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Unlocking sustainability futures: a framework for digital product passports and material banks in a circular built environment

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Abstract

Purpose – This study aims to develop and analytically test an integrated implementation framework linking digital product passports (DPPs), digital materials banks (DMBs) and circular economy (CE) principles to address structural barriers to material reuse, carbon reduction and intelligent waste management in the built environment. It examines how digitally enabled lifecycle data flows can shift construction from linear to regenerative systems.

Design/methodology/approach – The framework was derived and validated through a three-stage research design: a systematic synthesis of over 30 peer-reviewed studies; three co-design workshops with 14 international experts from academia, industry and policy; and cross-sector validation by an eight-member panel. The resulting DPP–DMB implementation framework (DDIF) comprises eight lifecycle-aligned stages mapped to EN 15978 and embeds BIM, IoT, blockchain, AI and digital twins as enabling technologies.

Findings – The analysis demonstrates that the DDIF enhances material traceability, lifecycle transparency and stakeholder coordination while enabling real-time monitoring and ESG-aligned compliance. It operationalises circular construction through market-based reuse mechanisms, predictive decision-making and interoperability with international standards and policy instruments, including the EU Green Deal, ISO 23387 and associated EU Level(s). Its modular architecture indicates scalability across regulatory contexts and asset types.

Originality/value – Whereas prior studies typically examine DPPs, material databases or CE strategies in isolation, this paper integrates them into a single, lifecycle-structured framework validated through practitioner engagement. Unlike largely conceptual models or technology-focused roadmaps, the DDIF links digital infrastructures to concrete decision points, reuse markets and regulatory processes

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across asset stages, advancing the field from fragmented approaches towards deployable system-level implementation.

Keywords Carbon neutrality, Circular built environment, Digital material banks, Digital product passports, Life cycle data integration

Paper type Research paper

1. Introduction

The transition towards carbon neutrality and a circular economy (CE) has become a global imperative (Habert, 2023; Huang *et al.*, 2022). The built environment is one of the most resource-intensive sectors, responsible for nearly 40% of global energy-related CO_2 emissions and over one-third of worldwide waste generation (UNEP, 2025; Awuzie *et al.*, 2024). This scale of impact poses significant challenges to achieving SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Despite increasing awareness, progress remains constrained by systemic barriers, including fragmented data ecosystems, weak lifecycle traceability, limited end-of-life (EoL) planning and the absence of digital infrastructure to enable closed-loop material flows (Moghayedi and Awuzie, 2025).

Digital product passports (DPPs), digital materials banks (DMBs) have emerged as promising mechanisms to address these gaps. DPPs function as structured digital systems that capture and share comprehensive lifecycle information on construction materials, from origin and composition to carbon impact and reuse potential, while DMBs act as centralised repositories linking available materials to future applications (European Commission, 2024; Langley *et al.*, 2023; Heinrich and Lang, 2022). Together, they enhance transparency, facilitate circular design and procurement, support LCA-based decision-making and strengthen compliance across the built environment value chain. By preserving verified material and performance data across lifecycle stages, DPP–DMB integration enables the quantification of avoided embodied carbon through reuse, life extension and displacement of virgin materials, thereby supporting measurable carbon reduction outcomes rather than inferred benefits alone.

Importantly, DPPs and DMBs fulfil distinct but complementary functions: DPPs provide asset- and component-level lifecycle intelligence and traceability, whereas DMBs operationalise this information by enabling material recovery, reuse and market exchange at scale. Evidence from recent studies suggests that DPP-only approaches often remain data-rich but operationally passive, while DMB-centric initiatives lack verified provenance and performance data. Their integration is therefore essential to translate lifecycle transparency into actionable CE outcomes rather than treating either instrument as a standalone solution.

However, their adoption remains limited due to several persistent challenges. These include the absence of an integrated framework that aligns environmental objectives with technological and regulatory requirements, poor interoperability between digital systems and unclear role definitions across lifecycle stages (Wicaksono *et al.*, 2025; Kebede *et al.*, 2024). Existing approaches frequently fall short of converting material traceability into actionable CE outcomes or providing feedback loops that inform reuse and recycling strategies at EoL. These gaps highlight the need for a cohesive, scalable and implementation-ready framework.

Despite increasing scholarly and policy attention to DPPs and DMBs, existing research remains fragmented, often addressing data traceability, CE strategies or digital technologies in isolation and at single lifecycle stages, with limited consideration of how these elements can be operationally integrated across the full building lifecycle. Consequently, there is a clear gap for an implementation-oriented, lifecycle-aligned framework that systematically links digital material intelligence with governance mechanisms, market-based reuse pathways and measurable carbon and CE outcomes in real-world construction contexts.

In response, this study develops a comprehensive DPP–DMB adoption and implementation framework aimed at enabling EoL lifecycle transparency, improving material traceability and supporting measurable gains in circularity performance and carbon reduction. The study pursues three core objectives:

(1) to conceptualise the role of DPPs and DMBs in enabling lifecycle transparency, traceability and enhanced circularity and carbon neutrality performance;

(2) to identify and integrate the enabling technologies required for interoperable, real-time DPP–DMB deployment across building lifecycles; and

(3) to design and evaluate a practical, adaptive, stakeholder-oriented framework that defines implementation pathways and assesses its contributions to waste reduction, ESG compliance, circular procurement and EoL recovery.

This study presents a novel, integrated and implementation-ready framework that demonstrates the potential benefits of combining DPPs and DMBs to enhance carbon neutrality and circularity performance in the built environment. Moving beyond isolated technologies and theoretical models, DDIF synthesises insights from over 30 recent studies, spanning both practical and conceptual domains, and aligns them with emerging policy frameworks, enabling technologies and stakeholder roles. It uniquely bridges the gap between material traceability and actionable CE outcomes through a lifecycle-based, stakeholder-driven and interoperable approach.

DDIF distinguishes itself through a modular design that supports adaptability across project scales and regional contexts, alongside a clear mapping of stakeholder responsibilities and value flows throughout the built asset lifecycle. It incorporates interoperability-enhancing mechanisms supported by innovative tools and is purposefully aligned with major global policy instruments, including the EU Green Deal, the CE Action Plan and ISO sustainability standards. In doing so, it addresses a critical gap in both literature and practice by offering a scalable, systematic and policy-responsive pathway for the real-world adoption and implementation of DPPs and DMBs. This study contributes to the construction innovation domain by advancing an implementation-oriented digital governance model that integrates technological innovation, lifecycle management and organisational coordination within the built environment.

2. Review of related literature

2.1 Linking material waste management with circular and carbon neutral performance

As global efforts intensify to decarbonise and dematerialise the built environment, there is growing consensus that CE principles and carbon neutrality must be pursued in tandem. Rather than treating them as parallel strategies, recent literature suggests they are interdependent goals, especially when applied through lifecycle thinking in construction and demolition sectors (Kebede *et al.*, 2024; Moghayedi and Awuzie, 2023). CE-oriented approaches such as reuse, modular construction and design for disassembly can substantially lower embodied carbon while reducing material waste and resource extraction (Pittri *et al.*, 2026).

Lifecycle assessments (LCAs), following EN 15978 and ISO 14040/44 standards, divide environmental performance into four stages: product and construction (A), use (B), EoL (C) and benefits beyond the system boundary (D). Carbon emissions are most concentrated in Stages A and B due to embodied and operational energy (Zhao *et al.*, 2023), whereas Stages C and D offer the greatest potential for improving circularity through strategies like disassembly, reuse and recycling, helping retain material value and reduce virgin resource use (Moghayedi and Awuzie, 2025). Crucially, carbon reductions associated with reuse and life extension can only be quantified where reliable, component-level lifecycle data is available to support Stage D accounting and avoided-burden calculations.

However, material reuse and recycling rates remain low due to poor traceability, lack of standardised documentation and limited planning for EoL recovery (Munaro and Tavares, 2021). A recurring limitation identified in the literature is that material data, even when available at product level, rarely persists across lifecycle stages or translates into actionable recovery decisions. This fragmentation undermines the ability to measure avoided emissions associated with reuse, refurbishment or extended service life. DPPs and related tools offer a solution by improving visibility into material composition, environmental impact and recovery potential, especially during refurbishment and demolition (European Commission, 2024). Tools like Rhino Circular (Heisel and Rau-Oberhuber, 2020) and Forest2Building (Ott *et al.*, 2023) show how digital models and data-driven strategies can enable early-stage circularity planning and track material flows more effectively.

While circularity and carbon neutrality are often treated separately, they are increasingly recognised as complementary. Design strategies such as modular construction, adaptive reuse and material recovery can significantly reduce embodied carbon (Moghayedi and Awuzie, 2023). Yet, challenges persist in quantifying these benefits across lifecycle stages. Scholars advocate integrating DPPs with LCA tools to enable measurable carbon and material waste accounting, particularly in Stages C and D (Schaubroeck *et al.*, 2022; Morganti *et al.*, 2024). At the same time, recent studies highlight that lifecycle data alone is insufficient without mechanisms that operationalise reuse and recirculation beyond individual projects. Frameworks such as the cascade database (Schaubroeck *et al.*, 2022) demonstrate how combining product, assembly and process data can enhance traceability and performance tracking. These advances point to an emerging integrated model in which DPPs enable carbon measurement and decision support, while DMBs translate this information into material reuse pathways capable of delivering verifiable carbon savings at scale, thereby strengthening material waste management and carbon neutrality outcomes.

Despite the widespread adoption of lifecycle-based sustainability frameworks, such as EN 15978 and cradle-to-cradle principles, their practical implementation in the built environment remains limited. The literature consistently reports that lifecycle thinking is often applied conceptually at the assessment stage but weakly operationalised across project delivery and asset management phases (Munaro and Tavares, 2021; Kebede *et al.*, 2024). In practice, lifecycle data frequently deteriorates at handover points between design, construction, operation and EoL, driven by project-based procurement models, fragmented responsibilities and the absence of accountable data custodians beyond construction completion (Çetin *et al.*, 2023; Neligan *et al.*, 2023). As a result, materials assessed as “circular” or “low-carbon” at design stage rarely retain traceable identity or recovery pathways at deconstruction, limiting the realisation of benefits anticipated in Stages C and D. Recent studies therefore argue that lifecycle theory alone is insufficient without digital and organisational mechanisms that preserve data continuity, assign responsibility across lifecycle stages and translate assessment outputs into actionable reuse and recirculation decisions (Schaubroeck *et al.*, 2022; Morganti *et al.*, 2024). This gap between lifecycle theory and implementation capacity provides a critical rationale for integrating data-centric instruments such as DPPs with material-oriented systems capable of operationalising recovery and reuse at scale.

2.2 Digital product passports and digital material banks

DPPs are structured, interoperable systems that capture and share comprehensive lifecycle data on materials, products and components used in construction (Stella *et al.*, 2023). They support transparency, traceability and circularity by enabling access to key information across the building lifecycle (Kebede *et al.*, 2024). Their primary function is informational: to ensure that verified, standardised lifecycle data remains accessible and transferable across actors and phases.

DPPs typically comprise of layered data units: digital material passports (DMPs) provide details on material origin, embodied carbon and recyclability; digital element passports (DEPs) consolidate these into functional assemblies with added information on installation and repairability; and digital component passports (DCPs) focus on prefabricated components, including technical specifications and performance metrics. Together, these layers form a unified DPP that facilitates circular procurement, carbon tracking and EoL planning (Stella *et al.*, 2023; Kebede *et al.*, 2024).

The regulatory landscape for DPPs is shaped by the EU Green Deal, CE Action Plan and DPP Initiative, which promote standardised digital data flows across supply chains (European Commission, 2024). Complementary standards, ISO 23387, ISO 22057 and Level(s), define semantic and interoperability requirements, fostering integration with national regulations and certification schemes (UN/CEFACT, 2024; BUILD UP, 2024).

Extant literature identifies several benefits of DPPs and DMBs across the built environment value chain. Firstly, these platforms improve material traceability, allowing for the accurate tracking of components from production through to EoL (Büchel and Neligan, 2025). This transparency not only supports carbon footprint calculations but also enhances circular design strategies by making material origin, durability and reuse potential explicit from the outset (Çetin *et al.*, 2023). Secondly, DPPs enable better decision-making for asset managers, designers and contractors by providing real-time access to verified material data. This, in turn, supports regulatory compliance, ESG reporting and circular procurement practices (UN/CEFACT, 2024).

On the other hand, DMBs perform a market-facing and operational role by aggregating, cataloguing and matching recovered materials with future construction or retrofitting demand. DMBs amplify the value of DPPs by transforming verified lifecycle data into actionable reuse, resale and recirculation pathways, particularly at EoL stages where material value is otherwise lost. Without DMBs, DPP-enabled traceability risks remaining informational rather than transformative; without DPPs, DMBs lack the verified provenance and performance data required for trust and regulatory acceptance.

Pilot platforms such as Madaster enable digital material documentation for circularity and carbon accounting (Heisel and Nelson, 2020), while Web3-based systems explore blockchain-secured ownership and access control (Jayarathna *et al.*, 2025). Integration with BIM allows for real-time lifecycle monitoring and data updates, positioning the combined use of DPPs and DMBs, rather than either instrument alone, as core enablers of scalable digital circular construction (Elghaish *et al.*, 2023).

2.3 A review of digital product passport/digital materials bank-enabling technologies

The deployment of DPPs and DMBs relies heavily on advanced digital technologies that enable data collection, lifecycle traceability, real-time monitoring and stakeholder collaboration, critical for achieving circularity and carbon neutrality (Çetin *et al.*, 2021). To support implementation clarity, these enabling technologies can be conceptually distinguished between foundational technologies, which are required to establish baseline DPP/DMB functionality, and augmenting technologies, which enhance intelligence, automation and scalability depending on project maturity and context. Key enabling technologies include Building Information Modelling (BIM), DTs, internet of things (IoT), blockchain and artificial intelligence (AI).

BIM serves as a foundational platform for DPP integration by digitally representing physical and functional building characteristics (Elghaish *et al.*, 2023). It allows for embedding DMPs data, supporting environmental assessments, design for disassembly and alignment with standards such as ISO 22057 and EU Level(s) (European Commission, 2024). Together with standardised data schemas and open formats, BIM provides the minimum digital infrastructure required for consistent passport creation and lifecycle data continuity.

IoT, blockchain and AI are best understood as augmenting technologies that extend DPP/DMB capabilities beyond baseline implementation. IoT sensors embedded in components monitor usage, environmental conditions and degradation, enabling real-time lifecycle updates and adaptive asset management (Çetin *et al.*, 2024). Blockchain secures material traceability through immutable ledgers and smart contracts, ensuring ownership authentication, compliance and trust in multi-stakeholder environments (Jayarathna *et al.*, 2025). AI contributes predictive analytics and automated classification, supporting material recognition, anomaly detection and efficient reuse scenario generation, particularly valuable for retrofitting and social housing contexts (Voulgaridis *et al.*, 2024).

DTs stand out as the most integrative technology. A DT is a real-time digital counterpart of a physical asset, continuously updated via IoT data and system integrations (Shehadeh *et al.*, 2025; Magaisa *et al.*, 2022). While not strictly required for baseline DPP/DMB deployment, DTs play a critical role in advanced implementations by integrating data streams across lifecycle stages. DTs enable predictive lifecycle analysis, circularity assessments and scenario-based decision-making across asset lifecycles. The Forest2Building framework illustrates how DTs can trace wood products across the supply chain, enhancing transparency and circularity performance (Ott *et al.*, 2023).

Together, these technologies form the digital backbone of scalable DPP/DMB ecosystems. Distinguishing between foundational and augmenting technologies helps explain how DPP/DMB adoption can proceed incrementally, enabling early implementation under constrained conditions while supporting progressive enhancement as data availability, governance maturity and regulatory requirements evolve. Their convergence supports robust circular construction practices, ensures regulatory alignment and enables stakeholder collaboration for real-world adoption and impact.

While recent studies (KC *et al.*, 2025; Byers *et al.*, 2025) have synthesised digital technologies for material passports and their contribution to circularity and net-zero objectives, these studies primarily focus on technological capabilities rather than on structured lifecycle implementation and governance integration. The present study builds on this foundation by embedding these technologies within an EN 15978-aligned, DPP-DMB implementation pathway that explicitly connects information flows, material looping and accountability mechanisms.

2.4 Limitations of current approaches

Although there is strong conceptual alignment between DPPs/DMBs and circularity and carbon neutrality goals, particularly in closing resource loops and extending material lifecycles, real-world adoption remains limited. Most implementations are fragmented and lack scalability, largely due to data silos, lifecycle disconnects and technology fragmentation (Kebede *et al.*, 2024; Langley *et al.*, 2023).

Data silos, where material, carbon, and performance data are stored in disconnected systems, obstruct unified product histories and reduce decision-making transparency (Munaro and Tavares, 2021). This fragmentation is both technical and organisational, due to inconsistent terminologies and workflows across stakeholders (Çetin *et al.*, 2023; Neligan *et al.*, 2023).

Lifecycle disconnects further compound the issue. While BIM is widely used during design and construction, it is rarely updated during operation or demolition phases, limiting reuse feedback and EoL planning (Elghaish *et al.*, 2023). Similarly, LCAs are typically one-time assessments, lacking dynamic integration for tracking real-time impacts (Morganti *et al.*, 2024).

While technologies like blockchain, IoT, AI and DTs offer potential for enhanced material traceability, their effectiveness is hampered by limited interoperability and the lack of integration protocols (Voulgaridis *et al.*, 2024). Many systems remain proprietary or context-specific, making them unsuitable for wider deployment or regulatory alignment. The absence of harmonised data standards also makes it difficult to meet ESG reporting and compliance needs (UN/CEFACT, 2024).

Moreover, measuring the tangible impact of DPPs/DMBs on circularity performance remains challenging, and the consistent application of CE strategies across all lifecycle stages is still rare (Abedi *et al.*, 2024; Gianvincenzi *et al.*, 2025).

Overall, the literature reflects a broad exploration of technical, regulatory and operational issues but highlights the pressing need for a unified, interoperable and stakeholder-aligned framework. The DDIF developed in this study builds on these findings and is informed by the diverse contributions summarised in Table 1.

2.5 Non-technical enablers: skills, governance and market structures

Although digital technologies underpin DPP and DMB deployment, the literature consistently shows that technical capability alone is insufficient to achieve circular and low-carbon outcomes. Organisational arrangements, skills capacity, governance mechanisms and procurement models critically shape whether lifecycle data is preserved and operationalised across asset stages (Munaro and Tavares, 2021; Çetin *et al.*, 2023; Neligan *et al.*, 2023).

Fragmented project delivery structures and unclear data custodianship, particularly at handover and EoL phases, are repeatedly identified as major barriers to lifecycle continuity (Elghaish *et al.*, 2023; Morganti *et al.*, 2024; Kebede *et al.*, 2024). In parallel, weak standardisation frameworks, liability uncertainties and uneven digital literacy across supply chains constrain interoperability and limit SME participation (UN/CEFACT, 2024; Voulgaridis *et al.*, 2024; Çetin *et al.*, 2024).

Market and policy structures further condition DPP/DMB viability. Tendering regimes that privilege upfront cost over lifecycle value, together with limited incentives for secondary material markets, impede reuse-oriented business models (Abedi *et al.*, 2024; Gianvincenzi *et al.*, 2025; Morganti *et al.*, 2024). Collectively, these studies indicate that effective DPP–DMB adoption depends on coordinated progress in governance, workforce capability, procurement reform and regulatory alignment alongside digital infrastructures, reinforcing the need for the DDIF proposed in this study.

3. Methodology

This study adopts a pragmatic research philosophical stance, enabling the flexible use of diverse methods to address complex, real-world problems (Morgan, 2014). Accordingly, a multi-layered research approach was employed to combine theoretical exploration of the emergent framework with its empirical validation. This approach was chosen to enable a holistic understanding of digital, technological and stakeholder dimensions and to support the development of a solution that is grounded in both literature and practice. This method combined extensive literature synthesis, expert consultation and an iterative design process to ensure that the resulting framework was both theoretically grounded and practically

Table 1. Synthesis of key literature informing the DPP–DMB implementation framework (DDIF)

Framework component	Key implementation requirements	Primary stakeholders	Indicative success metrics	Sources
Digital infrastructure	Integration of blockchain, BIM, DTs, cloud-based platforms, secure and interoperable data systems	IT providers, BIM and DT specialists, construction firms	System interoperability, real-time data integration, cybersecurity robustness	1–6
Material traceability	Standardised DPP templates, material passports, certified product data, DT-enabled synchronisation of material flows	Material suppliers, certifying bodies, contractors	Material traceability, data completeness, reuse certification validity	3, 7–11
Stakeholder coordination	Defined roles and workflows, collaboration platforms, digital onboarding and training, DT-enabled role visualisation	Designers, contractors, policymakers, facility managers	Clarity of responsibilities, stakeholder engagement levels, coordination efficiency	3, 6, 12–15
Circular strategy integration	Reuse and recycling protocols, end-of-life planning, DMB integration, DT-supported scenario modelling for circularity	Architects, contractors, demolition teams, CE consultants	Increase in reuse rates, reduction in lifecycle waste, improvement in value retention	8, 11, 16–19
Regulatory alignment	Compliance with environmental and construction codes, data protection, auditability via DTs and DPP logs	Policymakers, legal experts, industry bodies	Policy compliance rates, audit readiness, adaptability to regulation changes	1, 2, 6, 11, 20–22
Performance monitoring	IoT-connected assets, LCA tools, carbon and circularity indicators, DT dashboards	Facility managers, ESG analysts, sustainability researchers	Accuracy of performance forecasts, improvements in ESG reporting and decision support	1, 3–5, 18–19

Note(s): 1: Elghaish *et al.* (2023); 2: Voulgaridis *et al.* (2024); 3: Çetin *et al.* (2024); 4: Magaisa *et al.* (2022); 5: Monteiro *et al.* (2024); 6: UN/CEFACT (2024); 7: Stella *et al.* (2023); 8: Kebede *et al.* (2024); 9: Büchel and Neligan (2025); 10: Heisel and Rau-Oberhuber (2020); 11: European Commission (2024); 12: Munaro and Tavares (2021); 13: Neligan *et al.* (2023); 14: Abedi *et al.* (2024); 15: Gianvincenzi *et al.* (2025); 16: Moghayedi and Awuzie (2023); 17: Ott *et al.* (2023); 18: Schaubroeck *et al.* (2022); 19: Morganti *et al.* (2024); 20: ISO 23387; 21: ISO 22057; 22: BUILD UP (2024)
Source(s): Authors' compilation (2026)

relevant while maintaining methodological transparency and procedural traceability to support reproducibility.

3.1 Framework development process

As indicated previously, the emergent framework was developed through a three-stage process that integrated conceptual exploration with practitioner insights.

3.1.1 Stage 1: Exploratory literature synthesis. The first stage involved a comprehensive literature synthesis of relevant documents and studies within past five years, which focused on DPPs, DMBs and CE strategies. This review aimed to identify the critical factors necessary for enabling digital lifecycle management, including data standardisation, technology integration, stakeholder roles, regulatory alignment and performance metrics. It highlighted common barriers, such as data silos, lifecycle disconnects and technological fragmentation, which the framework aims to address. The literature synthesis was conducted using a purposive, non-systematic approach, reflecting the emergent and fragmented nature of research on DPPs, DMBs and digitally enabled circular construction. Knowledge in this domain is distributed across peer-reviewed studies, policy instruments, standards, industry reports and pilot initiatives that are not yet consistently indexed in academic databases. Accordingly, a non-systematic strategy was adopted to capture this heterogeneous evidence base and support exploratory theory building and framework conceptualisation rather than quantitative aggregation or hypothesis testing, consistent with methodological guidance for design-oriented research in nascent fields (Cloutier, 2024).

To enhance methodological transparency and analytical traceability, the literature identification followed an explicit, albeit non-systematic, selection logic. Sources were retrieved through targeted searches across Scopus, Web of Science, Google Scholar, institutional repositories, EU policy portals and sector-specific platforms. Inclusion criteria were: publication within the past five years; direct relevance to DPPs, DMBs, digital traceability or circular construction; and substantive contribution to lifecycle implementation, governance or regulatory alignment. Sources lacking lifecycle relevance, implementation depth or applicability to the built environment context were excluded. Rather than pursuing quantitative aggregation, the synthesis focused on identifying recurring implementation barriers, enabling conditions and functional requirements that could be systematically translated into framework components. All sources were catalogued and analysed using a consistent framework-aligned structure enabling reproducibility and facilitating future replication or extension as the evidence base matures.

3.1.2 Stage 2: Expert workshops and thematic consolidation. The second stage of the framework development process involved three expert workshops, each lasting 90 min on the average, which was conducted over a four-week period. These workshops were designed to structure and refine the key components and relationships identified during the literature synthesis and to assess their practical relevance, feasibility and adaptability to the built environment sector. A total of 14 experts representing a diverse cross-section of academic disciplines and professional backgrounds participated in these workshops. These participants were drawn from Europe, the USA, Australia and Africa, hence ensuring the elicitation of an international and cross-contextual perspective. Details pertaining to the demographic information of these experts are articulated in Table 2.

The workshops were conducted virtually to enable broader participation and were structured around the following key activities:

- Presentation of the preliminary framework for contextual understanding.

Table 2. Demographic information of experts in development and validation stage

Area of expertise	No of experts (dev and val)	Geographic location	Sector affiliation
Digital construction and smart technologies	3 and 3	Europe, Oceania America	Academic, industry
Circular economy, LCA and sustainability	2 and 2	Europe, America, Africa	Industry, consultancy, academic
Material science and product certification	1 and 0	Europe	Industry
Architectural and engineering practices	3 and 0	Europe, Africa Oceania	Academic, industry
Public sector and policy advising	2 and 1	Europe	Government, public sector, consultancy
Facility and asset management	2 and 1	Europe, Africa	Industry
Off-site construction and low carbon manufacturing	1 and 1	Europe, Asia	Industry

Source(s): Authors' compilation (2026)

- Interactive mapping exercises to validate the relevance and interdependencies of key framework components (e.g. digital technologies, lifecycle stages, stakeholder roles).
- Scenario-based discussion prompts to assess framework applicability across conventional and innovative housing projects.
- Live annotation and polling tools to collect participant feedback in real time.

All workshop sessions were recorded and transcribed with the consent of participants. A structured thematic analysis was conducted following an inductive coding approach, consisting of open coding, axial grouping and cross-workshop comparison to identify recurring patterns and convergent insights.

Initial coding was undertaken independently by two members of the research team to reduce individual bias. Codes were subsequently compared and consolidated through iterative discussion, with disagreements resolved through consensus and reference to the research objectives. Higher-order themes were formed by clustering conceptually related codes that recurred across workshops and stakeholder groups.

Five dominant themes consistently emerged across the workshops: lifecycle data continuity and traceability gaps; interoperability and standards alignment challenges; unclear stakeholder roles and data ownership; limited integration of EoL feedback into design decisions; and governance, reporting and regulatory readiness requirements. These themes were mapped to specific framework elements. For example, lifecycle data continuity informed the "Digital Lifecycle Monitoring" block; interoperability challenges directly shaped the "Data Standardisation" and "Technological Integration" stages; stakeholder role ambiguity led to the explicit "Reporting and Governance" layer; and EoL feedback gaps informed the "Circularity Assessment" and DMB integration stages (see Appendix Table A1: mapping of workshop themes to framework components and A2: traceability matrix linking expert workshop themes to DDIF framework components for more details).

3.1.3 Stage 3: Structured framework construction and refinement. This synthesis process consolidated fragmented evidence into a lifecycle-aligned implementation logic that informed the DDIF structure. To formalise framework construction, a structured, iterative design logic was applied. Dominant themes derived from the literature synthesis and expert workshops were first consolidated through axial coding and then mapped against EN 15978 lifecycle phases to ensure coverage across all asset stages. Enabling technologies and governance mechanisms were subsequently assigned to each stage according to functional relevance and stakeholder responsibility. Successive framework drafts were refined through expert feedback, practical case insights and alignment with policy instruments such as the EU CE Action Plan, ISO 23387 and Level(s), with each modification documented to maintain analytical traceability.

3.2 Framework validation approach

To ensure the reliability and applicability of the proposed framework, a validation process was initiated. The validation process involved a structured expert panel review aimed at evaluating the clarity, coherence and practical utility of the emergent framework. The validation panel comprised eight experts: three who had participated in the earlier workshops and five newly recruited members, included to introduce fresh perspectives and minimise confirmation bias. The expert panel used for the validation phase consisted of professionals with relevant expertise and drawn from both academic and industry sectors, to ensure diverse inputs. As shown in Table 2, the panel of experts comprised of consultancy firms, construction technology providers and representatives of university-based research groups.

The validation was carried out using a structured evaluation protocol, which included:

- a framework summary document and visual model shared in advance; and
- a structured questionnaire employing a dichotomous agreement scale (agree/disagree) to assess the framework's relevance, completeness, practical usability and adaptability across contexts. A follow-up semi-structured interview with each expert to clarify responses and gather more nuanced feedback and to ensure that consensus was reached on a particular item.

The responses were analysed using a dichotomous consensus approach, which helped identify areas of agreement and disagreement while avoiding ambiguous or neutral responses. This enabled a clear assessment of the framework's perceived strengths and limitations. Additionally, qualitative feedback gathered through follow-up interviews was instrumental in refining key aspects of the framework, including:

- terminology of framework stages, to ensure alignment with industry-standard language;
- clarity and definition of stakeholder roles and corresponding data exchange flows across lifecycle stages; and
- scalability and adaptability of the framework across different building typologies and regional implementation contexts.

This iterative validation process ensured that the framework maintained academic rigour while meeting practical requirements, thereby enhancing its applicability across real-world built environment contexts. The overall research protocol adopted for this study is presented in Figure 1.

While the adopted methodology is well suited to exploratory framework development in an emergent research domain, several limitations should be acknowledged. The non-systematic literature synthesis, although appropriate for capturing policy, standards and early implementation evidence, may limit completeness and introduce selection bias. The expert-based development and validation reflect informed consensus rather than statistical generalisation, and the modest sample size, despite its international and cross-sectoral nature, may constrain the breadth of perspectives captured. Accordingly, the study's results are presented as a design-oriented framework synthesis rather than as

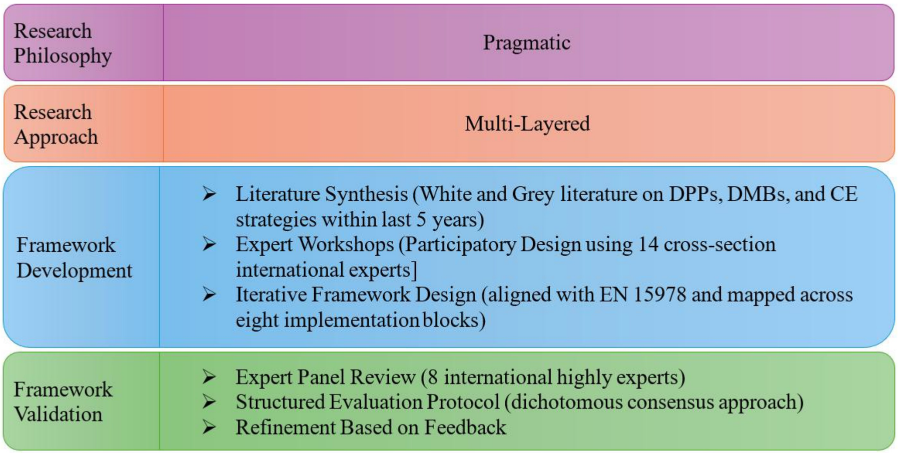


Figure 1. Research protocol
Source: Authors' compilation (2026)

analytical or hypothesis-testing outcomes, which is consistent with its exploratory and constructivist intent. In addition, the framework has been validated conceptually rather than through longitudinal or large-scale implementation, and its performance may evolve across different regulatory and market contexts. These limitations indicate the need for future empirical testing, longitudinal case studies and quantitative validation as DPP and DMB practices mature.

3.3 Ethical considerations

Ethical approval for this study was obtained from the University of the West of England (UWE), School of Architecture and Environment (Ethics Approval No. 4020). All expert participants involved in the workshops and validation stages were provided with an information sheet outlining the study objectives, data use and confidentiality arrangements, and informed consent was obtained prior to participation. The study was conducted in accordance with UWE ethical guidelines and the General Data Protection Regulation (GDPR). All data were anonymised during transcription and analysis, and participants were informed of their right to withdraw at any stage without consequence.

4. Development of the digital product passport-digital materials bank implementation framework

Informed by the framework construction process described in Section 3, this section presents the emergent DPP–DMB implementation framework (DDIF). The framework translates consolidated insights from the literature synthesis and expert consultations into eight interlinked implementation stages aligned with EN 15978 lifecycle phases (A–D). These stages collectively define a lifecycle-spanning structure that integrates digital enablers and governance mechanisms to enhance material traceability, circularity and carbon performance across built environment projects.

As shown in Figure 2, the DDIF is structured into eight interlinked implementation stages. Each stage represents a core process area necessary for successful DPP and DMB implementation. These stages follow a logical, lifecycle-based flow that aligns with EN 15978's A–D stages and reflects the digital-physical interdependencies identified during the

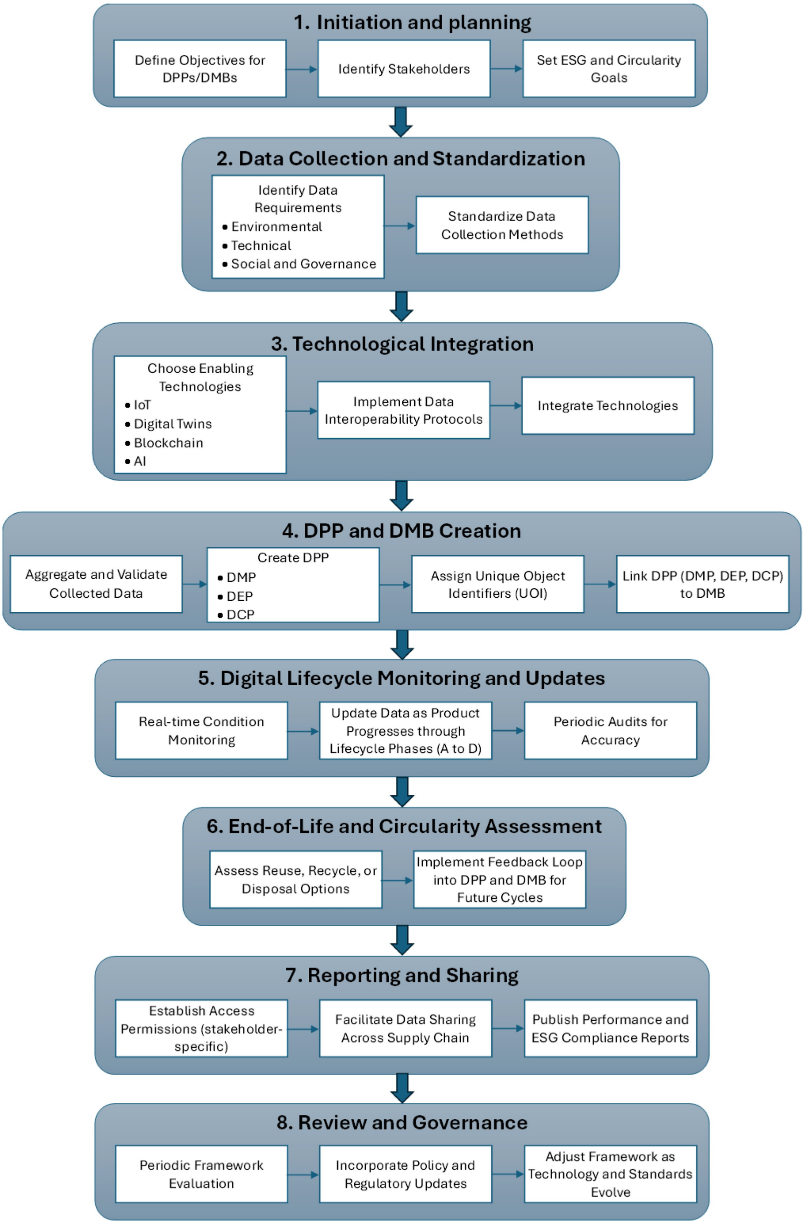


Figure 2. DPP-DMB implementation framework (DDIF) for built environment projects
Source: Authors' compilation (2026)

consultations with the experts. Each stage is described in detail in the following subsections, emphasising its purpose, key activities, enabling technologies and anticipated outcomes within the context of a circular and carbon-conscious built environment.

4.1 Initiation and planning

The first stage of the DDIF is referred to as the initiation and planning stage. This stage lays the foundation for the effective implementation of digital tools that support circularity and carbon neutrality. It involves defining project-specific goals for integrating DPP and DMB, identifying key stakeholders and aligning the project vision with broader sustainability objectives.

4.1.1 Defining objectives for digital product passports and digital materials banks. A critical early step is to establish clear, measurable objectives for implementing DPPs and DMBs. These objectives should reflect both project-level needs such as improved lifecycle data management, enhanced traceability, streamlined material recovery and alignment with organisational or regulatory drivers, such as compliance with EU CE Action Plan, ISO 23387 or national circular procurement mandates. For example, DPPs may be introduced to ensure transparent material documentation and inform future reuse strategies, while DMBs may serve as a repository to catalogue surplus materials for upcoming developments. Defining these objectives upfront ensures that digital infrastructure choices, data collection protocols and reporting mechanisms are developed with a purpose-driven approach, rather than being adopted as isolated technologies.

4.1.2 Stakeholder mapping. Effective deployment of DPPs and DMBs requires collaboration across a multi-actor value chain. At this stage, a stakeholder mapping exercise is conducted to identify and clarify the roles, responsibilities and data contributions of key actors throughout the project lifecycle. These actors usually include:

- designers and architects, who provide data inputs on material specifications, modular design intent and design-for-disassembly considerations;
- contractors and fabricators, who document product sourcing, on-site adaptations and installation data;
- suppliers and manufacturers, who contribute data on material composition, performance ratings, certifications and embodied carbon; and
- policymakers and regulators, who provide guidance on compliance, data standards and monitoring requirements.

Stakeholder engagement at the initiation phase helps avoid downstream conflicts, ensures adequate data availability and establishes shared ownership of the DPP–DMB implementation process.

4.1.3 Setting sustainability targets. Lastly, this phase involves the articulation of sustainability targets, which guide the digital and operational strategies of the project. These targets may relate to:

- environmental, social and governance (ESG) performance;
- net-zero carbon goals (e.g. operational and embodied emissions limits); and
- circularity indicators (e.g. material reuse rates, recycled content, design adaptability).

Clear sustainability benchmarks allow for the selection of appropriate digital tools, LCA strategies and DPP data fields. For example, projects with a strong focus on carbon reduction may prioritise real-time environmental performance tracking, while those targeting circularity may emphasise material disassembly potential and recovery mapping within the DMB. By aligning the adoption of relevant digital strategies and technologies with sustainability goals from the outset, this stage ensures that DPPs and DMBs contribute meaningfully to broader environmental and regulatory commitments, thereby establishing a robust foundation for lifecycle-driven decision-making.

4.2 Data collection and standardisation

The second stage of the DDIF centres on data collection and standardisation, which are essential for ensuring lifecycle traceability, accurate environmental reporting and long-term material recovery. This phase involves identifying relevant data categories and establishing consistent structures to enable reliable and interoperable data exchange among stakeholders.

4.2.1 Identifying multidimensional data. To fulfil the potential of DPPs across the building lifecycle, a broad set of multi-dimensional data is required, including:

- Environmental data: Embodied and operational carbon, water use, energy performance, recyclability and LCA indicators (Hu, 2020; Kovacic *et al.*, 2018; Waldman *et al.*, 2020).
- Technical data: Product specifications, material composition, durability, safety ratings and design compatibility, particularly for modular or disassembly-ready structures (Dams *et al.*, 2021; Kang *et al.*, 2022; Gamage *et al.*, 2024).
- Social and governance data: Supplier certifications, ethical sourcing, labour and environmental compliance and ESG reporting documentation (Bibby, 2024; Dathe *et al.*, 2024; Vörösmarty, 2025).

Together, these data sets ensure the DPP goes beyond environmental transparency to support social accountability, responsible sourcing and compliance across the supply chain.

4.2.2 Standardising data input and formats. Standardisation ensures DPP and DMB systems remain interoperable across technologies and project contexts. This involves aligning data structures with established protocols, such as:

- ISO 23386/23387: for defining data templates and attributes for construction products.
- Level(s): the EU sustainable performance framework with metrics suitable for integration into DPPs.
- COBie: for structuring asset data in BIM-based environments.

These standards enable seamless data exchange across platforms like BIM, IoT and DTs while also facilitating automated reporting for regulators, financiers and certification schemes. Emphasis is also placed on adopting open data formats and semantic ontologies to ensure future compatibility with evolving systems and technologies.

4.3 Technological integration

Technological integration is vital for operationalising DPPs and DMBs. This stage identifies and aligns digital tools that enable data capture, lifecycle traceability, interoperability and intelligent decision-making. Rather than deploying technologies in isolation, DDIF promotes their synergistic integration into a unified ecosystem spanning all lifecycle stages of built assets.

4.3.1 Selecting enabling technologies. Building on the technologies discussed in Section 2.3, DDIF advocates context-sensitive integration of tools such as BIM, IoT, blockchain, AI and DTs. BIM forms the foundation for embedding material and environmental data early in the process. IoT sensors enable real-time updates to DPPs through continuous monitoring of component performance. Blockchain ensures secure, decentralised tracking of provenance and compliance, while smart contracts automate lifecycle triggers. AI provides predictive analytics, anomaly detection and automated data classification. These elements converge within DTs, offering live digital replicas that support monitoring, simulation and decision support across the lifecycle.

4.3.2 Interoperability and systems integration. The true value of these technologies emerges through interoperability, enabling automated, standardised data exchange between platforms and stakeholders. A lack of interoperability remains a major barrier to scalable DPP–DMB adoption.

The DDIF addresses this challenge by promoting:

- open data formats (e.g. IFC, COBie);
- API-based platform integration (e.g. BIM to DTs or DMBs); and
- use of standardised ontologies and templates (e.g. ISO 23386/23387).

This systems-level integration ensures that DPPs function as dynamic, living data structures, embedded into workflows across design, construction, operation and EoL stages while facilitating cross-stakeholder collaboration and measurable progress towards circularity and decarbonisation goals.

4.4 Digital product passport and digital materials bank creation

The fourth stage of the DDIF focuses on the creation of DPPs and their integration into DMBs. This stage operationalises the data infrastructure established in earlier phases by aggregating verified lifecycle information, structuring it into usable digital passports and linking material components to platforms that support reuse, exchange or recovery. The processes outlined here are critical to ensuring that data is not only available but also searchable, reliable and transferable across the value chain.

4.4.1 Aggregation and validation of lifecycle data. The creation of DPPs begins with the aggregation of verified lifecycle data sourced from various actors and digital systems. This includes environmental data from LCA tools, material specifications from BIM models, performance records from IoT devices and compliance documentation from suppliers and manufacturers. A key aspect of this process is data validation, which ensures consistency, accuracy and trustworthiness. Validation protocols may involve automated checks (e.g. through AI or blockchain-ledgers), manual review by responsible parties or third-party verification depending on regulatory requirements.

This aggregation process enables the DPP to serve as a single source of truth for material and product information throughout the building's lifecycle.

4.4.2 Creating digital materials banks, digital element passports and digital component passports. Once validated, the data is structured into a hierarchy of digital passports:

- DMPs store detailed information about raw or processed materials, such as their composition, recyclability, embodied carbon and sourcing certifications.
- DEPs consolidate DMPs into functional assemblies, like walls, façades or floors and document properties such as disassembly potential and repairability.
- DCPs focus on prefabricated or standalone building systems such as windows, HVAC units or modular frames, including performance ratings, service life and maintenance history.

These passport layers provide both granular and aggregated visibility of materials and systems across the asset.

4.4.3 Assigning unique object identifiers and linking to the digital materials banks. Each DPP, whether at the material, element or component level, is assigned a unique digital object identifier (DOI) or globally unique identifier (GUID) that ensures traceability and links the passport to broader digital systems, including BIM environments, asset management tools and the DMB. These identifiers allow stakeholders to track the location, condition and ownership of products across time and projects. Linking DPPs to the DMB allows components, especially those nearing the end of their service life, to be catalogued for future reuse. Within the DMB, stakeholders can access information on material availability, specifications, reuse potential and previous lifecycle history. This functionality enables circular procurement, supports waste minimisation strategies and creates new economic value from recovered materials. Ultimately, this stage ensures that DPPs are not static records but living digital assets, actively supporting transparent, circular and data-driven material flows within the built environment.

4.5 Digital lifecycle monitoring and updates

Once created, DPPs and DMBs are continuously updated through lifecycle monitoring to reflect changes arising from operation, retrofit and deconstruction. Ongoing monitoring enhances traceability, transparency and quality assurance across all lifecycle stages, from material production to EoL and post-use applications.

4.5.1 Real-time monitoring across lifecycle stages. Enabled by IoT sensors, BIM platforms and DTs, real-time monitoring captures material conditions, usage and performance throughout the asset's life. Updates are automatically reflected in the DPP as changes such as retrofitting, maintenance or replacements occur. Aligned with Stages A–D (product and construction, use, EoL and beyond-system benefits), this approach allows:

- initial capture of embodied carbon and material provenance (Stage A);
- continuous logging of operational performance and maintenance (Stage B);
- documentation of disassembly and recovery during deconstruction (Stage C); and
- recording of reuse, recycling or repurposing outcomes (Stage D).

This continuous monitoring supports predictive maintenance, reuse planning and enhanced circularity.

4.5.2 Ensuring traceability, quality and transparency. Unbroken traceability is central to the DPP–DMB model. Each material's origin, transformation and current state is digitally recorded, creating a transparent and auditable chain of custody. Quality is maintained through automated validations and, when necessary, third-party verifications. Permissioned access allows stakeholders, designers, operators, regulators, to retrieve accurate lifecycle data on demand, supporting compliance and circular strategies.

4.5.3 Periodic data audits. To uphold data integrity, routine audits, manual or automated, assess the accuracy, completeness and relevance of DPP and DMB entries. Any inconsistencies are flagged and corrected, while audit trails ensure accountability. These audits also help identify data gaps and guide updates to align with new standards and regulations. This cyclical auditing ensures the DPP–DMB system remains a responsive digital infrastructure that supports long-term carbon reduction and circularity goals.

4.6 End-of-life and circularity assessment

The sixth stage of the DDIF focuses on the EoL phase, crucial for maximising circularity through strategic recovery, reuse, recycling or environmentally responsible disposal. DPP-enabled traceability and DMB-based visibility support quality-based recovery and reintegration of components into future construction cycles.

4.6.1 Assessing reuse, recycling and disposal pathways. At EoL, DDIF leverages DPP data, such as material composition, degradation status and disassembly instructions, to guide decisions on reuse, recycling or disposal. The DMB supports this process by matching recovered materials with new projects based on sustainability and performance criteria. Where reuse or recycling is not viable, DPP data informs responsible deconstruction, waste tracking and emissions reporting.

4.6.2 Enabling feedback loops. A key innovation of this stage is the integration of feedback loops to inform future project design and DPP/DMB updates. Insights gained from EoL processes, such as disassembly challenges, reuse performance and material recovery outcomes, are fed back to:

- improve product and component design for reuse;
- guide construction methods (e.g. modular assembly); and
- refine passport structure and data fields for better traceability.

These continuous feedback mechanisms strengthen circular practices over time, reducing dependency on virgin materials and advancing a regenerative, low-carbon built environment.

4.7 Reporting and sharing

The DDIF's seventh stage focuses on reporting and data sharing, both of which are essential for ensuring transparency, accountability and value creation across the built asset lifecycle. As DPPs evolve into dynamic digital assets and DMBs become repositories of recoverable materials, it is critical that the information they contain is shared in a secure, structured and role-specific manner.

4.7.1 Defining stakeholder-specific access. To balance transparency with data governance, the DDIF establishes role-based access protocols. This ensures that different stakeholders such as designers, contractors, facility managers, material suppliers and regulators can access the specific data fields relevant to their responsibilities. For instance, a contractor may require real-time access to installation or product warranty data, while a policymaker may focus on aggregated metrics related to circularity, embodied carbon or compliance status. This targeted access enhances data usability and avoids information overload or security concerns.

4.7.2 Sharing across the value chain. The DDIF enables collaborative sharing of verified lifecycle data across the entire construction and built asset value chain. Through integrations with BIM platforms, DTs and cloud-based project management tools, stakeholders can seamlessly exchange data on material availability, lifecycle performance, maintenance records and EoL status. This improves coordination in design, procurement, construction and deconstruction phases and promotes a systems-thinking approach to resource management. Sharing also supports the activation of secondary markets by making recovered materials visible to new project teams, thereby fostering circular supply chains and reducing reliance on virgin materials.

4.7.3 Environmental, social and governance reporting and compliance mechanisms. A key function of this stage is enabling ESG reporting and supporting compliance with regulatory frameworks. DPPs can be structured to align with ESG performance indicators such as material circularity, carbon intensity, waste reduction and responsible sourcing. This information can be extracted automatically to support:

- corporate sustainability disclosures (e.g. CSRD, GRI);
- green building certifications (e.g. BREEAM, LEED); and
- policy compliance (e.g. EU Green Deal, CE Action Plan)

Automated reporting mechanisms also reduce administrative burden and enhance the credibility of sustainability claims through traceable, verifiable data streams.

4.8 Review and governance

The final stage of the DDIF addresses the need for ongoing review, governance and strategic refinement to ensure that the system remains relevant, scalable and aligned with evolving industry practices, technologies and policy landscapes. This stage establishes mechanisms for stewardship of the DDIF beyond initial implementation, supporting its long-term sustainability and impact.

4.8.1 Framework evolution with policies and technologies. As the regulatory and technological landscape continues to evolve because of instruments such as the EU CE Action Plan, the DPP Initiative and ISO data standards, the emergent framework is expected to remain adaptive.

Governance structures should include dedicated roles or working groups responsible for:

- monitoring changes in policy requirements (e.g. new ESG disclosure rules, digital compliance mandates);
- tracking technological advancements, such as improvements in AI, blockchain or materials sensing technologies; and
- updating digital templates, ontologies and system interfaces to remain compatible with industry-wide standards.

This ensures that the DDIF remains interoperable, legally compliant and technically future-proof across different regional and project contexts.

4.8.2 Continuous evaluation and refinement. To support continuous improvement, DDIF incorporates periodic evaluation cycles through which performance data, user feedback and audit findings are analysed and used to refine both the digital infrastructure and operational processes. Evaluation should consider:

- data quality and completeness across lifecycle stages;
- user engagement and adoption metrics; and
- outcomes in terms of circularity, carbon savings and reuse rates.

Refinements may include adding new DPP data fields, updating stakeholder workflows, improving system usability or introducing new reporting capabilities. Ideally, these updates are informed by feedback loops from EoL assessments, learnings from new case study and developments in policy and certification systems. By embedding governance and review as an ongoing strategic function, not a one-off exercise the framework remains a living, adaptive tool capable of supporting resilient, circular and data-driven transformation in the built environment. In practical terms, the governance layer can be operationalised through public procurement. For example, contracting authorities may require DPP as part of tender documentation to verify embodied carbon, material provenance and reuse eligibility of construction components. During project delivery, DPP-linked DMBs enable compliance checks against circular procurement criteria, while lifecycle updates support post-occupancy reporting and auditability. This allows public clients to move beyond static declarations toward verifiable, data-driven compliance with CE and carbon reduction targets.

Taken together, the eight stages of the DDIF operate as an integrated and iterative system rather than a linear sequence. Early-stage activities related to initiation, data definition and technological integration establish the foundations for reliable digital traceability, while subsequent stages enable dynamic lifecycle monitoring, circularity assessment and material recirculation through the DMB. Information generated during use and EoL phases feeds back into design, procurement and governance processes, reinforcing continuous learning and improvement across project cycles. The interaction between stages is mediated by the DPP, which functions as a persistent digital backbone, ensuring continuity of data, alignment of stakeholder actions and traceability across EN 15978 lifecycle phases. This systemic interaction enables the framework to support both operational decision-making and long-term circular and carbon-reduction objectives across diverse built environment contexts.

Table 3 synthesises the alignment between DDIF stages, EN 15978 lifecycle phases and enabling technologies, while distinguishing mandatory core stages required for traceability and circularity from adaptive stages that may be implemented progressively depending on project scale, lifecycle phase and regulatory context. Prior studies have mapped digital technologies to lifecycle phases to support CE and Industry 4.0 transitions in construction (Lara *et al.*, 2025; KC *et al.*, 2025; Çetin *et al.*, 2023; Dalirazar *et al.*, 2023). However, these mappings typically emphasise technological integration for decarbonisation or process optimisation rather than structured lifecycle governance and DPP–DMB interoperability. Building upon these foundations, Table 3 extends existing lifecycle–technology mappings by integrating DPPs and DMBs within an EN 15978-aligned implementation sequence, explicitly linking information flows to material looping and governance mechanisms.

5. Integrated information and material flow across the lifecycle

Effective circularity in the built environment depends on continuous information flows that shape how materials are tracked, managed, reused and reintegrated across asset lifecycles, thereby determining the extent to which material value is retained, recovered or lost. In the absence of a comprehensive DDIF, built assets often follow a linear cradle-to-grave trajectory, from production (A1–A3) to construction (A4–A5), use (B1–B8) and EoL (C1–C4), with limited potential for recovery or reuse. This results in substantial material loss, particularly at Stage C4, where components are typically disposed of or downcycled. Even within the EU, reuse rates remain below 30%, and recycling rates average around 40%, often involving downcycling that erodes both material quality and market value (Build Up, 2024). These figures are generally lower in developing countries, where infrastructure for high-quality material recovery is limited.

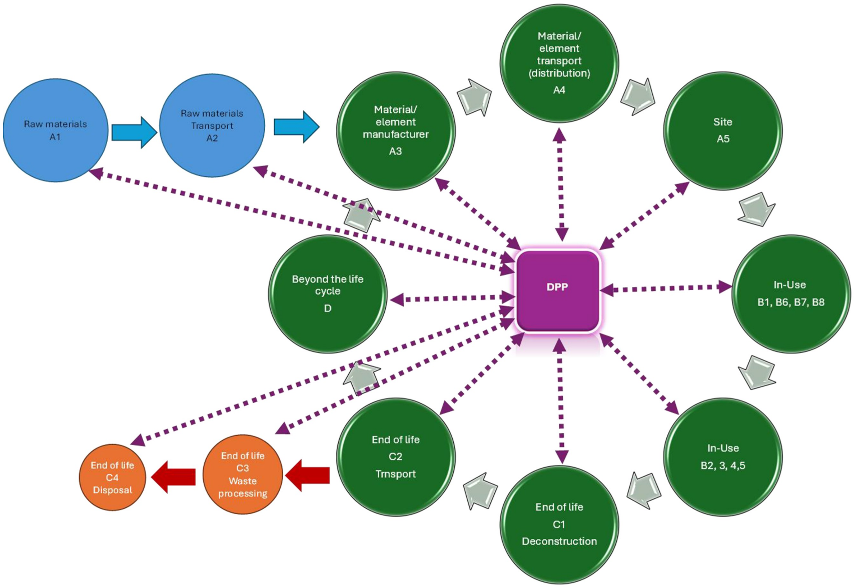
Despite the recognised importance of lifecycle connectivity discussed in Section 2, breakdowns at handover points continue to disrupt traceability and reuse decisions in practice. As a result, information generated during design and construction is frequently lost, degraded or inaccessible during operation and EoL phases, undermining reuse and value recovery despite the existence of digital tools.

Application of the DDIF restructures this linear pattern into a circular, cradle-to-cradle configuration, as illustrated in Figures 3(a) and (b). Rather than reiterating the conceptual roles of its core instruments, the section focuses on how their coordinated operation enables closed-loop flows: verified lifecycle data are propagated forward across stages, while EoL outputs are channelled back into upstream decision-making and procurement

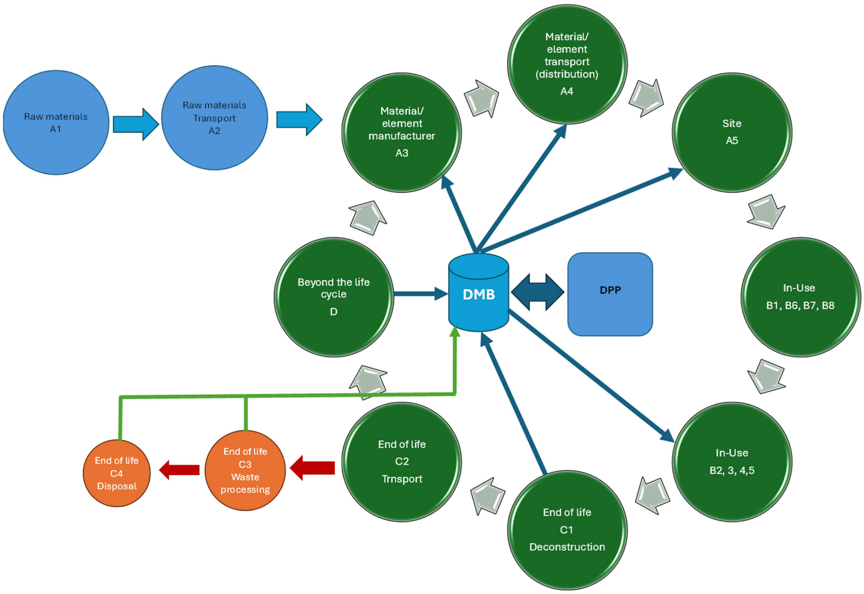
Table 3. Alignment of DDIF stages with lifecycle phases, technologies and flows

DDIF stage	Lifecycle phase(s) (EN 15978)	Key enabling technologies	Role in information and material flow	Implementation status
1 Initiation and planning	A0–A1	BIM, digital collaboration platforms	Defines circular objectives, stakeholder roles and data requirements that govern downstream information and material flows	Mandatory
2 Data collection and standardisation	A1–A3	BIM, ISO 23386/23387 templates, EPD databases	Establishes standardised data structures enabling lifecycle-wide traceability and interoperability	Mandatory
3 Technological integration	A1–D	BIM, IoT, AI, blockchain, digital twins (overarching)	Integrates data streams into a unified digital environment; DTs synchronise real-time information across lifecycle stages	Mandatory
4 DPP and DMB creation	A1–A5 (with updates across B–D)	BIM, blockchain, DPP/DMB platforms	Creates and continuously validates DPPs; links verified components to DMB entries for future reuse	Mandatory
5 Digital lifecycle monitoring and updates	B1–B8, C1–C4	IoT, AI, digital twins	Maintains real-time performance, condition and carbon data feeding forward into reuse and recovery decisions	Adaptive
6 End-of-life and circularity assessment	C1–C4 → A3, D	DPPs, DMBs, AI, digital twins	Enables quality-based recovery and material looping from C stages back to A3, as shown in Figure 5	Mandatory
7 Reporting and sharing	A–D	DPP platforms, ESG and compliance tools	Provides stakeholder-specific access to verified data supporting compliance, procurement and transparency	Adaptive
8 Review and governance	A–D	Blockchain, audit tools, digital twins	Oversees data integrity, policy alignment and continuous framework refinement	Mandatory

Source(s): Authors' compilation (2026)



(a)



(b)

Figure 3. (a) Integrated information flow across the building lifecycle enabled by DPPs (b). Circular material flow enabled by the integration of DPPs and DMBs
Source: Authors' compilation (2026)

processes, reducing information asymmetry, transaction costs and uncertainty associated with material reuse.

Figure 3(a) illustrates the integrated bidirectional information flow across the lifecycle, enabled by DPPs. The purple arrows indicate how data is both received and redistributed across project stages, transforming the DPP into a living DT. This enables lifecycle feedback loops, from installation, use and maintenance to disassembly, feeding verified data into future design cycles and supporting second-life applications that extend asset lifespans and improve returns on material investment.

Complementing the DPP, the DMB acts as a digital repository and marketplace for reusable and surplus materials. As shown in Figure 3(b), validated components from deconstruction phases (C1–C3) are catalogued and made available for reuse in other projects. The green arrow illustrates how these components can re-enter the value chain at manufacturing (A3), replacing virgin materials. By enabling quality-assured material matching and reuse, the DMB supports secondary materials markets, reduces procurement costs and mitigates exposure to price volatility in primary material supply. This integration diverts materials from disposal (C4) and enables material recirculation based on quality, performance and sustainability data.

Together, these integrated information and material loops shift project delivery from reactive waste handling toward anticipatory resource management. By linking lifecycle data continuity with reuse pathways and market activation, the DDIF supports value retention, improved carbon accounting and ESG-aligned decision-making, while Figures 3(a) and (b), visualises the operational transformation achieved when linear project workflows are replaced with digitally mediated circular systems.

6. Discussion

6.1 Practical application of the DDIF in built environment projects

The development of the DDIF marks a significant advancement in operationalising circularity and carbon neutrality in the built environment by translating digital traceability concepts into actionable practices for material selection, utilisation and waste management. Evaluating the DDIF's contribution involves assessing its alignment with policy imperatives, technological feasibility and practical applicability, while comparing it with existing tools and identifying pathways for regulatory integration.

DDIF is strongly aligned with the EU Green Deal and CE Action Plan, both of which prioritise digital traceability and resource efficiency. By embedding interoperable DPPs across lifecycle stages, it supports the EU DPP Initiative's goals around product durability, circularity and transparency. EoL feedback and material reuse through the DMB complement the Level(s) framework and ISO 20887, while the modular structure based on EN 15978 ensures consistency with LCA standards and GPP criteria.

A key strength of the DDIF is its capacity to enable data-informed decision-making across all lifecycle stages. The DPP acts as a real-time digital knowledge base, supporting decisions on material selection, reuse and EoL strategies. This facilitates carbon reduction, construction waste minimisation and reuse optimisation, echoing findings by Çetin *et al.* (2023) on the value of integrated data models in reuse planning and performance tracking.

Crucially, the DDIF addresses not only technical integration but also the structural and institutional causes of data fragmentation that have been widely reported in the literature, including lifecycle handover failures, unclear data custodianship, misaligned incentives and weak accountability for EoL outcomes (Munaro and Tavares, 2021; Çetin *et al.*, 2023; Neligan *et al.*, 2023). While prior studies largely diagnose these challenges as barriers to effective DPP and CE implementation, they often stop short of operational solutions (Kebede *et al.*, 2024; Gianvincenzi *et al.*, 2025). By embedding explicit governance layers, lifecycle feedback loops and market-facing mechanisms through the DMB, the DDIF responds directly to these documented gaps, enabling continuity of information beyond design and construction and supporting accountable reuse and recovery decisions at EoL. In doing so, the DDIF contributes to ongoing debates in construction innovation concerning the translation of digital technologies from conceptual potential into structured, governance-supported implementation models.

Designed to be technology-independent and modular, DDIF is adaptable to different project types and levels of digital maturity. This flexibility supports wide-scale deployment across diverse contexts, consistent with digital construction best practices (Dalirazar *et al.*, 2023). It integrates established technologies, BIM, IoT, blockchain, AI and DTs, that are already used in asset management for real-time monitoring and LCA (Byers, 2025; Trubina *et al.*, 2024). The adoption of open data standards (ISO 23387, IFC, COBie) enhances interoperability and reduces vendor lock-in, aligning with digital sustainability goals (Markou *et al.*, 2025).

6.2 Positioning the DDIF relative to existing frameworks and literature

In contrast to existing approaches reported in the literature, such as static material passports, digital logbooks or product-centric DPP pilots (e.g. Madaster), the DDIF advances the state of the art by explicitly integrating continuous lifecycle monitoring, EoL feedback loops and market-facing material recirculation mechanisms.

Compared to existing models such as static material passports or digital logbooks (e.g. Madaster), the DDIF distinguishes itself through its dynamic, bidirectional data flows and feedback loops. Rather than focusing solely on early lifecycle phases, it supports continuous updates throughout use and EoL stages, powered by AI and DTs. Unlike sector-specific implementations in fields like electronics or textiles, the DDIF offers a comprehensive, built environment-specific framework that integrates environmental, technical and governance considerations into a unified, scalable structure.

7. Practical and policy implications

Building on the predominantly conceptual focus of prior literature, this section demonstrates how the DDIF translates fragmented technical, regulatory and practice-oriented insights into a lifecycle-aligned implementation logic for real-world deployment. Whereas earlier studies have often examined DPPs, material databases or CE strategies in isolation or at discrete lifecycle stages, the DDIF integrates these elements into an operational structure linking lifecycle phases, digital enablers and governance mechanisms. In doing so, the framework advances existing conceptual narratives by converting abstract circularity principles into implementable stages applicable across diverse regulatory and project contexts.

The implications of this integration are examined across two complementary horizons: near-term measures that can be embedded within existing project workflows, and longer-term transformations requiring coordinated policy, market and governance reform. The following subsections consider practical, environmental and economic impacts for industry stakeholders, alongside implementation risks and scalability constraints.

7.1 Practical implications for industry stakeholders

- The DDIF enables near-term innovation in design, construction and asset management by embedding digital material traceability within everyday project workflows. Rather than introducing standalone digital tools, the framework restructures handover procedures, data responsibilities and decision points across lifecycle stages, allowing material intelligence to persist from early design through operation and deconstruction. For designers and engineers, DDIF offers access to structured, up-to-date material intelligence that persists across lifecycle stages, enabling near-term integration of DPP data into BIM-based design decisions, while supporting circular design decisions that remain actionable during construction, operation and EoL phases.

- Contractors and facility owners benefit from continuous material records linked to maintenance and deconstruction activities, which can be implemented incrementally through improved data capture at handover and retrofit stages, reducing information loss at handover points and increasing the residual and reuse value of assets. Policymakers and regulators gain access to auditable, lifecycle-consistent data that improves compliance monitoring, ESG reporting and enforcement credibility, although full realisation depends on broader regulatory alignment and uptake across projects.

Additionally, DDIF supports interoperable data exchange among tools and stakeholders, shifting material information from project-bound documentation to asset-bound digital records, thereby reducing silos and enabling coordinated decision-making across the project lifecycle. To realise these benefits fully, implementation must be supported by collaborative data governance models, incentives for open data sharing, and capacity-building programs to improve digital literacy among industry stakeholders.

7.2 Environmental implications

Environmentally, the DDIF embeds reuse planning, lifecycle monitoring and EoL feedback loops into routine project workflows, enabling systematic diversion of recoverable materials from disposal and reducing demand for virgin resources. Continuous updates to DPP records improve the reliability of embodied-carbon inventories and allow reuse and life-extension scenarios to be evaluated prospectively across Stages A–D. At portfolio scale, standardised environmental data extraction supports consistent tracking of circularity and carbon performance targets across projects, although the magnitude of these benefits depends on uptake across supply chains and jurisdictions.

7.3 Economic implications and market alignment

The DDIF reframes material traceability as an economically productive capability rather than a compliance-only function. At the project level, structured documentation of components through DPPs allows stakeholders to reduce disposal costs, preserve residual asset value and plan reuse strategies during operation and refurbishment rather than only at deconstruction. Linking these verified components to DMB-enabled exchanges further enables secondary material markets in which recovered elements retain measurable financial value instead of becoming sunk costs at EoL.

At portfolio scale, these mechanisms support reduced dependence on virgin materials, lower procurement risk and delayed capital expenditure through reuse, resale and redeployment of existing components. Automated extraction of compliance and certification data from DPP streams also lowers transaction costs associated with auditing and regulatory reporting, shortening approval lead times for green building certifications and sustainability disclosures.

While the literature highlights the importance of regulatory recognition and harmonised quality assurance for market maturation, the DDIF operationalises these requirements by embedding standardised data templates, verification protocols and governance layers directly within project workflows. Alignment with evolving regulatory instruments, such as the Construction Products Regulation and Corporate Sustainability Reporting Directive, positions material transparency as both a risk-mitigation mechanism and a source of competitive advantage for early adopters.

These economic effects are contingent on supportive policy instruments, procurement reform and cross-project participation, linking this section directly to the scalability considerations discussed in Section 7.4.

7.4 Implementation risks and scalability considerations

While the DDIF provides a structured and implementation-ready pathway for advancing circularity and carbon neutrality, its real-world adoption is subject to several practical constraints. Initial implementation costs associated with data capture, system integration and digital upskilling, may limit participation by SMEs and projects with limited digital maturity. Data ownership, custodianship and liability remain critical concerns, especially at EoL stages where multiple stakeholders interact and commercial sensitivities. In addition, uneven digital readiness across regions and legacy assets with incomplete or low-quality data can constrain full lifecycle integration.

Scalability is further influenced by fragmented supply chains and varying regulatory requirements across jurisdictions. To mitigate these risks, the DDIF supports phased and adaptive implementation, distinguishing mandatory core stages from context-dependent components. Public procurement mandates shared digital infrastructures (e.g. platform-based DMBs), and alignment with open standards can reduce entry barriers and distribute costs over time. These considerations highlight that effective scaling of the DDIF depends not only on technical readiness but also on supportive governance, incentives and coordinated industry–policy action.

8. Conclusion and further research

This study presents the DDIF as a robust, modular strategy to embed circularity and carbon neutrality within the built environment through improved material traceability, reuse and waste reduction. Developed through a rigorous, multi-phase process and validated by expert input, the DDIF leverages widely adopted digital technologies, including BIM, IoT, blockchain, AI and DTs, to enable real-time data integration across all lifecycle stages, in alignment with EN 15978. By utilising open data standards such as ISO 23387, IFC and COBie, the DDIF promotes interoperability, scalability and reduced vendor lock-in. Rather than introducing novel digital technologies, the key contribution of this study lies in the structured synthesis and operationalisation of fragmented technical, policy and practice-based knowledge into a coherent, lifecycle-aligned implementation framework. Specifically, the DDIF addresses persistent real-world failures in data continuity by systematically linking lifecycle phases, enabling technologies and governance mechanisms, thereby translating conceptual principles of DPPs and CE into implementable stages.

The combined functionality of DPPs and DMBs enables centralised lifecycle documentation, reuse mapping and regulatory compliance, hence laying the groundwork for a closed-loop construction system that significantly mitigates material waste while unlocking new forms of value creation through secondary material markets and reduced lifecycle risk.

Effective implementation requires coordinated efforts across policy, industry and technology sectors. This includes mandating DPPs in public procurement, integrating DPP data into BIM workflows, and ensuring accurate, verifiable data contributions during retrofitting and deconstruction phases. Technology providers must support this shift by developing interoperable systems underpinned by standardised ontologies and open APIs. Further research is essential to enhance the DDIF's scalability and intelligence. Key directions include automated DPP generation using AI, predictive analytics for material reuse potential, city-scale DMBs and the integration of blockchain-enabled smart contracts for lifecycle governance. Advancing these capabilities will strengthen the digital infrastructure necessary to enable a truly circular and carbon-neutral construction industry and built environment, transforming systemic material inefficiencies into opportunities for long-term sustainability.

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Appendix

Table A1. Mapping of workshop themes to framework components

Workshop theme	Indicative expert inputs (examples)	Implication identified	Corresponding DDIF framework element(s)
Lifecycle data continuity and traceability gaps	"Data disappears after handover"; "No continuity between construction and demolition data"	Need for continuous, dynamic lifecycle data capture across A–D stages	Digital lifecycle monitoring and updates (Section 4.5); DPP creation logic
Interoperability and standards alignment challenges	"Systems don't talk to each other"; "too many proprietary formats"	Requirement for standardised data templates and open interoperability	Data collection and standardisation (Section 4.2); technological integration (Section 4.3)
Unclear stakeholder roles and data ownership	"Who owns the passport data?"; "responsibilities shift across lifecycle stages"	Need to explicitly define stakeholder responsibilities and access rights	Initiation and planning (Section 4.1); reporting and sharing (Section 4.7); governance (Section 4.8)
Weak integration of end-of-life feedback into design	"Demolition data is never reused"; "design teams don't learn from end-of-life"	Need for feedback loops linking end-of-life outcomes to future projects	End-of-life and circularity assessment (Section 4.6); DMB integration
Governance, reporting, and regulatory readiness	"Frameworks must support ESG reporting"; "policy alignment is essential"	Necessity for governance, auditing, and compliance mechanisms	Reporting and sharing (Section 4.7); review and governance (Section 4.8)

Source(s): Authors' compilation (2026)

Table A2. Traceability matrix linking expert workshop themes to DDIF framework components

Expert workshop themes	Initiation and planning	Data standards	Technology integration	DPP/DMB creation	Lifecycle monitoring	End-of-life and circularity	Reporting and sharing	Governance and review
Lifecycle data continuity gaps (loss of data across A–D stages)				✓	✓	✓		
Interoperability and standards issues (fragmented tools, formats)		✓	✓	✓			✓	✓
Unclear stakeholder roles and ownership (data access, responsibility)	✓							
Weak end-of-life feedback loops (design not informed by end-of-life data)					✓	✓		
Governance, ESG and regulatory readiness (auditability, reporting, compliance)	✓						✓	✓

Source(s): Authors' compilation (2026)