPPs, geospatial systems, and cadastral registries may also enhance the integration of material intelligence into land-use planning.

As buildings become increasingly data-rich and digitally connected, the potential to embed circularity at scale continues to grow. Realising this potential will require integrated thinking, robust digital infrastructure, and a commitment to long-term lifecycle intelligence that reshapes how the built environment operates as a regenerative system.

REFERENCES

Al-Qazzaz, Ihab (2025) *BIM-based building circularity assessment for sustainable construction.* PhD thesis, University of Nottingham.

Balasbaneh, A.T., Sher, W. and Li, J., 2025. A systematic review of the life cycle cost estimation of upgrading buildings for sustainability. *Environmental Science and Pollution Research*, pp.1-23.

Boell, S. K., & Cecez-Kecmanovic, D. (2015). On being 'systematic' in literature reviews in IS. *Journal of information technology*, *30*(2), 161-173.

Charef, R. (2022). The use of Building Information Modelling in the circular economy context: Several models and a new dimension of BIM (8D). *Cleaner Engineering and Technology*, *7*, 100414.

de Alcantara, D.P. and Martens, M.L., 2019. Technology Roadmapping (TRM): a systematic review of the literature focusing on models. *Technological Forecasting and Social Change*, *138*, pp.127-138.

De Wolf, C., Byers, B.S., Raghu, D., Gordon, M., Schwarzkopf, V. and Triantafyllidis, E., 2024. D5 digital circular workflow: five digital steps towards matchmaking for material reuse in construction. *npj Materials Sustainability*, *2*(1), p.36.

DEFRA (2022) *UK Statistics on Waste*. London: Department for Environment, Food and Rural Affairs. Available at: https://www.gov.uk/government/statistics/uk-waste-data/uk-statistics-on-waste

European Commission (2020) *Circular Economy Action Plan*. [online] Available at: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

European Commission (2020) *Buildings as Material Banks (BAMB) – Enabling a circular future for the built environment*. [online] Available at: https://www.bamb2020.eu

European Commission (2023) *CIRPASS – Digital Product Passport initiative for the circular economy*. [online] Available at: https://cirpassproject.eu

Ho, O., Iyer-Raniga, U., Sadykova, C., Balasooriya, M., Sylva, K., Dissanayaka, M., Sukwanchai, K., Pal, I., Bhatia, A., Jain, D. and Sivapalan, S., 2024. A conceptual model for integrating circular economy in the built environment: An analysis of literature and local-based case studies. *Journal of cleaner production*, *449*, p.141516.

Kebede, R., Moscati, A., Tan, H. and Johansson, P., 2024. A modular ontology modeling approach to developing digital product passports to promote circular economy in the built environment. *Sustainable Production and Consumption*, *48*, pp.248-268.

Incelli, F., Cardellicchio, L., & Rossetti, M. (2023). Circularity indicators as a design tool for design and construction strategies in architecture. *Buildings*, *13*(7), 1706.

Lira, J. S., & da Silva, E. A. (2025). A Systematic Literature Review of Dynamic Life Cycle Assessment in Buildings: Challenges and Guidelines. *Journal of Building Engineering*, 113503.

Ma, W., Hao, J.L., Zhang, C., Guo, F. and Di Sarno, L., 2022. System dynamics-life cycle assessment causal loop model for evaluating the carbon emissions of building refurbishment construction and demolition waste. *Waste and Biomass Valorization*, *13*(9), pp.4099-4113.

Moghayedi, A. and Awuzie, B.O., 2025. A Framework for Facilitating Low-Income Net-Zero Energy Housing Delivery in Developing Countries: Insights from a Practical Case in South Africa. *Building and Environment*, *276*, p.112847.

Moghayedi, A. and Awuzie, B., 2023. Towards a net-zero carbon economy: A sustainability performance assessment of innovative prefabricated construction methods for affordable housing in Southern Africa. *Sustainable Cities and Society*, *99*, p.104907.

Moghayedi, A., Mahachi, J., Lediga, R., Mosiea, T. and Phalafala, E., 2024. Revolutionizing affordable housing in Africa: A comprehensive technical and sustainability study of 3D-printing technology. *Sustainable cities and Society*, *105*, p.105329.

Pristerà, G., Sanyé-Mengual, E., Wierzgala, P., & Sala, S. (2025). Testing circularity measures: Lifespan and end-of-life modelling influence on the environmental impact of the EU residential building stock. *Sustainable Production and Consumption*, *56*, 207-220.

Pomponi, F. and Moncaster, A., 2017. Circular economy for the built environment: A research framework. *Journal of cleaner production*, *143*, pp.710-718.

Samani, P. (2023). Synergies and gaps between circularity assessment and Life Cycle Assessment (LCA). *Science of The Total Environment*, *903*, 166611.

Thakuri, P.K., Alkki, L. and Aarikka-Stenroos, L., 2025. Digital technologies enabling component reuse in circular value chains: Using digital twin, internet of things and robots in construction and manufacturing sectors. *R&D Management*, *55*(4), pp.1161-1216.

Thomas, J., & Harden, A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC medical research methodology*, *8*(1), 45.

World Green Building Council (2021) *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon*. [online] Available at: https://worldgbc.org/climate-action/embodied-carbon/

UK Green Building Council (2023) *What is embodied carbon in construction? Everything but operating the building*. [online] UKGBC. Available at: https://ukgbc.org/news/what-is-embodied-carbon-in-construction/

CONTACTS

Dr Alireza Moghayedi
School of Architecture and Environment, University of the West of England, Bristol, UK
Sustainability + Cyber-oriented Research Unit for the Built Environment (S+CUBE),
Department of Construction Economics and Management, University of Cape Town, South Africa
alireza.moghayedi@uwe.ac.uk

Professor Bankole Awuzie
Department of Construction Management and Quantity Surveying, University of Johannesburg, Johannesburg, South Africa
boawuzie@uj.ac.za