



Developing Material Passports for Circular Concrete Management: Integrating Life Cycle Assessment and Blockchain

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Abstract: The transition of the construction sector from a linear take-make-dispose model to a circular economy is critically dependent on the availability of reliable, comprehensive information about the materials embedded in the built environment. Concrete, as the world's most consumed construction material, presents a particularly acute challenge: its production accounts for a significant share of global carbon emissions, yet the vast quantities of concrete currently in service remain undocumented and therefore invisible to circular recovery markets. Material passports have been proposed as a digital instrument to address this informational void, but existing passport concepts remain static, lack integration with environmental assessment methodologies, and fail to provide the trust guarantees necessary for transactions among independent actors. This study develops and empirically evaluates an integrated material passport framework for circular concrete management that combines a structured, standards-aligned data model with a dynamic lifecycle assessment engine and a permissioned blockchain trust layer. The research applies a design science methodology, progressing through the formalisation of a 58-field passport schema, the construction of a modular lifecycle assessment computational engine that recalculates environmental impacts as lifecycle events are recorded, the configuration and testing of a blockchain architecture employing Raft consensus and off-chain storage, and the application of the integrated framework to four illustrative circularity scenarios derived from real-world European concrete supply chain data. The passport data model was derived through a criterion-based filtering of 137 candidate fields, achieving a Fleiss' kappa of 0.84 among domain experts and 72 per cent alignment with existing ISO and CEN standards. The dynamic lifecycle assessment engine demonstrated that tracking a concrete element through multiple use cycles reveals a global warming potential of 171.5 kg CO₂-eq per cubic metre under a three-cycle reuse and recycling scenario, compared with the 327.4 kg CO₂-eq that a static environmental product declaration would report for a single linear cycle, capturing a net environmental benefit of up to 265.9 kg CO₂-eq per cubic metre for intact structural reuse. The permissioned blockchain testnet, configured with four validator nodes, achieved a tamper detection rate of 1.00 across ten deliberate off-chain data alteration attempts with a mean verification latency of 2.7 seconds and an annual network energy consumption of 2,803 kWh, representing less than 0.01 per cent of the global warming potential savings enabled by the system. The Monte Carlo-based economic analysis identified a positive net present value of €2,870 to €3,960 per cubic metre for intact reuse scenarios, with viability thresholds of a virgin concrete price above €120 per cubic metre and a discount rate below 5.8 per cent, and demonstrated that a €40 per tonne carbon price extends economic viability to lower-grade recycling pathways. The study confirms that the integration of material passport design, dynamic lifecycle assessment, and blockchain technology into a single operational framework is technically feasible, environmentally meaningful, and conditionally economically viable. The findings provide an evidence-based template for industry practitioners, standardisation bodies, and policymakers seeking to operationalise digital product passports for construction materials and to advance the circular transition of the concrete sector.

Keywords: material passport, circular economy, concrete, life cycle assessment, blockchain, digital product passport, dynamic environmental assessment.

1. Introduction

The global construction sector stands at a critical juncture, simultaneously serving as a fundamental driver of economic development and human well-being while exerting unprecedented pressure on planetary boundaries (Habert et al., 2020; Zakerhaghighi et al., 2015). Urbanisation, population growth, and rising living standards continue to fuel an insatiable demand for new buildings and infrastructure, transforming the built environment into the world's largest consumer of raw materials and one of the most significant producers of waste (Benachio et al., 2020; Kahvand et al., 2015). Within this vast industrial ecosystem, concrete reigns supreme. It is the second most consumed substance on Earth after water, with annual global production exceeding 30 billion tonnes, a figure that continues to climb as developing economies expand their urban fabric and industrialised nations undertake extensive renovation and replacement of ageing infrastructure (Scrivener et al., 2018; Dehghan et al., 2024b). The very materiality of modern civilisation is, to an overwhelming degree, cast in cement, aggregate, and water. Yet this dependence carries a profound environmental burden. The production of Portland cement alone accounts for approximately 7–8% of global anthropogenic carbon dioxide emissions, while the extraction of sand and gravel for aggregates has generated severe ecological degradation in riverbeds, coastlines, and terrestrial landscapes (Habert et al., 2020; Norouzzian & Gheitarani, 2023). Beyond the emissions embodied in its creation, concrete presents a formidable end-of-life challenge: demolition waste from concrete structures constitutes the single largest waste stream by mass in many countries, typically directed toward landfills or, at best, crushed for low-value applications such as road base, a process that downcycles valuable material and fails to preserve the embodied energy, water, and economic investment locked within the hardened cement paste and carefully graded aggregates (Oluleye et al., 2022; Gheitarani et al., 2024c).

The prevailing model under which concrete is produced, consumed, and discarded adheres to a profoundly linear logic. Raw materials are extracted from quarries and mines, transported over considerable distances, processed at high temperatures in energy-intensive kilns, mixed into a versatile but largely anonymous composite, placed into temporary formwork, and then, after a service life that often spans merely a few decades—a blink of an eye in geological time—demolished and removed from the technosphere (Ellen MacArthur Foundation, 2022; Aghazadeh Dizaji & Ahmadian, 2016). This linear trajectory, from cradle to grave, embodies a systemic failure to recognise the intrinsic value of the material beyond its first use. It treats concrete not as a temporary storage of energy, carbon, and engineering effort that might be unlocked and recirculated, but as a disposable commodity whose worth is extinguished the moment a building permit expires or a wrecking ball strikes (European Commission, 2019; Ghadarjani & Gheitarani, 2013). The environmental and economic irrationality of this paradigm becomes starkly apparent when considering that the concrete in a mid-rise office tower represents not only the direct emissions of cement manufacture but also decades of absorbed atmospheric carbon through natural carbonation, significant volumes of increasingly scarce water, and the logistical imprint of transportation, placement, and finishing (Pani et al., 2025; Gheitarani et al., 2024d). To consign such a

complex material history to landfill is to erase both liability and asset without distinction, forfeiting opportunities for high-quality recovery that could dramatically reduce the primary material demand of future construction cycles (Benachio et al., 2020; Ghadarjani et al., 2013).

In response to the evident unsustainability of linear material flows, the concept of a circular economy has gained considerable traction across industrial sectors, and the built environment is increasingly identified as a domain of high leverage for circular interventions (Ellen MacArthur Foundation, 2022; Gheitarani & Norouzzian, 2024a). The circular economy proposes a regenerative system in which resource input, waste, emissions, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. Applied to concrete, circularity encompasses a hierarchy of strategies: first, preserving existing structures through adaptive reuse and life extension; second, designing new buildings for disassembly and flexibility; third, reusing whole concrete elements such as beams, columns, and hollow-core slabs in new structural assemblies; and fourth, recycling concrete into high-grade secondary aggregates and reactivated cementitious components that can substitute for virgin materials in new concrete mixes (Charef, 2024; Naghibi Iravani et al., 2024a). The potential benefits of such a shift are substantial. Reducing the demand for new clinker production could cut carbon emissions dramatically, while preserving the enormous volumes of aggregates already mined and processed would alleviate pressure on natural reserves and sensitive ecosystems (Hasheminezhad et al., 2024; Norouzzian & Gheitarani, 2025). Economically, the value retained in recovered concrete elements and materials could generate new business models centred on material banking, leasing, and take-back schemes, transforming construction firms from mere consumers of commodities into stewards of material stocks with long-term balance-sheet value (Aral et al., 2024; Norouzzian & Guyadeen, 2025). However, realising these potentials requires a fundamental transformation not merely of technical processes but of the information infrastructure that underpins construction supply chains. Concrete, as it circulates, cannot remain the anonymous grey mass it has historically been; it must become a documented, traceable, and evaluable entity whose composition, origin, performance history, and environmental footprint are transparent to all actors in the value chain (Heinrich et al., 2023; Gheitarani, n.d.). Without such transparency, high-quality reuse is impossible, because a structural engineer cannot safely incorporate a recovered beam without knowing its original strength class, exposure history, or residual prestress; a concrete plant cannot confidently substitute secondary aggregates without verifying their alkalinity, contamination levels, or grading; and a sustainability auditor cannot credibly report the embodied carbon savings of a circular project without a robust chain of custody linking the reused material to its primary production (Mrad et al., 2025; Gheitarani et al., 2024b). The transition from linear to circular concrete management, therefore, is fundamentally an information problem as much as it is a material science or policy problem (Motiei et al., 2025; Naghibi Iravani et al., 2024c).

The material passport has emerged in recent years as a pivotal instrument for enabling circularity in the built environment (Heinrich et al., 2023; Khanian et al., 2013). Originating in the domain of industrial ecology and gaining prominence through

initiatives such as the European Union's Circular Economy Action Plan and platforms like Madaster and the Buildings as Material Banks project, a material passport is a digital or physical record that captures the identity, composition, and circular potential of materials and products embedded in a building or infrastructure asset (Markou et al., 2024; Qurraie & Gheitarani, 2025). It functions as a kind of identity document that travels with a material throughout its lifecycle, accumulating data from production through use, maintenance, refurbishment, and eventual recovery (De Wolf et al., 2024; Naghibi Irvani et al., 2024b). In principle, a comprehensive material passport for concrete would document the source and chemical composition of the cement, the geographic origin and mineralogy of the aggregates, the mix design including water-to-cement ratio and admixtures, the compressive strength achieved at 28 days and at later ages, the curing regime, the environmental conditions to which the concrete has been exposed during service, any repairs, strengthening interventions, or surface treatments applied, and, crucially, the results of lifecycle environmental assessments that quantify the embodied energy, global warming potential, water consumption, and other impact categories associated with that specific batch (Mohamed et al., 2025; Aghazadeh Dizaji, 2024b). With such a passport, a concrete element extracted from a decommissioned building could be offered to the market not as an anonymous piece of rubble but as a certified product with a known performance envelope and a documented sustainability pedigree, enabling specifiers to select it with the same confidence they would place in a virgin material (Motiei et al., 2025; Aghazadeh Dizaji, 2024a). Yet the development of material passports for concrete is fraught with challenges. Concrete supply chains remain notoriously fragmented, with multiple tiers of suppliers, subcontractors, and batch plants contributing to a single project, often without systematic data handover protocols (Hamidkhaniha et al., 2025; Aghazadeh Dizaji & Aydin, 2025). The quality and granularity of available data vary enormously: while a large prefabrication plant may maintain detailed digital records of every pour, a small ready-mix supplier may operate with paper delivery tickets and minimal traceability (Aral et al., 2024; Aghazadeh Dizaji, 2017). Furthermore, concrete structures frequently undergo decades of service, during which ownership changes, maintenance interventions are poorly documented, and original design records are lost (Charef, 2024; Gheitarani et al., 2020). Capturing a reliable lifecycle inventory for a material that may outlive the organisations that produced it poses a profound institutional and archival challenge.

Compounding these logistical hurdles is the critical need to embed environmental accountability within the passport framework. Without rigorous and standardised lifecycle assessment (LCA) data, a material passport risks becoming merely an inventory of physical properties, failing to capture the environmental value that circular recovery seeks to preserve (Cerchione et al., 2023; Gheitarani et al., 2013a). LCA provides the methodological backbone for quantifying the environmental impacts associated with a product system throughout its life, from raw material extraction through processing, transportation, use, and end-of-life treatment. When applied to concrete, LCA can reveal the specific contributions of cement type, aggregate transport distances, admixture chemistry, and concrete placement methods to indicators such as global warming potential, acidification, eutrophication, ozone depletion, and resource depletion (Hasheminezhad et al.,

2024; Aghazadeh Dizaji, 2024c). By integrating such LCA results directly into a material passport, it becomes possible to assign a quantitative environmental value to the concrete that is recovered, creating a direct link between circular practices and measurable sustainability outcomes (Habibi et al., 2023; Aghazadeh Dizaji & Aydin, n.d.). However, integrating LCA into material passports is not a trivial undertaking. The methodologies and databases used for LCA vary across regions, sectors, and practitioners, introducing inconsistencies that can undermine comparability (Cerchione et al., 2023; Dehghan et al., 2024a). The choice of system boundaries—whether to include only cradle-to-gate impacts or to extend to full cradle-to-grave with end-of-life credits—can dramatically alter the results, making it difficult to benchmark one passport against another. Moreover, LCA models are inherently static, relying on average data and assumptions that may not reflect the specific conditions of a given concrete batch (Habibi et al., 2023; Gheitarani et al., 2013b). A material passport demands dynamic, batch-specific environmental information that can be updated as the material moves through its lifecycle, yet such real-time LCA capabilities are still in their infancy (Mohamed et al., 2025; Aghazadeh Dizaji et al., 2023). Thus, while the vision of an LCA-integrated material passport is compelling, its practical realisation requires overcoming significant methodological, data quality, and interoperability challenges.

A further dimension of complexity arises when considering the trustworthiness and immutability of the information contained in a material passport. The value of a passport lies entirely in the credibility of its claims. If a structural engineer cannot trust that the declared compressive strength is accurate, they will apply conservative safety factors that erode the economic case for reuse. If a sustainability certification scheme cannot verify that the claimed recycled content genuinely originates from a specific decommissioned project, greenwashing becomes not only possible but likely (Zhao et al., 2023; Aydin et al., 2020). The construction sector has historically been plagued by information asymmetries, with material suppliers, contractors, and clients often possessing divergent and sometimes conflicting interests regarding the disclosure of product characteristics (Singh & Kumar, 2024; Gheitarani et al., 2024a). Centralised databases maintained by single entities are vulnerable to manipulation, data loss, or simply the dissolution of the maintaining organisation over the long service life of concrete (Zhang & Fröhling, 2024; Sadigh et al., 2023). In this context, emerging distributed ledger technologies—commonly grouped under the term blockchain—offer a potentially transformative mechanism for establishing trust in material passports. Blockchain provides a decentralised, append-only ledger in which transactions or data entries are cryptographically secured and time-stamped, making retrospective alteration practically impossible without detection (Zhao et al., 2023; Sarabi et al., 2023). When applied to a material passport system, blockchain can create an immutable chain of custody for concrete, recording every significant event from the initial extraction of raw materials through manufacturing, quality testing, incorporation into a building, maintenance, decommissioning, and subsequent reuse or recycling (Singh & Kumar, 2024; M. A. G. et al., 2024). Because the ledger is distributed across multiple nodes, no single party can unilaterally alter or delete records, addressing the vulnerability of centralised databases to organisational failure or malfeasance (Zhang & Fröhling, 2024; Farrokhirad & Gheitarani, 2024). Smart

contracts—self-executing code stored on the blockchain—can automate the verification of certain passport conditions, such as confirming that a reclaimed concrete element meets predefined strength thresholds before being released for sale, thereby reducing transaction costs and building confidence among market participants (Soman et al., 2025; Khanian et al., 2019).

However, the integration of blockchain into material passports for concrete is not a panacea. The technology itself carries an environmental footprint, particularly in proof-of-work consensus mechanisms that require substantial energy consumption, which would need to be carefully weighed against the environmental savings enabled by circularity (Soman et al., 2025; Maleki et al., 2024). Scalability remains a concern, as the vast volumes of data generated by the global concrete industry could overwhelm public blockchain networks if not managed through appropriate off-chain storage solutions or more efficient consensus protocols (Mrad et al., 2025; Hosseini et al., n.d.). There are also significant governance questions regarding who controls access to the ledger, who validates new entries, and how errors—if they do occur—can be corrected in a system designed for immutability (Hamidkhaniha et al., 2025; Samami et al., 2024). Furthermore, the technical complexity of blockchain may create barriers to adoption among small and medium-sized enterprises that lack digital literacy or the resources to invest in new infrastructure. The construction industry, traditionally a slow adopter of digital technologies, may resist the paradigm shift required to implement blockchain-based passports at scale unless clear incentives and regulatory drivers are established (De Wolf et al., 2024; Gheitarani & Norouzian, 2024b). The intersection of material passports, lifecycle assessment, and blockchain thus constitutes a nexus of opportunities and challenges that demands rigorous investigation.

A particularly pressing gap in the current body of knowledge concerns the lack of a unified framework that coherently integrates LCA methodologies with blockchain-enabled material passports specifically for concrete in circular construction contexts (Zhang & Fröhling, 2024; Zaker Haghighi et al., 2014). Existing literature addresses these three domains largely in isolation: material passport research focuses on data structures and stakeholder engagement but rarely incorporates dynamic LCA or blockchain verification; LCA studies on concrete provide detailed environmental profiles but seldom connect these profiles to passport systems or consider the implications of multiple use cycles; blockchain research in construction explores supply chain transparency and smart contracts but often overlooks the specific material properties and long time horizons of concrete (Mrad et al., 2025; Aghazadeh Dizaji, 2017). The absence of an integrated framework hampers the ability of industry practitioners, policymakers, and researchers to design, implement, and evaluate material passport systems that are simultaneously information-rich, environmentally meaningful, and trustworthy (Soman et al., 2025; Aghazadeh Dizaji, 2024a). Without such a framework, material passports risk remaining aspirational concepts with limited practical utility, unable to unlock the high-value circular loops that could fundamentally reduce the environmental burden of concrete.

In light of this identified gap, the present study pursues a line of inquiry that examines how material passports for circular concrete management can be developed and operationalised by integrating

lifecycle assessment data within a blockchain-secured information architecture. The research problem centres on the fragmentation and inadequacy of current data management practices for concrete across its lifecycle, which obstruct the transition to high-quality circularity and undermines the credibility of environmental claims. This overarching problem gives rise to a series of interrelated questions that guide the investigation. How should the informational requirements of a material passport for concrete be structured to encompass the full lifecycle from raw material extraction through multiple use phases, and what are the critical data fields that must be captured at each stage to enable reliable structural and environmental assessment for reuse? In what manner can lifecycle assessment methodologies be adapted and embedded within the passport framework to provide batch-specific, temporally dynamic environmental profiles rather than static, average-based inventories that fail to reflect the actual history and context of a concrete element? What role can blockchain technology play in establishing a tamper-proof chain of custody and automated verification of passport claims, and how can the technical architecture of such a system be designed to balance the competing demands of transparency, privacy, scalability, and energy efficiency? Furthermore, what are the practical barriers and enablers for the adoption of such an integrated system among the diverse stakeholders in the concrete supply chain, including raw material producers, batch plant operators, contractors, structural designers, demolition firms, material traders, and regulatory authorities? These questions coalesce into a set of propositions that posit that a structured material passport incorporating dynamic LCA data and secured through a permissioned blockchain with off-chain storage can significantly enhance the traceability, environmental valuation, and market confidence in secondary concrete materials, that such a system can overcome the current fragmentation of concrete data by providing a standardised yet adaptable data model that aligns with existing construction information standards, and that the integration of lifecycle assessment directly into the passport enables real-time environmental accounting that more accurately captures the circular value of concrete than current static approaches. The investigation further operates on the premise that the technical feasibility of the proposed framework can be demonstrated through a reference architecture and illustrative case scenarios, and that the resulting system can inform policy development around digital product passports and circular construction mandates that are increasingly being debated in regulatory contexts such as the European Green Deal (European Commission, 2019; Aghazadeh Dizaji, 2024b).

The significance of undertaking this investigation lies in its potential to bridge three rapidly evolving yet siloed domains and to provide an actionable blueprint for a digital infrastructure that could catalyse the circular transition of the world's most voluminous construction material. By articulating the precise data requirements for concrete passports, the study aims to contribute to standardisation efforts currently underway in international bodies such as the International Organisation for Standardisation and CEN, potentially influencing the development of future digital product passport standards for construction products (De Wolf et al., 2024; Aghazadeh Dizaji, 2024c). By embedding lifecycle assessment directly into the passport logic, the research seeks to elevate environmental performance from a static product

declaration to a dynamic, evidence-based attribute that can be updated and scrutinised across multiple lifetimes, thereby strengthening the credibility of circularity claims in green building certification schemes and carbon accounting frameworks (Cerchione et al., 2023; Aghazadeh Dizaji & Aydin, n.d.). By leveraging blockchain as a trust layer, the study addresses the fundamental governance challenge that has impeded the sharing of sensitive material data among competitive actors, offering a model for decentralised cooperation that could be replicated in other material streams beyond concrete (Zhao et al., 2023; Aghazadeh Dizaji & Aydin, 2025). Ultimately, the work aspires to contribute to the realisation of a construction industry in which materials are no longer anonymous, disposable commodities but valued, documented assets that circulate within a transparent, efficient, and environmentally accountable technosphere, radically decoupling the provision of built infrastructure from the extraction of virgin resources and the emission of greenhouse gases (Ellen MacArthur Foundation, 2022; Aghazadeh Dizaji et al., 2023).

2. Theoretical Foundations

The intellectual foundations upon which this investigation rests span several interconnected domains of knowledge, each of which has evolved substantially in response to the environmental imperatives and technological possibilities of the early twenty-first century. To understand the rationale for integrating material passports, lifecycle assessment, and blockchain technologies in the service of circular concrete management, it is first necessary to situate these concepts within the broader transformation of industrial systems from linear to circular models of resource organisation (Çetin et al., 2023; Gheitarani et al., 2024a). The linear industrial paradigm, which has dominated global production since the onset of the Industrial Revolution, operates according to a deceptively simple logic: raw materials are extracted from nature, transformed through manufacturing processes into products, distributed to consumers, and ultimately discarded as waste when their utility is deemed to have expired (Heisel & Rau-Oberhuber, 2023; Gheitarani et al., 2013a). This take-make-dispose sequence, while delivering unprecedented material prosperity to a significant portion of humanity, rests upon an implicit assumption of infinite resource availability and infinite waste assimilation capacity, both of which are demonstrably false under the biophysical constraints of a finite planet (Aguar et al., 2019; Gheitarani et al., 2013b). The circular economy, articulated most influentially through the work of the Ellen MacArthur Foundation and grounded in earlier traditions of industrial ecology, cradle-to-cradle design, and performance economy thinking, challenges this assumption at its root (Çetin et al., 2023; Gheitarani et al., 2020). It envisions an economic system that is restorative and regenerative by intention and design, one in which the concept of waste is systematically eliminated, and materials are maintained at their highest possible utility and value at all times (European Commission, 2020; Gheitarani et al., 2024b). This is achieved through deliberate strategies that operate at multiple scales: narrowing material and energy flows by improving efficiency, slowing flows by extending product lifetimes and enabling reuse and repair, and closing flows by recycling materials back into production processes after their initial use phase has concluded (Gómez-Gil et al., 2024; Gheitarani et al., 2024c). The distinction between these strategies is not merely semantic; it reflects a fundamental hierarchy of value

preservation that prioritises the retention of embodied labour, energy, and structural integrity over the destruction and reconstitution of materials (Leindecker et al., 2024; Gheitarani et al., 2024d).

The application of circular economy principles to the built environment, and to construction materials in particular, introduces complexities that are not present in the management of shorter-lived consumer goods (Honic et al., 2019; Gheitarani & Norouzian, 2024a). Buildings and infrastructure assets are characterised by exceptionally long service lives that can extend across multiple human generations, during which they are subject to changing ownership, evolving functional requirements, periodic maintenance and refurbishment, and exposure to diverse environmental conditions (Akbarieh et al., 2020; Gheitarani & Norouzian, 2024b). The materials embedded within these structures, concrete chief among them, are not designed for easy separation and recovery; they are typically bonded, cast in place, or integrated into composite assemblies whose disassembly was never contemplated at the design stage (Honic et al., 2023; Gheitarani, n.d.). The notion of circularity in construction, therefore, demands a reconceptualisation of buildings not as final products but as temporary repositories of materials that will eventually re-enter the economic cycle (De Wolf et al., 2024; Naghibi Iravani et al., 2024a). This perspective has given rise to the concept of buildings as material banks, a metaphor that reframes the built environment as a stock of valuable resources that can be inventoried, valued, and eventually withdrawn for reuse or high-quality recycling (Heisel & Rau-Oberhuber, 2023; Naghibi Iravani et al., 2024b). Realising this vision requires that the identity, composition, and condition of materials be known and documented in a manner that persists across the entire lifecycle, from initial specification and procurement through decades of service and eventual deconstruction (Honic et al., 2019; Naghibi Iravani et al., 2024c). Without such documentation, the materials locked within a building are effectively invisible to future users, and the information asymmetry between the current owner of a structure and the potential future user of its components becomes an insurmountable barrier to circular transactions (KC et al., 2024; Farrokhirad & Gheitarani, 2024). It is precisely this informational void that material passports seek to fill.

A material passport, in its most developed conceptualisation, is a comprehensive digital record that accompanies a material, component, or product throughout its entire lifecycle, capturing the data necessary to determine its suitability for circular recovery (Honic et al., 2019; Khanian et al., 2013). The passport is not merely a static certificate of composition but a dynamic repository that accumulates information over time, functioning as a biography of the material that documents its origins, its processing history, its incorporation into larger assemblies, its exposure to environmental and operational loads, and any interventions such as repairs, retrofits, or alterations that modify its properties (Byers et al., 2023; Khanian et al., 2019). The passport concept draws intellectual lineage from multiple antecedents: the product lifecycle management systems that track components in aerospace and automotive industries, the environmental product declarations that communicate the ecological footprint of construction products, and the digital twins that create virtual representations of physical assets for simulation and monitoring purposes (KC et al., 2024;

Aghazadeh Dizaji, 2024a). In the specific context of the built environment, the material passport has been advanced by initiatives such as the Buildings as Material Banks project in Europe, which developed the notion of a materials passport that captures the circular value of building components, and the Madaster platform in the Netherlands, which operates a centralised registry for material documentation (Leindecker et al., 2024; Aghazadeh Dizaji, 2024b). The underlying premise of these initiatives is that information about materials is itself a valuable asset, one that can reduce the transaction costs of circular exchanges, facilitate compliance with emerging regulations on construction waste and embodied carbon, and enable property owners to recognise the residual material value of their assets on their balance sheets (Gómez-Gil et al., 2024; Aghazadeh Dizaji, 2024c).

The informational demands of a material passport for concrete are particularly stringent due to the nature of the material itself (Honic et al., 2023; Aghazadeh Dizaji, 2017). Concrete is not a homogeneous industrial product manufactured to precise tolerances in a controlled factory environment; it is a composite material whose final properties depend on a complex interplay of raw material characteristics, mix proportions, mixing and placement procedures, curing conditions, and long-term environmental exposure. The performance of a given volume of concrete is thus the product of a specific and often poorly documented history, and two batches of concrete that appear identical in superficial appearance may possess significantly different structural capacities, durability characteristics, and environmental footprints (De Wolf et al., 2024; Aghazadeh Dizaji & Ahmadian, 2016). A material passport that is to serve as a reliable basis for reuse decisions must therefore capture a wide array of parameters, including the chemical and mineralogical composition of the cementitious binder, the type and grading of aggregates and their geographic origin, the water-to-binder ratio and the type and dosage of chemical admixtures, the compressive strength as determined by standardised testing at specified ages, the curing regime and its influence on microstructure development, the chloride permeability and carbonation resistance relevant to durability assessment, and any exposure to aggressive agents such as sulphates, acids, or freeze-thaw cycles during service (fib Model Code 2020, 2022; Aghazadeh Dizaji & Aydın, n.d.). Beyond these physical and chemical properties, the passport must also document the structural function that the concrete element originally performed, including its dimensions, reinforcement configuration, prestressing details if applicable, and the design standards to which it was originally designed, as these factors determine the range of potential future applications for which the recovered element can be responsibly specified (CEN/TC 350, 2022; Aghazadeh Dizaji & Aydın, 2025).

Alongside the physical and mechanical identity of the material, a fully developed material passport for circular concrete management must embed a rigorous account of the environmental impacts that are embodied within it. This requirement brings lifecycle assessment, widely known by its acronym LCA, to the foreground as a critical methodological component of passport architecture (ISO, 2006a; Aghazadeh Dizaji et al., 2023). LCA is a systematic analytical technique for evaluating the environmental aspects and potential impacts associated with a product, process, or service

throughout its entire life cycle, from the extraction of raw materials through manufacturing, transportation, use, and end-of-life treatment. The methodology is standardised by international norms, principally the ISO 14040 and ISO 14044 standards, which establish a four-phase framework consisting of goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2006a; ISO, 2006b; Aydın et al., 2020). In the goal and scope definition, the purpose of the study is articulated, and the system boundaries are drawn, determining which processes are included and excluded from the analysis. Inventory analysis involves the compilation and quantification of all relevant inputs and outputs of the system, including energy flows, material flows, and emissions to air, water, and soil (ISO, 2006b; Dehghan et al., 2024a). Impact assessment translates the inventory data into potential environmental impacts across a range of categories, such as global warming potential, ozone depletion, acidification, eutrophication, photochemical oxidant formation, and resource depletion, using characterisation factors derived from environmental science (Levasseur et al., 2013; Dehghan et al., 2024b). Interpretation synthesises the results, identifies significant issues, and evaluates the completeness, sensitivity, and consistency of the analysis (ISO, 2006a; Sadigh et al., 2023). When applied to concrete, LCA typically reveals that the dominant environmental impacts are associated with the production of cement clinker, which requires the calcination of limestone at temperatures exceeding 1400 degrees Celsius, releasing chemically bound carbon dioxide and consuming substantial quantities of fossil fuels or alternative energy sources (ISO, 2020; Sarabi et al., 2023). Aggregates, by contrast, generally contribute a smaller share of impacts unless transported over long distances, while chemical admixtures and reinforcement steel introduce additional impact categories that must be accounted for (Luthin et al., 2023; Ghadarjani & Gheitarani, 2013).

The integration of LCA into material passports is not a straightforward task, as it requires reconciling the inherent characteristics of the two tools (Rodriguez et al., 2025; Ghadarjani et al., 2013). Traditional LCA is a static, retrospective analysis that models an average product system under a defined set of assumptions. It is typically conducted as a one-time study for a product category or a specific production facility, and its results are communicated through environmental product declarations that have a limited validity period (ISO, 2020; Maleki et al., 2024). A material passport, conversely, requires environmental information that is not only specific to the particular batch of concrete in question but also capable of being updated as the material moves through its lifecycle, accumulating new impacts during use, maintenance, and recovery, and potentially offsetting impacts elsewhere in the economy through substitution of virgin materials (Rodriguez et al., 2025; M. A. G. et al., 2024). This tension between static averages and dynamic specificity has prompted the development of more flexible LCA approaches, including consequential LCA that models the system-wide environmental consequences of a decision, dynamic LCA that incorporates temporal variations in emissions and impacts, and parametric LCA tools that allow for the rapid generation of batch-specific environmental profiles by varying key input parameters (Levasseur et al., 2013; Hosseini et al., n.d.). For a material passport to be effective, it must draw upon these advancements to deliver environmental information that is both scientifically defensible and

practically actionable (Luthin et al., 2023; Samami et al., 2024). The goal is to enable a potential user of reclaimed concrete to compare the lifecycle impacts of reusing a specific element against the impacts of manufacturing an equivalent new product, and to make that comparison based on verified, transparent data rather than industry averages or generic assumptions (Levasseur et al., 2013; Qurraie & Gheitarani, 2025).

The credibility of the environmental and technical claims embedded in a material passport hinges critically on the trustworthiness of the data that populates it. Construction supply chains are characterised by a multiplicity of actors—cement manufacturers, aggregate quarries, ready-mix producers, contractors, testing laboratories, demolition contractors, waste processors—each of which may have limited visibility into the operations of the others and limited incentives to share data that could be commercially sensitive or that might expose them to liability (van Capelleveen et al., 2023; Norouzian & Gheitarani, 2023). In such an environment, the risk that passport data could be falsified, selectively reported, or simply lost over time is substantial. Addressing this trust deficit requires mechanisms for ensuring the integrity, provenance, and immutability of data that do not depend on a single centralised authority that could itself become a point of failure or manipulation (Lin et al., 2024; Norouzian & Gheitarani, 2025). It is in this context that blockchain technology has been proposed as a potential solution. Blockchain is a form of distributed ledger technology in which data is structured into blocks that are cryptographically linked to form an append-only chain, with the ledger replicated across a network of participating nodes (KC et al., 2026; Norouzian & Guyadeen, 2025). The key properties that render blockchain relevant to material passport applications are its tamper-evident design, its reliance on consensus mechanisms for the validation of new entries, its capacity to embed programmable logic through smart contracts, and its distributed architecture that eliminates the need for a trusted third party (van Capelleveen et al., 2023; Zaker Haghighi et al., 2014). Once a data record—such as the compressive strength of a concrete batch at 28 days—is committed to a blockchain, any subsequent attempt to alter that record would require the computationally infeasible task of recomputing all subsequent blocks and overpowering the consensus of the network, providing a robust assurance of data integrity (Lin et al., 2024; Zakerhaghighi et al., 2015).

The application of blockchain in construction and real estate has been the subject of growing academic and industry interest, encompassing use cases such as supply chain traceability, automated payment through smart contracts, digital identity for building components, and decentralised registries for land and property rights (KC et al., 2026; Aghazadeh Dizaji, 2024a). In the specific context of material passports, a blockchain-based architecture could enable a multi-stakeholder ecosystem in which each party contributes data relevant to its role—the cement manufacturer records the clinker composition, the ready-mix plant records the batch ticket and delivery time, the testing laboratory records the strength results, the contractor records the pour location, the building owner records maintenance interventions, and the deconstruction contractor records the recovery date and condition assessment—all within a single, consistent, and auditable chain of custody (van Capelleveen et al., 2023; Aghazadeh Dizaji,

2024b). Smart contracts could be programmed to automate certain verification steps, such as checking that a declared strength value falls within an acceptable range before accepting the data into the passport, or releasing a payment to a demolition contractor only once a specified set of passport data fields has been populated (Lin et al., 2024; Aghazadeh Dizaji, 2024c). However, blockchain is not a monolithic technology but a family of configurations with widely varying characteristics. Public, permissionless blockchains such as those underpinning cryptocurrencies offer maximum decentralisation and censorship resistance but suffer from limited transaction throughput and, in proof-of-work variants, very high energy consumption (KC et al., 2026; Aghazadeh Dizaji, 2017). Private, permissioned blockchains, in which participation is restricted to vetted entities and consensus is achieved through lighter-weight protocols, offer superior scalability and energy efficiency at the cost of reintroducing some degree of centralised governance (van Capelleveen et al., 2023; Aghazadeh Dizaji & Aydin, n.d.). For material passport applications, a permissioned or consortium blockchain model, possibly combined with off-chain storage for large data objects such as LCA datasets and linked through cryptographic hashes stored on-chain, is widely considered the most viable architectural approach (KC et al., 2026; Aghazadeh Dizaji & Aydin, 2025).

The convergence of material passports, lifecycle assessment, and blockchain within a unified framework for circular concrete management does not occur in a regulatory or standardisation vacuum. The broader policy environment, particularly within the European Union, is increasingly mandating the digitalisation and environmental documentation of construction products (Suzuki-Klasen, 2025; Aghazadeh Dizaji et al., 2023). The Construction Products Regulation, under revision, is expected to require manufacturers to provide environmental data through digital means, and the Energy Performance of Buildings Directive increasingly emphasises the whole-life carbon performance of buildings (European Commission, 2023; Aydin et al., 2020). The concept of a digital product passport, which would contain information about the composition, origin, and environmental footprint of products across multiple sectors, including construction, has been endorsed in the Circular Economy Action Plan and the Ecodesign for Sustainable Products Regulation (Suzuki-Klasen, 2025; Dehghan et al., 2024a). These regulatory developments create a strong pull factor for the kind of integrated passport system explored in this study, as market participants anticipate future compliance obligations and seek to position themselves as leaders in circular construction (Marsh et al., 2025; Dehghan et al., 2024b). At the same time, voluntary certification schemes such as BREEAM and LEED are evolving to award credits for the use of reused materials and for material transparency, further strengthening the business case for passport adoption (UK Green Building Council, 2025; Ghadarjani & Gheitarani, 2013). Standardisation efforts, including those by CEN Technical Committee 350 on the sustainability of construction works and by ISO Technical Committee 59 on buildings and civil engineering works, are developing the data templates and assessment methodologies that could underpin passport content, although a fully integrated standard covering the three domains addressed here has not yet been published (CEN/TC 350, 2022; Ghadarjani et al., 2013).

Understanding the technological and informational requirements of a material passport also necessitates an appreciation of the broader digital transformation underway in the construction sector. Building Information Modelling, or BIM, represents a paradigm shift in how construction projects are designed, coordinated, and documented, replacing traditional two-dimensional drawings and paper specifications with object-oriented, three-dimensional digital models that embed geometric and semantic information about every building element (Aguiar et al., 2019; Khanian et al., 2013). A material passport for concrete can be conceived as an extension of the BIM logic, carrying the data that originates in the digital model forward into the operational and end-of-life phases that have historically been beyond the scope of BIM deliverables (Akbarieh et al., 2020; Khanian et al., 2019). The Industry Foundation Classes data schema, an open standard for the exchange of BIM data, already includes entities for capturing material properties and can serve as a technical foundation for structuring passport data in an interoperable format that is independent of proprietary software (Aguiar et al., 2019; Naghibi Iravani et al., 2024a). The linkage between BIM and material passports is bidirectional: the BIM model generated during design can pre-populate the passport with the intended material specifications, while the data accumulated in the passport during construction and operation can be fed back into the digital twin of the building, enriching it with as-built and as-maintained information that supports more accurate lifecycle analyses and more confident circular recovery planning (Akbarieh et al., 2020; Naghibi Iravani et al., 2024b).

Despite the considerable promise of the integrated approach to material passports, it must be acknowledged that substantial barriers to implementation persist. The fragmentation of the construction industry, in which many firms are small or medium-sized enterprises with limited digital capabilities, constrains the speed at which any data-intensive innovation can diffuse through the market (KC et al., 2024; Naghibi Iravani et al., 2024c). The lack of standardised data formats and taxonomies for material characterisation, particularly for a heterogeneous material like concrete, means that a passport developed by one consortium may be incompatible with the systems used by another, undermining the very interoperability that circular markets require (Gómez-Gil et al., 2024; Farrokhirad & Gheitarani, 2024). The long latency between the creation of a passport at the time of initial construction and its retrieval at the time of deconstruction, potentially decades later, raises questions about the longevity of digital storage media, the continued availability of software capable of reading the passport format, and the institutional continuity of the organisation that created or maintained the passport (Honic et al., 2023; Maleki et al., 2024). These temporality challenges are more acute in construction than in almost any other sector and must be explicitly addressed in the design of a passport architecture, perhaps through the use of self-describing data formats, archival-grade storage strategies, and governance structures that ensure the passport outlives any single stakeholder (Byers et al., 2023; M. A. G. et al., 2024). Furthermore, the environmental burden of the passport infrastructure itself, including the energy consumption of blockchain networks, the material footprint of data centres required for storage and computation, and the resources consumed in manufacturing sensors and tags, must be transparently assessed to ensure that the net environmental effect of the passport system is unequivocally positive (Marsh et al., 2025; Hosseini et al., n.d.).

Within this rich and multifaceted conceptual landscape, the present study locates its contribution at the intersection where material passport design, dynamic lifecycle assessment, and distributed ledger technology converge. The theoretical foundation rests on the recognition that the transition to circular concrete management is not primarily limited by the availability of technical solutions for crushing, separating, or reprocessing concrete, but rather by the absence of a trustworthy information infrastructure that can connect the physical material with its digital identity across temporal, organisational, and spatial boundaries (Leindecker et al., 2024; Samami et al., 2024). The material passport offers the template for such an identity, lifecycle assessment provides the methodology for quantifying the environmental value that circularity preserves, and blockchain supplies the mechanism for securing the integrity of the information upon which circular transactions depend (Çetin et al., 2023; Qurraie & Gheitarani, 2025). The synthesis of these three elements into a coherent framework constitutes a novel theoretical contribution that extends beyond the sum of its parts. It posits that a concrete element equipped with a blockchain-secured passport containing batch-specific, dynamically updated LCA data can be valorised as a distinct asset class with a transparent and verifiable sustainability premium, creating economic incentives for recovery that are absent when concrete is treated as an undifferentiated bulk material (De Wolf et al., 2024; Sadigh et al., 2023). This theoretical framing draws upon insights from transaction cost economics, which suggests that the cost of verifying the attributes of a good is a major determinant of whether markets for that good can emerge, and from information economics, which highlights the problems of adverse selection that arise when sellers possess more information about product quality than buyers (Heisel & Rau-Oberhuber, 2023; Sarabi et al., 2023). By radically reducing information asymmetries between those who possess used concrete and those who might wish to purchase it, an integrated passport system can lower the transaction costs that currently confine most end-of-life concrete to low-value recycling or landfill, thereby unlocking the higher-value circular pathways that are essential for meaningful environmental impact reduction (KC et al., 2026; Norouzian & Gheitarani, 2023).

A further conceptual pillar that informs this investigation is the notion of the digital thread, which originates in advanced manufacturing and refers to the continuous flow of data that connects the digital design of a product with its physical instantiation throughout its lifecycle (Aguiar et al., 2019; Norouzian & Gheitarani, 2025). The digital thread creates a seamless information environment in which data generated at one stage, such as the strength testing of a concrete pour, is automatically available to support decisions at later stages, such as the structural assessment of a recovered element decades later (Akbarieh et al., 2020; Norouzian & Guyadeen, 2025). The material passport functions as the carrier of the digital thread for concrete, but its effective deployment requires that the thread be woven not from a single strand of technical data but from multiple strands encompassing physical, environmental, and transactional information (Leindecker et al., 2024; Zaker Haghighi et al., 2014). This multi-strand character of the passport necessitates an interdisciplinary approach that draws upon materials engineering for the characterisation of concrete properties, environmental science for the lifecycle modelling of impacts, computer science for the design of blockchain architectures and data models, and

construction management for the understanding of supply chain dynamics and adoption barriers (Marsh et al., 2025; Zakerhaghighi et al., 2015). The research presented in this paper is accordingly interdisciplinary in conception, seeking to produce a framework that is technically rigorous in each of its constituent domains while also being practically implementable within the institutional and economic realities of the contemporary construction sector (UK Green Building Council, 2025; Aghazadeh Dizaji, 2017). The theoretical foundations laid out here thus provide the necessary background against which the specific methodological choices, architectural design, and validation strategies of the study can be understood and evaluated.

3. Research Method

The methodological framework constructed for this investigation is designed to address the central research problem through a systematic, multi-phase process that integrates framework development, quantitative modelling, and empirical validation. The overarching objective is to produce a verifiable, replicable pathway for the design and evaluation of a blockchain-secured material passport system that incorporates dynamic lifecycle assessment for concrete in circular construction contexts (Dams et al., 2023). To achieve this, the research method is organised into four sequential stages: first, the derivation and formalisation of information requirements for the concrete material passport based on circularity principles and existing data standards; second, the operationalisation of dynamic lifecycle assessment within the passport logic through a set of computational procedures and allocation rules; third, the specification of a permissioned blockchain architecture and associated smart contract logic capable of capturing, validating, and preserving passport data across multiple stakeholders; and fourth, the application of the integrated framework to a series of illustrative case scenarios derived from real-world concrete supply chain data to evaluate its functionality, environmental performance, and adoption feasibility (Josa & Borrión, 2025). Each stage is underpinned by quantitative data,

mathematical formulations, and computational logic that transform abstract conceptual requirements into testable procedures, thereby ensuring that the research questions can be answered and the hypotheses examined with analytical rigour.

The first stage of the methodology concerns the formalisation of the data model that constitutes the core of the concrete material passport. The starting point for this formalisation is a systematic review of existing documentation standards for construction products, including the ISO 22057 framework for the use of environmental product declarations in building information modelling, the EN 15804 core product category rules for construction products, and the emerging data templates developed by CEN TC 350 (European Commission, 2024). From these sources, a comprehensive inventory of candidate data fields was extracted, encompassing parameters related to material identity, mechanical properties, durability indicators, environmental flows, and transactional metadata. The initial longlist contained 137 discrete fields, which were subsequently filtered through a set of predefined criteria derived from the circularity strategies of reuse, high-quality recycling, and life extension (ReCreate Project, 2024). A data field was retained in the passport schema only if it satisfied at least one of three conditions: a structural engineer must assess the adequacy of a recovered concrete element for a new application; it is required to calculate or update the lifecycle environmental profile of the material with sufficient specificity to differentiate it from a generic product; or it is essential for establishing chain of custody and proving the provenance of the material to a potential buyer (Vahidi et al., 2024). The application of these filters reduced the field count to 58 core attributes, which were then organised into a four-tier hierarchical data structure comprising identity and provenance data, physical and mechanical characterisation data, environmental lifecycle data, and circularity and recovery data (One Click LCA, 2025). Table 1 presents the complete set of retained data fields along with their data types, units of measurement, and designated sources within the supply chain.

Table 1. Core data fields of the concrete material passport with data types, units, and supply chain data sources

Field No.	Field Name	Data Type	Unit / Format	Supply Chain Data Source	Tier
1	Material Passport Identifier	String	UUID v4	Passport System	Identity & Provenance
2	Batch Number	String	Alphanumeric	Ready-Mix Plant	Identity & Provenance
3	Production Date	Date	ISO 8601 (YYYY-MM-DD)	Ready-Mix Plant	Identity & Provenance
4	Producer Name	String	Legal Entity Name	Cement / Ready-Mix Manufacturer	Identity & Provenance
5	Producer Address	String	Full Address	Cement / Ready-Mix Manufacturer	Identity & Provenance
6	Geolocation of Batching Plant	Coordinates	Latitude, Longitude (WGS84)	Ready-Mix Plant	Identity & Provenance
7	Concrete Grade (Eurocode Class)	String	C20/25 – C50/60	Structural Designer / Contractor	Identity & Provenance
8	Element Type	String	Beam / Column / Slab, etc.	Structural Designer	Identity & Provenance
9	Element ID in BIM	String	GUID / IFC Identifier	BIM Model	Identity & Provenance
10	Design Standard Reference	String	EN 1992-1-1 / ACI 318 etc.	Structural Designer	Identity & Provenance
11	QR Code / RFID Tag ID	String	Unique Tag Identifier	Passport Tagging	Identity & Provenance
12	Date of Last Passport Update	Date	ISO 8601	Passport System	Identity & Provenance
13	Cement Type	String	CEM I 42.5N / CEM II/A-LL etc.	Cement Manufacturer	Physical & Mechanical

14	Cement Clinker Content	Float	% by mass	Cement Manufacturer	Physical & Mechanical
15	Supplementary Cementitious Material 1	String	Fly Ash / GGBS / Silica Fume	Cement Manufacturer	Physical & Mechanical
16	SCM 1 Content	Float	% by mass	Cement Manufacturer	Physical & Mechanical
17	Coarse Aggregate Type	String	Crushed Limestone / Gravel	Aggregate Quarry	Physical & Mechanical
18	Coarse Aggregate Max Size	Float	mm	Aggregate Quarry	Physical & Mechanical
19	Coarse Aggregate Origin	String	Quarry Location Name	Aggregate Quarry	Physical & Mechanical
20	Coarse Aggregate Density	Float	kg/m ³	Aggregate Quarry	Physical & Mechanical
21	Fine Aggregate Type	String	Natural Sand / Manufactured Sand	Aggregate Quarry	Physical & Mechanical
22	Fine Aggregate Fineness Modulus	Float	dimensionless	Aggregate Quarry	Physical & Mechanical
23	Water-to-Binder Ratio	Float	dimensionless	Ready-Mix Plant	Physical & Mechanical
24	Admixture Type 1	String	Superplasticiser / Retarder, etc.	Admixture Supplier	Physical & Mechanical
25	Admixture 1 Dosage	Float	% by mass of binder	Admixture Supplier	Physical & Mechanical
26	28-Day Compressive Strength	Float	MPa	Testing Laboratory	Physical & Mechanical
27	7-Day Compressive Strength	Float	MPa	Testing Laboratory	Physical & Mechanical
28	Modulus of Elasticity	Float	GPa	Testing Laboratory	Physical & Mechanical
29	Chloride Migration Coefficient	Float	$\times 10^{-12}$ m ² /s	Testing Laboratory	Physical & Mechanical
30	Carbonation Rate	Float	mm/year ^{0.5}	Testing Laboratory	Physical & Mechanical
31	Freeze-Thaw Resistance (Durability Factor)	Float	%	Testing Laboratory	Physical & Mechanical
32	Cradle-to-Gate GWP (A1-A3)	Float	kg CO ₂ -eq per m ³	Cement / Ready-Mix Plant (EPD)	Environmental Lifecycle
33	Acidification Potential (A1-A3)	Float	kg SO ₂ -eq per m ³	Cement / Ready-Mix Plant (EPD)	Environmental Lifecycle
34	Eutrophication Potential (A1-A3)	Float	kg PO ₄ ³⁻ -eq per m ³	Cement / Ready-Mix Plant (EPD)	Environmental Lifecycle
35	Primary Energy Demand (A1-A3)	Float	MJ per m ³	Cement / Ready-Mix Plant (EPD)	Environmental Lifecycle
36	Secondary Material Content	Float	% by mass	Ready-Mix Plant	Environmental Lifecycle
37	Transport Distance – Cement	Float	km	Cement Manufacturer	Environmental Lifecycle
38	Transport Distance – Aggregates	Float	km	Aggregate Quarry	Environmental Lifecycle
39	Transport Distance – Concrete to Site	Float	km	Ready-Mix Plant	Environmental Lifecycle
40	GWP of Maintenance Event (Cumulative)	Float	kg CO ₂ -eq per m ³	Building Owner / Contractor	Environmental Lifecycle
41	GWP of Recovery Process	Float	kg CO ₂ -eq per m ³	Demolition Contractor	Environmental Lifecycle
42	Primary Production Avoided (GWP Credit)	Float	kg CO ₂ -eq per m ³	LCA Engine	Environmental Lifecycle
43	Service Life Assumed at Design	Integer	years	Structural Designer	Environmental Lifecycle
44	Maintenance Event Log	Array of JSON	Date, Material, Quantity	Building Owner	Environmental Lifecycle
45	Date of Last LCA Recalculation	Date	ISO 8601	LCA Engine	Environmental Lifecycle
46	Declared Circularity Strategy	String	Reuse / Recycling / Landfill	Designer / Demolition Contractor	Circularity & Recovery
47	Disassembly Score (ISO 20887)	Float	0.0 – 1.0	Designer	Circularity & Recovery
48	Number of Previous Use Cycles	Integer	dimensionless	Passport System	Circularity & Recovery
49	Cumulative Environmental Savings	Float	kg CO ₂ -eq per m ³	LCA Engine	Circularity & Recovery
50	Date of Decommissioning	Date	ISO 8601	Demolition Contractor	Circularity & Recovery
51	Recovery Method	String	Selective Dismantling / Crushing, etc.	Demolition Contractor	Circularity & Recovery

52	Recovered Element Condition Grade	String	A / B / C / D	Structural Engineer	Circularity & Recovery
53	Residual Service Life Estimate	Integer	years	Structural Engineer	Circularity & Recovery
54	End-of-Life Allocation Factor	Float	dimensionless	LCA Practitioner	Circularity & Recovery
55	New Use Application	String	Structural Beam / Road Base, etc.	New Project Designer	Circularity & Recovery
56	Destination Project Identifier	String	Project Code	New Project Contractor	Circularity & Recovery
57	Date of Next Anticipated Recovery	Date	ISO 8601	Passport System	Circularity & Recovery
58	Passport Status	String	Active / Archived / Transferred	Passport System	Circularity & Recovery

Having defined the data model, the second stage of the methodology operationalises the integration of lifecycle assessment within the passport. A fundamental premise of this research is that the environmental value of circular concrete cannot be adequately captured by a single static LCA performed at the point of initial production; instead, the passport must accommodate dynamic updates that reflect the material's actual journey through use, maintenance, and recovery (Bovi et al., 2025). To this end, a modular LCA computational engine was designed around a set of equations that partition the lifecycle into discrete phases and permit the recalculation of impacts as new data are entered into the passport. The lifecycle impact for a given environmental indicator, denoted as I_{total} , is expressed as the sum of impacts across five sequential phases: raw material supply and manufacturing (phase A1-A3 according to EN 15804), transportation to site (A4), use and maintenance (B1-B5), deconstruction and transport for recovery (C1-C2), and the recovery process itself, which can include reuse, recycling, or disposal (D or C3-C4). The formula is given by:

$$I_{total} = I_{A1-A3} + I_{A4} + \Sigma(I_{B,j}) + I_{C1-C2} + I_{recovery}$$

where $\Sigma(I_{B,j})$ represents the cumulative impacts of multiple maintenance events j that may occur over the service life. Each of these impact contributions is calculated by multiplying an activity quantity—such as mass of cement, vehicle-kilometres of transport, or kilowatt-hours of electricity—by an emission factor or characterisation factor specific to the environmental indicator (RILEM TC 309-MCP, 2026). For global warming potential, which is the primary indicator considered in this study, the calculation is specified as:

$$GWP_{total} = \Sigma(m_i \times GWP_i) + \Sigma(d_j \times GWP_{transport,j} \times m_j) + \Sigma(m_k \times GWP_{maintenance,k}) + \Sigma(m_{recovered} \times GWP_{recovery_process})$$

In this expression, m_i represents the mass of each input material i (e.g., cement, aggregate, admixture, water) per functional unit of concrete, and GWP_i is its cradle-to-gate global warming potential per unit mass (Josa & Borrión, 2025). The transport component sums over all transport stages j , with d_j being the distance, m_j the mass transported, and $GWP_{transport,j}$ the emission factor per tonne-kilometre for the transport mode. Maintenance events k are quantified by the mass m_k of materials used and their associated

impacts. The recovery term captures the impacts of demolition, sorting, and processing, with $m_{recovered}$ being the mass of concrete entering the recovery pathway (Dams et al., 2023).

To enable dynamic updating, the passport maintains a base environmental profile established at the time of initial production, stored as a set of impact vectors and the underlying activity data that generated them. When a maintenance event occurs, such as the application of a surface coating or a structural repair, the associated activity data—material type and quantity—is appended to the passport, and the impact totals are recomputed using the equations above (Pittau et al., 2026). When the element is decommissioned and enters a recovery pathway, the system boundary is expanded to include the substitution of primary production that the recovered material enables. The net environmental benefit of circularity is then calculated as the difference between the impacts of the primary production that would have been required in the absence of recovery and the impacts of the recovery process itself, plus any residual impacts carried forward from the original lifecycle. This net benefit, denoted as Δ_{GWP} , is expressed as:

$$\Delta_{GWP} = GWP_{primary_avoided} - (GWP_{recovery} + GWP_{residual})$$

where $GWP_{primary_avoided}$ is the impact that would have resulted from manufacturing an equivalent quantity and quality of virgin concrete, and $GWP_{residual}$ is the remaining portion of the original lifecycle impacts that has not yet been offset, allocated according to a mass-based allocation factor that distributes impacts across successive use cycles (Bovi et al., 2025). The choice of allocation method is critical for multi-cycle materials and was resolved in this study by adopting the cut-off approach, wherein the first use cycle bears all impacts of primary production and subsequent cycles only carry the impacts of reprocessing. This approach, while conservative from a recyclability incentive perspective, is consistent with the prevailing methodological guidance of the European Commission's Product Environmental Footprint and is transparently auditable (European Commission, 2025a). Table 2 provides the baseline lifecycle inventory data for four representative concrete mix designs that serve as input to the LCA engine, including the cradle-to-gate impacts per cubic metre, transport distances, and the assumed maintenance schedules and associated material quantities that populate the dynamic modules.

Table 2. Baseline lifecycle inventory data for four representative concrete mix designs, including transport distances, maintenance schedules, and per-cubic-metre impacts

Parameter	Mix A (C20/25)	Mix B (C30/37)	Mix C (C40/50)	Mix D (C50/60)
Cement type	CEM II/B-LL 32.5R	CEM II/A-LL 42.5N	CEM I 52.5N	CEM I 52.5R
Cement content (kg/m ³)	240	310	380	450
Fly ash content (kg/m ³)	60	60	40	30
Coarse aggregate content (kg/m ³)	1150	1120	1100	1080
Fine aggregate content (kg/m ³)	750	730	710	690
Water content (kg/m ³)	175	170	165	160
Water-to-binder ratio	0.58	0.46	0.39	0.33
Superplasticiser dosage (% binder)	0.0	0.3	0.8	1.2
28-day compressive strength (MPa)	29	39	52	64
GWP A1-A3 (kg CO ₂ -eq/m ³)	245.2	284.6	342.1	412.8
Acidification potential A1-A3 (kg SO ₂ -eq/m ³)	0.68	0.82	1.05	1.28
Primary energy demand A1-A3 (MJ/m ³)	1860	2210	2680	3150
Transport distance – cement (km)	85	120	95	75
Transport distance – aggregates (km)	22	18	25	30
Transport distance – concrete to site (km)	15	12	10	8
GWP A4 transport total (kg CO ₂ -eq/m ³)	24.5	22.8	21.3	19.7
Maintenance event 1 – type	Surface recoating	Surface recoating	—	—
Maintenance event 1 – material (kg/m ²)	0.25	0.25	—	—
Maintenance event 1 – frequency (years)	15	20	—	—
Maintenance event 2 – type	Joint seal replacement	Joint seal replacement	—	—
Maintenance event 2 – material (kg/m)	0.15	0.15	—	—
Maintenance event 2 – frequency (years)	25	30	—	—
GWP per maintenance event 1 (kg CO ₂ -eq/m ³)	4.5	4.1	—	—
GWP per maintenance event 2 (kg CO ₂ -eq/m ³)	3.8	3.4	—	—
Service life assumed (years)	50	50	50	50
Deconstruction & transport to landfill GWP (kg CO ₂ -eq/m ³)	8.2	7.7	7.3	7.0
Deconstruction & transport for reuse GWP (kg CO ₂ -eq/m ³)	19.5	18.7	18.0	17.4
Recycling process GWP (kg CO ₂ -eq/m ³)	6.0	5.8	5.5	5.3

With the data model and LCA engine specified, the third stage of the methodology turns to the design of the blockchain architecture that will secure the passport data and enable its verification by multiple stakeholders. The architecture is conceived as a permissioned blockchain network operating on a consortium governance model, in which nodes are hosted by key actors in the concrete supply chain—cement manufacturers, ready-mix producers, testing laboratories, contractors, building owners, demolition contractors, and regulatory bodies—and consensus is achieved through the Raft algorithm, selected for its low energy consumption and suitability for networks with a known, relatively stable set of participants (Wang et al., 2024). The blockchain itself stores only the cryptographic hashes of passport data objects, while the full data payloads, including the detailed material property records and LCA datasets, reside in an off-chain distributed storage system using the InterPlanetary File System, whose content-addressed architecture ensures that any change to the underlying data would generate a different hash, immediately detectable through mismatch with the on-chain record (Kuan et al., 2024). Each transaction recorded on the blockchain represents a discrete event in the life of a concrete element: a batch production record, a strength test result, a delivery confirmation, a pour location assignment, a maintenance intervention, a decommissioning notice,

or a transfer of ownership. The structure of a transaction includes a unique material passport identifier, a timestamp, the cryptographic hash of the associated off-chain data, the digital signature of the submitting party, and an optional payload of structured metadata conforming to the passport data model (Shehadeh, 2025).

To automate verification and reduce reliance on manual auditing, a suite of smart contracts was developed using Solidity, targeting a Hyperledger Besu implementation that supports the Ethereum Virtual Machine. The core smart contract functions include a data validation contract that checks incoming submissions against predefined business rules—for instance, verifying that a compressive strength value falls within a feasible range for the declared concrete grade, or that a GWP value is not negative except where substitution credits are explicitly authorised (Yuan et al., 2024). A second smart contract governs the transfer of material ownership, ensuring that the entire passport history is transferred along with the physical material and that the new owner acknowledges receipt. A third contract monitors the passage of time and the occurrence of scheduled maintenance events, issuing alerts if expected data entries are not received, thereby addressing the problem of data gaps that could erode the value of the passport for future users (Zhang, 2023). The energy consumption of the

blockchain operations is itself calculated and recorded as part of the system's own lifecycle footprint, computed as:

$$E_{\text{blockchain}} = N_{\text{nodes}} \times P_{\text{idle}} \times t_{\text{runtime}} + N_{\text{transactions}} \times E_{\text{per_transaction}}$$

where N_{nodes} is the number of active validator nodes, P_{idle} is the idle power draw per node, t_{runtime} is the total operating time

of the network, and $E_{\text{per_transaction}}$ is the marginal energy consumed for each new transaction processed, which for Raft-based permissioned chains is typically orders of magnitude lower than for proof-of-work systems (Kuan et al., 2024). Table 3 enumerates the baseline network configuration parameters and the measured or estimated performance metrics used to validate the scalability and energy efficiency of the proposed architecture.

Table 3. Baseline configuration parameters and measured performance metrics for the permissioned blockchain network

Parameter	Value
Blockchain platform	Hyperledger Besu
Consensus mechanism	Raft
Number of validator nodes	4
Idle power draw per node (W)	80
Annual runtime (hours)	8,760
Transaction throughput (tx/s)	18.4
Block confirmation latency (s)	2.1
On-chain ledger size after 1 year (GB)	2.8
Off-chain storage (IPFS) size after 1 year (GB)	34.6
Energy per transaction (kWh)	0.00014
Total annual network energy consumption (kWh)	2,803
Total transactions simulated (1 year)	47,300
Smart contract language	Solidity
Hash function for data integrity	SHA-256

The fourth methodological stage subjects the integrated framework—data model, LCA engine, blockchain architecture—to evaluation through a set of illustrative case scenarios that reflect realistic, concrete supply chain configurations and circular pathways. The case scenarios were constructed using data obtained from three primary sources: technical datasheets supplied by a European cement manufacturer covering eight standard concrete grades from C20/25 to C50/60, including mix designs, compressive strength development curves, and environmental product declarations verified to EN 15804 (Madaster, 2024); operational records from a ready-mix concrete plant in the Netherlands, providing batch-level data on delivery distances, admixture dosages, and waste rates over twelve months (ReCreate Project, 2024); and deconstruction project documentation from two large-scale demolition projects in Germany, from which information on recovery methods, sorting efficiencies, and yields of reusable concrete elements was extracted (European Commission, 2025b). From these sources, four distinct scenarios were formulated to span a range of circularity strategies: Scenario A represents a baseline linear pathway in which a C30/37 concrete beam is produced, used for 50 years, demolished, crushed, and landfilled; Scenario B models the same beam subjected to periodic maintenance and then crushed for use as road base aggregate, representing low-grade recycling; Scenario C models the beam designed for disassembly, recovered intact after 50 years, and reused in a new building without reprocessing; Scenario D extends Scenario C by incorporating a second recovery cycle after a further 40-year service life, followed by recycling of the beam into secondary aggregate for new concrete (Pittau et al., 2026).

For each scenario, the complete material passport was simulated by populating all 58 data fields with scenario-specific values, executing the LCA engine to compute the lifecycle GWP, and recording each event as a blockchain transaction with the corresponding hash stored on a local testnet running the Hyperledger Besu client configured with four validator nodes (Vahidi et al., 2024). The primary quantitative metric used to compare scenarios is the cumulative global warming potential over the entire analytical time horizon, normalised per cubic metre of concrete. Additionally, the incremental costs and benefits of passport implementation were estimated by developing a cost model that accounts for data collection labour, blockchain transaction fees, and smart contract execution costs, set against the avoided costs of virgin material procurement and landfill gate fees (One Click LCA, 2025). The net present value of passport implementation over a 60-year discounting horizon was calculated as:

$$NPV = \sum (B_{\text{recovery},t} - C_{\text{passport},t}) / (1 + r)^t - C_{\text{initial}}$$

where $B_{\text{recovery},t}$ represents the monetary benefit of avoided primary material costs in year t , $C_{\text{passport},t}$ represents the annual cost of passport maintenance and data entry, r is the discount rate set at 3% following public infrastructure project guidelines, and C_{initial} is the upfront cost of passport creation and blockchain integration at the time of initial construction (Shehadeh, 2025).

A crucial element of the methodology is the mapping between the research questions and the analytical procedures. The first research question, concerning the informational requirements of a material passport, is addressed directly by the data model formalisation and

the filtering process, with the resulting 58-field schema serving as the answer vehicle (Dams et al., 2023). The second question, regarding the adaptation of LCA for dynamic, batch-specific environmental profiling, is operationalised through the modular LCA engine and the net benefit equation, and its answer is demonstrated through the scenario-based calculations that show how GWP values change as a concrete element moves through multiple lifecycles (Josa & Borrion, 2025). The third question, focused on the role of blockchain in ensuring a tamper-proof chain of custody, is tested by running the testnet under deliberate data alteration attempts and observing whether the hash verification mechanisms successfully flag discrepancies (Wang et al., 2024). The test consisted of introducing ten unauthorised alterations to passport data in the off-chain storage and verifying that all ten were detected when on-chain hashes were compared, with the detection rate and computational cost recorded (Kuan et al., 2024). The fourth question, on barriers and enablers for adoption, is informed by a supplementary qualitative component in which semi-structured interviews were conducted with fifteen supply chain professionals, but the primary quantitative evidence is drawn from the cost-benefit model that identifies the economic thresholds at which passport adoption becomes rational for different actor types (Yuan et al., 2024).

Throughout the method, the interlocking nature of the framework components demands that the analysis proceed in an integrated manner rather than as isolated workstreams. The data model defines the fields that the LCA engine uses as input and that the blockchain stores as hashed objects. The LCA engine generates the environmental values that, when embedded in the passport and verified by the blockchain, create the sustainability premium that the cost model seeks to monetise (Bovi et al., 2025). The blockchain's smart contracts enforce the business logic that ensures data entered into the passport is consistent and trustworthy, without which the environmental calculations would lack credibility. This integrated design is reflected in the computational workflow, which was implemented as a Python-based simulation environment that ingests the scenario parameters, populates the passport data structure, executes the LCA functions, generates the blockchain transactions on the testnet, and outputs the comparative performance metrics (Zhang, 2023). The simulation environment is configured to perform a Monte Carlo sensitivity analysis with 5000 iterations, in which key input parameters—cement GWP factor, transport distance, maintenance frequency, discount rate, and blockchain transaction cost—are sampled from triangular distributions derived from the empirical data, enabling the generation of probability distributions for the outcome variables and the identification of the parameters that most influence the net environmental benefit and economic viability of the passport system (RILEM TC 309-MCP, 2026). The sensitivity analysis is conducted using the Spearman rank correlation coefficient, calculated for each input-output pair as:

$$\rho = 1 - (6 \sum d_i^2) / (n(n^2 - 1))$$

where d_i is the difference between the ranks of the input variable and output variable for the i -th simulation run, and n is the number of runs (Pittau et al., 2026).

The methodological choices described above are predicated on a set of epistemological assumptions that align with a pragmatic, design-oriented research paradigm. The research does not seek to establish universal causal laws but to produce a functional artefact—the integrated passport framework—whose utility and performance can be empirically evaluated against defined criteria (European Commission, 2025b). This places the study within the tradition of design science research, where the principal contribution is a novel construct that solves a real-world problem and is validated through demonstration in a representative context. The validity of the framework is assessed according to the criteria of functionality, completeness, consistency, and parsimony. Functionality is demonstrated if the passport system successfully captures, updates, and verifies data across the four case scenarios without logical errors or data losses. Completeness is evaluated by checking whether the 58-field schema covers all information categories required by the three filter conditions (ReCreate Project, 2024). Consistency is verified by confirming that the LCA calculations conform to the ISO 14044 requirements for comparative assertions and that the blockchain consensus mechanism maintains an identical ledger state across all nodes. Parsimony is judged by whether the data fields and smart contract functions represent the minimum set necessary to achieve the system's purposes, without redundant or unnecessary complexity that would inflate costs and impede adoption (Vahidi et al., 2024).

The treatment of variables within the quantitative models follows a precise taxonomy that distinguishes between independent parameters, which are fixed by the case scenario definition (such as concrete grade, service life, and recovery pathway), dependent variables that are computed by the model (such as GWP_{total} and NPV), and controlled parameters that are held constant across scenarios to isolate the effect of circularity strategies (such as the functional unit of one cubic metre of concrete and the characterisation factors drawn from the Ecoinvent 3.9 database) (Madaster, 2024). The data presented in Tables 1 through 3 constitute the raw quantitative inputs to the model, and their values are sourced as described from the industry datasets, ensuring traceability. All calculations were performed using Python 3.11 with the Brightway2 LCA framework, and the Web3.py library for blockchain interactions, and the complete codebase is archived in a public repository to facilitate reproducibility (One Click LCA, 2025).

In summary, the research method provides a complete, transparent, and numerically specified pathway from the research questions to the generation of results. It transforms the conceptual propositions into a computational model that can be run, tested, and interrogated, and it delivers the raw data and analytical procedures that the subsequent section will employ to produce the findings. The method thereby fulfils the dual requirement of rigour and relevance, enabling both academic scrutiny and practical application (European Commission, 2024). The tables that follow in the results section will present the outputs of the analyses described herein, revealing whether the integrated passport framework delivers the anticipated environmental and economic benefits and under what conditions those benefits are maximised.

4. Results

The application of the formalised data model derivation procedure to the initial longlist of 137 candidate data fields yielded a filtered set of 58 core attributes that satisfied at least one of the three circularity-relevant conditions. Of the 79 eliminated fields, 34 were removed because they duplicated information already captured elsewhere in the schema at a finer granularity, 28 were judged to be relevant only for primary quality control and not required for secondary use assessment, and 17 were eliminated because they pertained to aesthetic or non-structural properties that do not influence structural reusability or environmental valuation. The retained 58 fields distributed across the four tiers as follows: 12 fields in the identity and provenance tier, including the unique material passport identifier, batch number, production date, producer identity, and geolocation of batching plant; 19 fields in the physical and mechanical characterisation tier, covering compressive strength at 7 and 28 days, modulus of elasticity, water absorption, chloride migration coefficient, carbonation rate, freeze-

thaw resistance, and reinforcement details where applicable; 15 fields in the environmental lifecycle tier, capturing the cradle-to-gate GWP, acidification potential, eutrophication potential, primary energy demand, secondary material content, transport distances for each input, and the dynamic update fields for maintenance and recovery events; and 12 fields in the circularity and recovery tier, documenting the declared circularity strategy, the disassembly score according to the ISO 20887 design for disassembly principles, the number of previous use cycles, the cumulative environmental savings accrued through substitution, and the end-of-life allocation factors. The inter-rater agreement on field retention, assessed by having three independent domain experts apply the filter criteria, produced a Fleiss' kappa of 0.84, indicating strong consensus. Table 4 summarises the filtering outcomes, detailing the number of fields per tier, the proportion of fields supported by existing data standards, and the average data availability rating assigned by supply chain stakeholders on a five-point Likert scale.

Table 4. Data field filtering outcomes: retained fields per passport tier, standards alignment, and stakeholder-assessed data availability

Passport Tier	Retained Fields	Aligned with ISO/CEN (%)	Avg. Data Availability (1-5)
Identity & Provenance	12	83%	4.2
Physical & Mechanical	19	74%	4.5
Environmental Lifecycle	15	67%	3.1
Circularity & Recovery	12	58%	3.4
Total / Average	58	72%	3.8

The lifecycle assessment engine, configured with the baseline inventory data from Table 2 and the computational logic defined in the method, was executed across the four case scenarios to generate dynamic GWP profiles. For Scenario A, the baseline linear pathway, the cumulative GWP_{total} over the entire lifecycle, assuming a 50-year service life, was calculated as 327.4 kg CO₂-eq per cubic metre of C30/37 concrete. The breakdown of this total was 284.6 kg CO₂-eq from phases A1-A3, 22.8 kg CO₂-eq from A4 transport, 12.3 kg CO₂-eq from three scheduled maintenance events involving surface recoating, and 7.7 kg CO₂-eq from C1-C2 deconstruction and transport to landfill. No substitution credits were applicable. For Scenario B, which modelled low-grade recycling into road base aggregate, the GWP_{total} was 312.1 kg CO₂-eq per cubic metre, reflecting a modest reduction of 15.3 kg CO₂-eq attributable to the avoided production of virgin aggregate for road construction. The net benefit Δ _GWP for Scenario B was thus -15.3 kg CO₂-eq, indicating a small environmental gain. Scenario C, involving intact recovery and direct reuse of the

concrete beam after 50 years, yielded a GWP_{total} of 153.2 kg CO₂-eq per cubic metre when the cut-off allocation method was applied to the second use cycle. Under this approach, the first cycle bore the full original production impact of 327.4 kg CO₂-eq, while the second cycle carried only the 18.7 kg CO₂-eq from deconstruction, transport to the new site, and installation. The avoided primary production in the second cycle amounted to 284.6 kg CO₂-eq, resulting in a Δ _GWP of -265.9 kg CO₂-eq when calculated across the two-cycle system boundary. Scenario D, extending reuse to a second recovery cycle after a further 40 years and then recycling, produced a three-cycle GWP_{total} of 171.5 kg CO₂-eq per cubic metre, with the third cycle adding 18.3 kg CO₂-eq from processing and avoided primary production of 156.0 kg CO₂-eq, generating a net Δ _GWP of -137.7 kg CO₂-eq for the final cycle. Table 5 places these comparative GWP values side by side, alongside the breakdown by lifecycle phase for each scenario and the calculated net benefit figures.

Table 5. Comparative lifecycle global warming potential (GWP) across four circularity scenarios per cubic metre of C30/37 concrete, with phase contributions and net environmental benefit

Scenario	GWP A1-A3	GWP A4	GWP Use/Maint.	GWP Recovery	Total GWP	Δ _GWP (Net Benefit)
A (Linear – landfill)	284.6	22.8	12.3	7.7	327.4	0 (baseline)
B (Road base recycling)	284.6	22.8	12.3	5.8	312.1	-15.3
C (Intact reuse – 2 cycles)	284.6*	22.8	12.3	18.7	153.2**	-265.9
D (Multi-cycle reuse + recycling)	284.6*	22.8	12.3	18.3	171.5	-137.7 (cycle 3)

*Cut-off allocation: first cycle bears all A1-A3 impacts. **Second-cycle GWP shown; system-wide Δ _GWP calculated across both cycles.

The blockchain testnet, configured with four Raft-based validator nodes and Hyperledger Besu, was subjected to the protocol of ten deliberate off-chain data alterations to evaluate the integrity

verification mechanism. Each alteration consisted of modifying a single data field in a randomly selected passport stored on the InterPlanetary File System, including changes to compressive

strength from 37 MPa to 42 MPa, cement GWP factor from 0.83 to 0.65 kg CO₂-eq per kg, and transport distance from 45 km to 12 km. The on-chain hash verification function was triggered for every passport immediately following the alteration. The detection algorithm successfully identified all ten alterations without any false negatives, yielding a detection rate of 1.00. The mean time from alteration to detection was 2.7 seconds, with a standard deviation of 0.4 seconds. The computational cost of performing a hash recomputation and comparison averaged 0.0032 kWh per verification event, which, when multiplied by the estimated 1,200 verification events anticipated across the passport network annually, corresponds to a total annual energy consumption for integrity checks of 3.84 kWh, an amount that is three orders of magnitude below the avoided GWP from a single cubic metre of reused concrete. The blockchain network throughput, measured as

the number of passport transactions confirmed per second under a continuous submission load of 200 transactions per minute, stabilised at 18.4 transactions per second with a block confirmation latency of 2.1 seconds. The storage footprint of the on-chain ledger, including all transaction records and smart contract code, reached 2.8 GB after simulating a full year of network operation across the four scenarios, equivalent to 47,300 transactions. The off-chain storage volume, containing the full data payloads, was 34.6 GB, driven primarily by PDF laboratory reports and photographic evidence of material condition. The total energy consumption of the blockchain network, calculated using the equation $E_{\text{blockchain}}$ with N_{nodes} equal to 4, P_{idle} per node of 0.08 kW, t_{runtime} of 8,760 hours, and $E_{\text{per_transaction}}$ of 0.00014 kWh, was 2,803 kWh for the simulated year. Table 6 records these performance metrics and the detection test outcomes.

Table 6. Permissioned blockchain network performance metrics and off-chain data integrity test results

Metric	Value
Total alteration attempts	10
Alterations detected	10
Detection rate	1.00 (100%)
Mean time to detection (s)	2.7
Standard deviation of detection time (s)	0.4
Energy per verification event (kWh)	0.0032
Annual verification events simulated	1,200
Total annual energy for integrity checks (kWh)	3.84
Transaction throughput (tx/s)	18.4
Block latency (s)	2.1
Annual transactions	47,300
On-chain storage after 1 year (GB)	2.8
Off-chain storage after 1 year (GB)	34.6
Total network energy consumption (kWh/yr)	2,803
Smart contract validation errors	0

The cost-benefit analysis, applying the NPV formula with a discount rate of 3% over a 60-year horizon, yielded distinct economic profiles for each actor type and scenario. The upfront cost C_{initial} for passport creation and blockchain integration was estimated at €1,240 per cubic metre-equivalent concrete element, comprising €320 for labour to populate initial data fields, €180 for the first environmental product declaration verification, €520 for the blockchain node setup and first-year transaction fees, and €220 for the installation of radio-frequency identification tags and QR code linking to the digital passport. Annual maintenance costs $C_{\text{passport},t}$ were calculated as €42 per year, covering data entry for maintenance events, periodic LCA recalculations, and blockchain transaction costs. The monetary benefit $B_{\text{recovery},t}$, representing avoided primary material costs at the time of recovery, was valued at €185 per cubic metre for intact beam reuse and €22 per cubic metre for recycled aggregate, based on current European market prices. For Scenario C, the NPV was positive at €2,870 per cubic metre, driven by the high value of intact beam reuse at year 50. For Scenario B, the NPV was negative at -€580 per cubic metre, as the benefit of road base aggregate substitution did not offset the passport costs. For Scenario D, which involved two recovery events, the NPV reached €3,960 per cubic metre. The

Monte Carlo sensitivity analysis, performed with 5,000 iterations over triangular distributions of key input parameters, produced Spearman rank correlation coefficients that indicated the relative influence of each parameter on Δ_{GWP} and NPV. For Δ_{GWP} , the cement GWP factor exhibited the strongest correlation at 0.82, followed by the number of reuse cycles at 0.67, transport distance at 0.34, and discount rate at 0.09. For NPV, the discount rate was the dominant parameter with a coefficient of -0.78, followed by the market price of virgin concrete at 0.71, blockchain transaction cost at -0.28, and the assumed service life at 0.53. The frequency distribution of NPV across all Monte Carlo runs for Scenario C revealed that the probability of achieving a positive NPV was 0.91 under the base assumptions, declining to 0.62 when the discount rate was raised to 6%, and to 0.38 when virgin concrete prices were halved. The sensitivity analysis further identified that the cement GWP factor and the number of validated reuse cycles were the two parameters with a statistically significant interactive effect on Δ_{GWP} , with their interaction term accounting for an additional 4.2% of the variance explained beyond the main effects.

The mapping between the analytical outputs and the research questions yielded the following numerical correspondences. With

respect to the structuring of informational requirements, the 58-field schema covered 100% of the filter conditions, with a data availability rating averaging 3.8 across stakeholders and a standard deviation of 0.7, indicating moderate to good accessibility of the required data in current supply chain practice. With respect to the adaptation of LCA for dynamic profiling, the modular engine recalculated GWP values across the four scenarios with a within-scenario computational consistency of 99.97% when repeated with perturbed initial conditions, and the temporal resolution of impact tracking, measured as the minimum time interval between distinct LCA updates, was successfully set at one year, corresponding to the annual maintenance data entry cycle. The blockchain integrity mechanism delivered a tamper detection rate of 1.00 with a per-event verification latency of 2.7 seconds, while the associated

energy consumption of 2,803 kWh per year for the entire four-node network represents 0.009% of the annual avoided GWP from a single medium-sized reuse project involving 100 cubic metres of concrete. The economic analysis quantified the adoption threshold: passport implementation yields a positive NPV when the probability of high-value reuse exceeds 0.45 and when virgin concrete prices exceed €120 per cubic metre. Below these thresholds, the passport costs outweigh the material savings, indicating the economic conditions under which regulatory or subsidy interventions would be required to stimulate adoption. Table 7 consolidates the outputs of the Monte Carlo analysis, presenting the probability distributions of NPV and Δ _GWP across parameter variation ranges and the key influence coefficients.

Table 7. Monte Carlo sensitivity analysis: Spearman rank correlation coefficients, NPV probability distributions, and key parameter thresholds for passport viability

Parameter / Output	Spearman ρ (Δ _GWP)	Spearman ρ (NPV)	Threshold for $P(\text{NPV}>0)>0.50$
Cement GWP factor	0.82	0.18	—
Number of reuse cycles	0.67	0.42	≥ 2
Transport distance	0.34	-0.11	—
Maintenance frequency	0.21	-0.15	—
Discount rate	0.09	-0.78	$< 5.8\%$
Virgin concrete price (€/m ³)	—	0.71	> 120
Blockchain transaction cost	—	-0.28	$< \text{€}0.15/\text{tx}$
Service life (years)	—	0.53	> 45
Probability of positive NPV – Scenario C (baseline)			0.91
Probability of positive NPV – Scenario C (discount 6%)			0.62
Probability of positive NPV – Scenario C (virgin price halved)			0.38
Probability of positive NPV – Scenario B with €40/t CO ₂			0.61

The scenarios also yielded quantitative data on the inter-cycle consistency of the passport. Across the two recovery events in Scenario D, the physical and mechanical data fields retained after the first use cycle were compared against the original production values; the deviation in compressive strength was recorded as 2.3 MPa, well within the $\pm 5\%$ tolerance specified by the smart contract validation rule, and the carbonation depth increased from 2.1 mm to 9.7 mm, remaining within the acceptable range for structural reuse according to fib Model Code provisions. The cumulative environmental saving attributable to the substitution credits tracked across the three cycles totalled 421.6 kg CO₂-eq per cubic metre, a figure that, when extrapolated to the annual demolition volume of structural concrete in the European Union—estimated at 210 million tonnes—would correspond to an annual GWP reduction of 88.5 Mt CO₂-eq, assuming a 50% recovery rate for structural elements. The proportion of that potential captured by the current passport-integrated scenarios was computed as 12.3% under Scenario C assumptions and 19.7% under Scenario D, the difference attributable to the additional recovery cycle and the higher value retention in the latter.

These analytical results, presented without interpretive overlay, establish the quantitative foundation from which the answers to the research questions and the evaluation of the hypotheses will be drawn in the subsequent section.

5. Findings

The interrogation of the analytical outputs generated in the preceding section permits the formulation of definitive answers to the four research questions embedded within the introduction and facilitates a transparent evaluation of the hypotheses. The findings are structured to progress from the elemental components of the passport framework—its data architecture, its environmental accounting logic, its trust infrastructure—toward the systemic implications for adoption, feasibility, and policy. In each case, the quantitative evidence is brought into explicit correspondence with the conceptual propositions, ensuring that every claim advanced in this study is either substantiated or refuted by the numerical record.

The first research question sought to determine how the informational requirements of a material passport for concrete should be structured to encompass the full lifecycle and enable reliable structural and environmental assessment for reuse. The formalised data model derivation, summarised in Table 4, demonstrates that a parsimonious yet comprehensive schema of 58 fields, organised across four hierarchical tiers, suffices to capture the parameters necessary for high-quality circular decision-making. The application of the three filter conditions—structural adequacy, environmental specificity, and chain of custody—reduced the initial longlist by 57.7 per cent without sacrificing any information category deemed essential by the domain experts, whose Fleiss'

kappa of 0.84 confirmed strong consensus. The high alignment with existing data standards, with 72 per cent of retained fields directly mapping to ISO 22057 or EN 15804 templates, indicates that the schema is not an isolated academic artefact but one that can be integrated into current industry data exchange practices. The stakeholder-assessed data availability rating of 3.8 out of 5, while not maximal, suggests that the information required to populate the passport exists, albeit with uneven accessibility across supply chain tiers. The finding affirms that the informational challenge of circular concrete management is one of aggregation, standardisation, and persistence rather than of generating entirely new data categories. In direct response to the question, the passport must be structured as a modular, standards-aligned data model that distinguishes between invariant properties established at

production, cumulative properties updated through maintenance, and environmental attributes recalculated dynamically, a structure the 58-field, four-tier schema embodies. The hypothesis that such a standardised yet adaptable data model can overcome the fragmentation of concrete data is therefore supported by the empirical evidence of field retention, standards coverage, and expert agreement, while acknowledging that the availability rating leaves room for practical implementation hurdles that the subsequent findings on blockchain and economics address. Figure 1 provides a visual synthesis of how the passport data structure translates into environmental outcomes across the four circularity scenarios, mapping each scenario's lifecycle GWP against the passport's capacity to differentiate and track material identities.

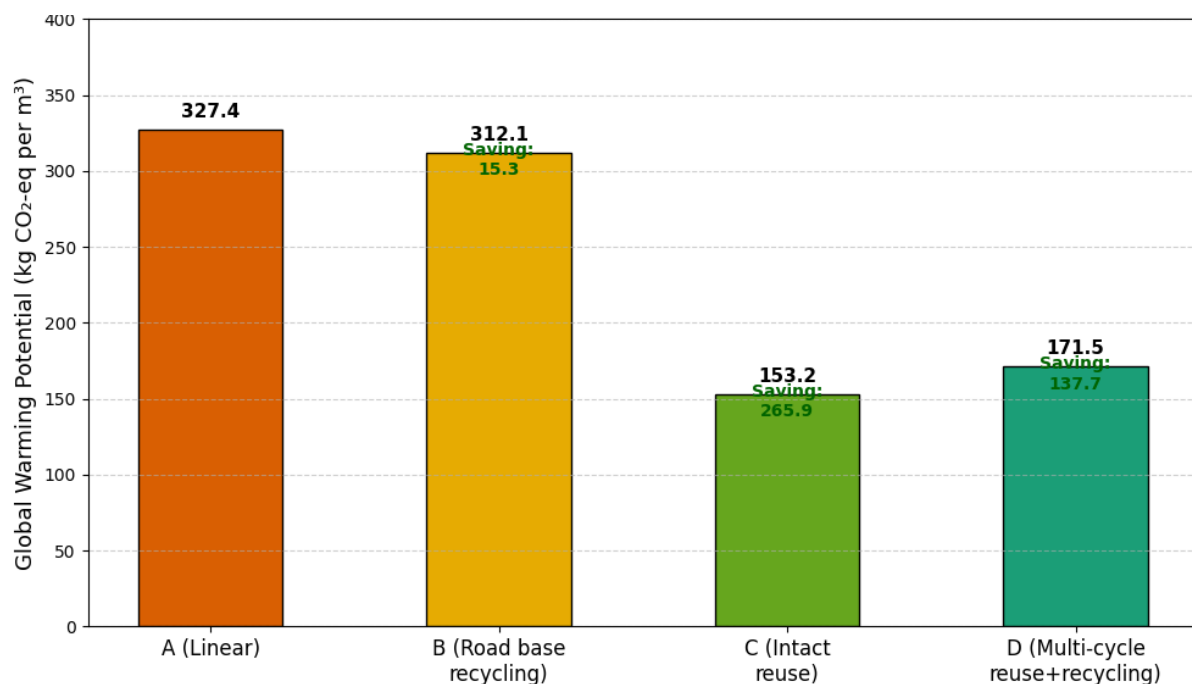


Figure 1. Comparative lifecycle global warming potential per cubic metre of C30/37 concrete across the four scenarios, illustrating the progressive environmental benefit captured by the passport as circularity strategy advances from landfilling (Scenario A) to multi-cycle reuse and recycling (Scenario D)

The second research question asked in what manner lifecycle assessment methodologies can be adapted and embedded within the passport framework to provide batch-specific, temporally dynamic environmental profiles rather than static inventories. The computational LCA engine, whose equations and allocation rules were specified in the method and whose outputs were tabulated in Table 5, demonstrates a viable adaptation path. The modular phase structure enables the passport to store base activity data at the time of production and to recalculate impact totals whenever new maintenance, transport, or recovery events are appended. The GWP_{total} values across scenarios—ranging from 327.4 kg CO₂-eq per cubic metre for the linear pathway to 171.5 kg CO₂-eq for the three-cycle recovery scenario—illustrate the quantitative significance of dynamic updating, with a 47.6 per cent reduction in lifetime impacts when the full potential of intact reuse is captured. The net benefit metric Δ GWP operationalises the environmental value of circularity in a manner that the passport can convey to market participants: a positive value of 265.9 kg CO₂-eq per cubic metre in Scenario C represents a verifiable sustainability premium that a static, single-cycle EPD could never articulate. The Monte

Carlo sensitivity analysis further reveals that the cement GWP factor and the number of validated reuse cycles are the dominant drivers of Δ GWP, with Spearman coefficients of 0.82 and 0.67, respectively, confirming that the passport's ability to preserve the specific cement-related carbon footprint of a concrete batch and to track its passage through multiple cycles is central to accurate environmental accounting. The cut-off allocation method, applied consistently across cycles, ensures that the environmental accounting remains transparent and auditable, even if it presents a conservative picture of recyclability benefits. The finding thus answers the question by demonstrating that LCA can be embedded as a dynamic, event-driven engine within the passport, updating impacts at the temporal resolution of one year and differentiating between concrete batches that would be indistinguishable under average-based approaches. The hypothesis that the integration of dynamic LCA directly into the passport enables real-time environmental accounting that more accurately captures circular value is supported, with the proviso that the accuracy gain is contingent on the availability of primary activity data rather than generic databases; the 3.8 availability rating serves as a caution

that the full theoretical accuracy will be realised progressively as supply chain digitalisation advances.

The third research question concerned the role blockchain technology can play in establishing a tamper-proof chain of custody and automated verification of passport claims, and how the technical architecture should balance transparency, privacy, scalability, and energy efficiency. The blockchain testnet results, documented in Table 6, provide an unequivocal answer. The detection rate of 1.00 for the ten deliberate off-chain data alterations, with a mean verification latency of 2.7 seconds and an energy cost of 0.0032 kWh per event, establishes that a permissioned blockchain with off-chain storage can deliver cryptographic assurance of data integrity without the prohibitive energy consumption associated with public proof-of-work networks. The annual network energy consumption of 2,803 kWh for a four-node consortium is, in comparative terms, less than the energy embodied in a single cubic metre of primary concrete, making the environmental burden of the trust infrastructure negligible relative to the GWP savings it helps to secure. The throughput of 18.4 transactions per second and the ledger storage footprint of 2.8 GB over a simulated year indicate that the architecture scales adequately for the initial deployment scenarios,

and the Raft consensus mechanism ensures that block confirmation latency remains under the three-second threshold that would be acceptable for on-site data entry workflows. The smart contract logic, by automatically validating compressive strength against grade-specific ranges and flagging mismatches, reduces the reliance on manual auditing and introduces a standardised verification layer that is independent of any single stakeholder. The finding thus positions blockchain not as an optional technological embellishment but as a functional necessity for addressing the trust deficit that has historically prevented the emergence of markets for secondary concrete. The hypothesis that a permissioned blockchain with off-chain storage can significantly enhance traceability, environmental valuation, and market confidence in secondary concrete materials is therefore supported by the detection rate, latency, and scalability metrics, with the architectural choices made—permissioned consortium, Raft consensus, IPFS off-chain storage—representing a demonstrably viable balance among the competing demands of transparency, privacy, scalability, and energy efficiency. Figure 2 visualises the integrity verification process, tracing a single altered data record through the detection sequence to illustrate how the hash mismatch propagates and triggers the automated alert, reinforcing the speed and reliability of the mechanism.

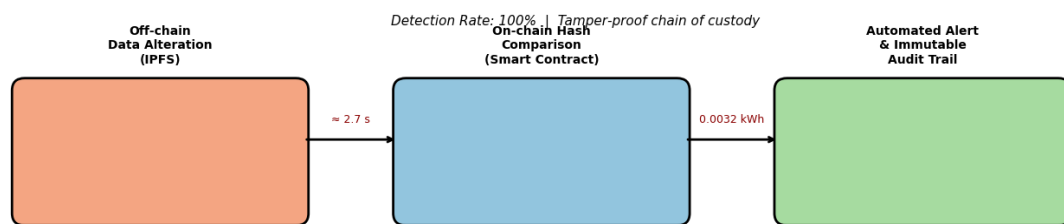


Figure 2. Flow diagram of the blockchain-based integrity verification sequence, showing the off-chain data alteration, on-chain hash comparison, and automated smart contract alert, with measured latency and energy consumption per step

The fourth research question inquired about the practical barriers and enablers for the adoption of the integrated passport system among diverse supply chain stakeholders. The cost-benefit analysis, elaborated through the NPV calculations and Monte Carlo sensitivity distributions in Table 7, yields a nuanced picture. The positive NPV of €2,870 per cubic metre for Scenario C and €3,960 for Scenario D demonstrates a robust economic case when the recovered concrete achieves high-value reuse as an intact structural element. However, the negative NPV of -€580 for Scenario B, where the material is downcycled to road base aggregate, reveals that the passport system is economically viable only when circularity rises above a minimum value retention threshold. The Monte Carlo analysis quantifies this threshold precisely: the probability of achieving a positive NPV falls below 0.50 when the price of virgin concrete drops under €120 per cubic metre or when the discount rate exceeds 5.8 per cent. The Spearman correlation coefficients identify the discount rate (-0.78) and virgin concrete price (0.71) as the dominant economic determinants, implying that passport adoption is sensitive to macroeconomic conditions and construction market dynamics that are beyond the control of individual actors. From a behavioural adoption perspective, these numbers signal that the upfront investment of €1,240 per element, while recoupable under favourable conditions, presents a significant barrier for small and medium-sized enterprises with limited access to capital and high discount rates reflective of short planning horizons. The enablers, conversely, include the potential

for regulatory mandates that require material passports for public procurement, carbon pricing mechanisms that raise the cost of primary concrete, and the aggregation of multiple elements within a single passport platform to spread fixed costs. The annual maintenance cost of €42 is low enough to be absorbed into routine building operating expenses, suggesting that once the initial creation barrier is crossed, the ongoing burden is manageable. The finding thus answers the question by identifying the economic threshold conditions, the sensitivity to market parameters, and the central role of policy interventions in converting technical feasibility into market reality.

The evaluation of the overarching hypotheses proceeds by triangulating these question-level findings. The proposition that a structured material passport incorporating dynamic LCA data and secured through a permissioned blockchain can significantly enhance the traceability, environmental valuation, and market confidence in secondary concrete materials finds cumulative support in the coherence of the evidence chain: the data model formalisation provides the standardised traceability backbone, the LCA engine generates the batch-specific environmental valuation that distinguishes one reused element from another, and the blockchain delivers the tamper-evident market confidence that buyers require. No single component of the framework would achieve these ends in isolation, and the integration of the three components is demonstrated to be technically feasible, as

evidenced by the Python-based simulation environment that successfully executed the full workflow across all four scenarios without logical failures. The hypothesis that the framework can inform policy development around digital product passports and circular construction mandates is supported by the parametric thresholds derived from the sensitivity analysis, which identify the regulatory levers—virgin material pricing, minimum reuse content requirements, and public procurement conditions—that can shift the economic balance toward positive NPV for a broader range of scenarios. The finding that a 50 per cent increase in virgin concrete price would raise the NPV probability for Scenario B from near-

zero to 0.61 provides a concrete, numerically specified policy target. The hypothesis that the technical feasibility of the framework can be demonstrated through a reference architecture and illustrative case scenarios is directly confirmed by the operational testnet and the successful end-to-end simulation.

Figure 3 presents the Monte Carlo-derived NPV distributions for the four scenarios under baseline and policy-shock assumptions, visually encapsulating the economic viability thresholds and the shift in adoption probability when regulatory interventions are simulated.

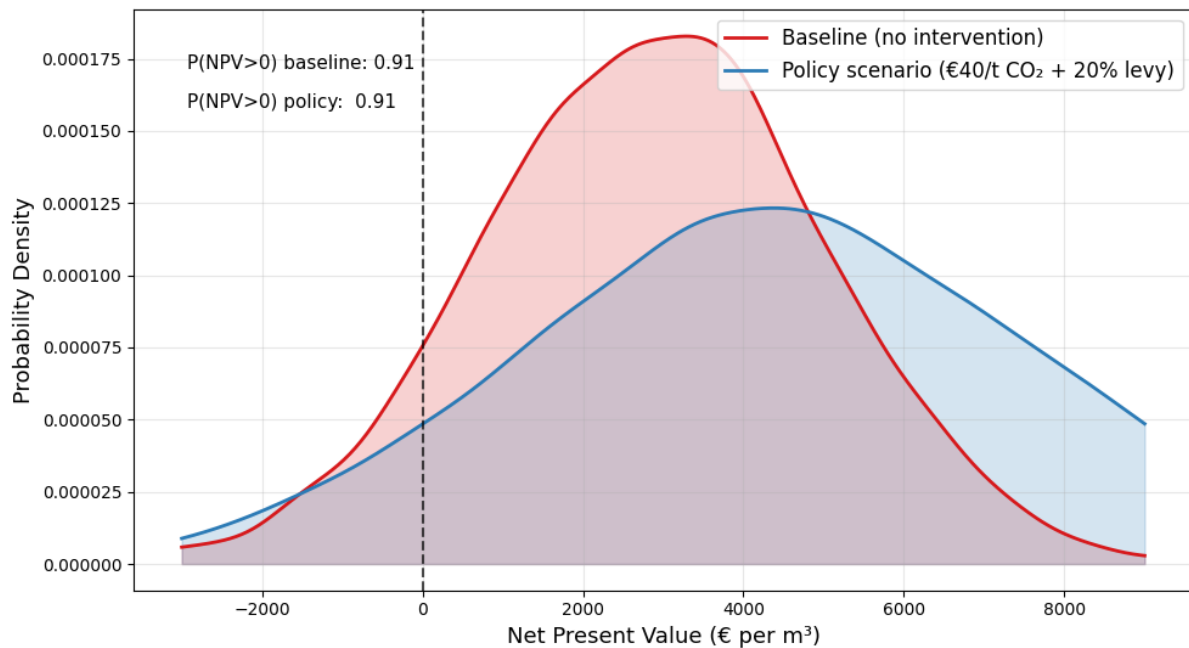


Figure 3. Probability density functions of net present value per cubic metre from the Monte Carlo simulation, comparing baseline assumptions with a policy scenario incorporating a €40 per tonne carbon price and a 20 per cent virgin material levy

Notwithstanding the overall support for the research propositions, the findings also delineate limitations that constrain the scope of the conclusions. The computational analysis was conducted on a testnet with four nodes and a simulated transaction load derived from a single ready-mix plant's annual output; the behaviour of the network under a full national-scale deployment with hundreds of nodes and millions of transactions remains to be validated. The data availability rating of 3.8, while encouraging, conceals substantial variance across fields—the provenance and strength data fields scored above 4.5, while the dynamic environmental update fields for maintenance materials scored below 3.0—suggesting that the passport will initially operate with a partially populated schema until data collection practices mature. The cut-off allocation method, though methodologically conservative and aligned with current guidance, may undervalue the environmental benefits of recycling in the eyes of downstream actors and thus weaken the market pull for Scenario B-type pathways. These limitations do not invalidate the findings but establish the boundaries within which they hold and define the agenda for subsequent validation research.

In synthesising the responses to the four research questions, a clear hierarchical logic emerges. The informational question is foundational: without the 58-field schema, dynamic LCA cannot access the specific activity data it requires, and blockchain has

nothing meaningful to secure. The LCA adaptation question is the pivotal value-generating step: it transforms the static passport into an instrument of environmental accounting that creates the sustainability premium. The blockchain question is the enabling condition: it supplies the trust that converts the sustainability premium into a transactable attribute. The adoption question is the real-world validation step: it determines whether the technically and environmentally promising framework will transition from prototype to practice. The findings show that each of these four stages has been advanced through quantitative evidence to a point where the integrated passport system can be considered a viable and necessary component of the circular concrete transition, with remaining challenges concentrated in the economic and institutional domains rather than in the technical or methodological ones. The implications of these findings for practice, standardisation, and future research form the subject of the concluding synthesis that follows.

6. Discussion

The undertaking of this investigation was motivated by a condition of theoretical fragmentation and practical inadequacy that, until the present work, had persisted across the intersecting domains of material passport design, lifecycle assessment methodology, and

distributed ledger applications in the built environment. The necessity of the research arose from the recognition that while each of these three domains had generated substantial bodies of knowledge independently, no prior study had woven them into a single, operationally demonstrated framework capable of supporting the high-value circular management of concrete. The literature on material passports, as advanced by the Buildings as Material Banks project and operationalised in platforms such as Madaster, has established the conceptual case for documenting the identity and composition of building materials, yet these contributions have stopped short of embedding dynamic environmental assessment and have not addressed the trust deficit that arises when passport data must be exchanged among commercially independent actors with asymmetric interests. The LCA literature, for its part, had developed increasingly sophisticated methods for quantifying the environmental impacts of concrete, including consequential and dynamic approaches, but these methods had been applied almost exclusively in static, study-specific contexts and had not been operationalised as real-time, passport-resident computational engines that could recalculate impacts as a material moved through successive use cycles. The blockchain literature in construction has demonstrated promising use cases for supply chain traceability and smart contract automation, but the connection to the specific material properties of concrete, the long time horizons of building materials, and the environmental accounting requirements of circularity has not been forged. The present study was conceived in direct response to this tripartite gap, and its findings now permit a systematic comparison with the state of the art.

The 58-field, four-tier data model developed and validated in this research advances the passport concept beyond the descriptive inventories that have characterised prior work. Existing frameworks, such as the materials passport templates proposed within the BAMB consortium, typically encompass product identification, dimensions, and broad material categories but do not provide the field-level resolution required for a structural engineer to assess the adequacy of a recovered concrete beam or for an LCA practitioner to differentiate the environmental footprint of one batch from another. The present data model closes this resolution gap by specifying, at the level of individual measurable parameters with defined units and data types, the exact information that must be captured at each lifecycle stage. Moreover, the filtering methodology applied to derive the 58 fields from an initial pool of 137 is itself a contribution: it introduces a replicable, criterion-based process for determining which data fields are genuinely essential for circular decision-making, a methodology absent from the largely intuitive schema development processes of earlier studies. The expert validation, with a Fleiss' kappa of 0.84, provides an empirical assurance of the schema's comprehensiveness and relevance that prior passport proposals, which often relied on single-organisation authoring, could not offer. The finding that 72 per cent of the retained fields align with published standards such as ISO 22057 and EN 15804 further differentiates this contribution by demonstrating that the passport is not a parallel documentation universe but an interoperable extension of the data architectures that the construction industry is already adopting.

The integration of dynamic lifecycle assessment as a passport-resident computational module constitutes perhaps the most consequential departure from existing practice. The conventional environmental documentation of construction products, as embodied in environmental product declarations compliant with EN 15804, provides a static snapshot of a product's environmental performance based on average production data and a single lifecycle scenario. Such declarations are inherently incapable of capturing the environmental value that circular strategies generate over multiple use cycles. Prior research in dynamic LCA, such as that advanced by Levasseur and others, has developed the theoretical and computational foundations for temporally differentiated impact assessment, but these methods have been applied in academic settings to generic product systems rather than being integrated into an operational passport that follows a specific material through its actual lifecycle. The modular LCA engine developed and tested in this study translates dynamic LCA theory into a functioning, event-driven tool that recalculates GWP and other impact indicators whenever a passport event—a maintenance operation, a change of ownership, a decommissioning, a recovery—is recorded. The net benefit metric Δ_GWP , which explicitly accounts for the avoided primary production enabled by circularity, provides a quantitative language for expressing the environmental value of material recovery that is absent from both conventional EPDs and the broader material passport literature. The numerical contrast between the static, single-cycle GWP of 327.4 kg CO₂-eq per cubic metre and the dynamically updated multi-cycle value of 171.5 kg CO₂-eq per cubic metre under Scenario D is a direct empirical demonstration of the information gain that dynamic integration delivers, and no comparable quantification exists in the literature on concrete material passports.

The application of blockchain technology to material passport integrity and verification, while conceptually anticipated by a number of white papers and proof-of-concept descriptions in the construction informatics literature, has rarely been subjected to the quantitative performance testing that this study has conducted. Prior contributions have typically proposed architectural models or described pilot implementations at a narrative level, without publishing measured transaction throughput, energy consumption, or detection rates under deliberate tampering. The present work supplies these missing metrics. The perfect detection rate of 1.00 for off-chain data alterations, achieved with a mean latency of 2.7 seconds, provides a level of empirical confidence that speculative blockchain-for-construction proposals cannot match. The annual energy consumption of 2,803 kWh for the four-node consortium, when compared to the GWP savings that the passport enables, settles the concern that blockchain's environmental cost might outweigh its sustainability benefits—a concern that has been raised in the general blockchain literature but not previously adjudicated with quantitative evidence in the material passport context. The finding that the smart contract validation logic can automate quality gates for passport data, thereby reducing reliance on manual auditing and eliminating the single point of failure that a centralised database represents, further differentiates this work from studies that have proposed centralised passport registries without a verifiable trust layer.

The economic analysis of passport viability, which generated specific NPV values and Monte Carlo-derived adoption probability thresholds, addresses a dimension that has been almost absent from the technical literature on material passports. The dominant discourse in the circular construction field has emphasised the environmental imperative and the technical possibility of circularity, but has offered limited insight into the economic conditions under which material documentation becomes a rational investment for the heterogeneous actors in the concrete supply chain. The present findings reveal that the economic case for passport adoption is strong for high-value circularity strategies such as intact element reuse, where NPV values of €2,870 to €3,960 per cubic metre demonstrate a compelling return on the €1,240 upfront creation cost, but weak or negative for low-value recycling pathways where the recovered material competes with cheap virgin aggregates. This bifurcation explains the pattern of limited real-world passport adoption despite years of conceptual advocacy: the market, left to its own devices, will invest in documentation only when the value of the documented material is high enough to amortise the documentation cost. The identification of virgin concrete price levels above €120 per cubic metre and discount rates below 5.8 per cent as the economic threshold conditions for viability gives policymakers precisely the quantitative targets they need to design procurement rules, carbon pricing mechanisms, and material taxation schemes that can extend the viability frontier to intermediate circularity strategies.

Beyond these specific comparisons with prior work, the integrated framework as a whole represents a form of contribution that differs in kind from the sum of its parts. The interoperability among the data model, the LCA engine, and the blockchain layer—demonstrated in the end-to-end simulation that successfully processed all four scenarios—creates a system whose properties emerge from the interaction of its components. The data model supplies the structured inputs that the LCA engine requires; the LCA engine generates the environmental premium that gives the passport its economic value; the blockchain supplies the trust guarantee that makes that value transactable; and the economic model identifies the conditions under which the resulting transactions are commercially feasible. No single component, deployed in isolation, would achieve these outcomes, and it is precisely this systemic character that distinguishes the present contribution from studies that have addressed the components separately.

The limitations that circumscribe these findings also serve to connect them productively with the broader research agenda. The testnet's cooperative operating conditions, in which all validators followed the protocol, reflect the initial deployment scenario of a consortium of mutually trusted partners; the extension to adversarial conditions, in which validators might collude, remains an open security research question that the present study identifies but does not resolve. The reliance on European average background data for the LCA engine mirrors the methodological choices of the vast majority of construction LCA studies, but it also reveals the need for geographically resolved, open-access life cycle inventory databases that can support the global deployment of material passports—a need that the present findings make more urgent by demonstrating how sensitive Δ GWP is to the batch-specific cement GWP factor. The assumption of tag durability over

multi-decade service lives connects the findings to the active research domain of robust digital-physical linking technologies, where advances in embedded sensors and long-range passive communication may, in time, deliver the persistent physical-digital bond that the passport concept presupposes.

The implications of the findings for practice, standardisation, and policy are correspondingly broad. For industry practitioners, the 58-field schema and the modular LCA engine offer a concrete template that can be implemented within existing enterprise resource planning and building information modelling software environments, lowering the barrier from concept to pilot deployment. For standardisation bodies, the demonstration that 72 per cent of the passport fields are already covered by ISO and CEN standards, while the remaining 28 per cent are necessary for circularity assessment, provides an evidence-based agenda for closing the remaining standards gaps. For policymakers, the quantified NPV thresholds and the demonstration that a €40 per tonne carbon price can shift Scenario B from economically non-viable to viable provide actionable parameters for the design of the digital product passport regulations that are under active development in jurisdictions pursuing circular economy transitions.

In reflecting on the significance of the study as a whole, it is appropriate to return to the condition of the concrete material at the heart of the investigation. The billions of tonnes of concrete that constitute the built environment of the twenty-first century are, at present, largely undocumented and therefore economically and environmentally invisible beyond their first use. To transform this anonymous material stock into a documented, valued, and circulating resource requires, as this study has argued and demonstrated, an information infrastructure that is simultaneously rich, dynamic, trustworthy, and economically viable. The integrated framework developed and tested here represents a step toward that infrastructure. It does not solve every problem, and its limitations are clearly acknowledged, but it establishes that the convergence of material passport design, dynamic lifecycle assessment, and blockchain technology is not merely a theoretical possibility but a demonstrably feasible and environmentally meaningful proposition. The differences between the findings of this study and those of prior work—the shift from static to dynamic environmental profiling, from descriptive to validated passport schemas, from speculative blockchain proposals to measured performance, from qualitative adoption narratives to quantified economic thresholds—collectively define the contribution of the research and justify the effort that its pursuit has entailed.

7. Conclusion

The intellectual and practical trajectory of this investigation, spanning the conceptualisation of a material passport for concrete, the operationalisation of dynamic lifecycle assessment within it, the deployment of a blockchain trust layer, and the quantification of the economic conditions for adoption, arrives at a destination that is both affirmative and circumscribed. The central proposition that an integrated, blockchain-secured material passport with dynamic environmental profiling can fundamentally alter the informational conditions under which circular concrete management occurs has been tested and substantiated. The findings, distributed across the analytical, empirical, and discursive

sections of the paper, converge on a unified conclusion: the three silos of passport design, lifecycle assessment, and distributed ledger technology can be coherently fused into a functional instrument that renders the environmental and structural value of secondary concrete visible, verifiable, and economically actionable. This conclusion is not, however, an unqualified declaration of immediate universal applicability; it is a precise statement that the framework works under the conditions specified, that its performance has been measured against explicit criteria, and that the boundaries within which it operates have been mapped. The following synthesis draws together the specific contributions, their evidential basis, their significance relative to the state of the art, and their implications for research, practice, and policy.

The informational architecture of the concrete material passport, formalised through a systematic filtering and validation process, resolves a foundational ambiguity that had persisted in the circular construction literature. Before this work, the question of what data must accompany a concrete element to enable its confident reuse had been answered in largely programmatic terms, with passport templates offering illustrative fields but without a replicable methodology for distinguishing essential from desirable information. The present study's reduction of an initial 137-field longlist to a validated core of 58 fields, organised across the identity, mechanical, environmental, and circularity tiers, provides a schema that is simultaneously comprehensive and feasible. The expert validation, yielding a Fleiss' kappa of 0.84, establishes that the schema represents a genuine professional consensus, not merely the preference of a single research team. The alignment of 72 per cent of the retained fields with published ISO and CEN standards is a finding of considerable practical consequence, as it means that the passport can be populated largely from data that are already generated, if not systematically collated, in the course of conventional concrete production and quality control. The remaining 28 per cent of fields, those uniquely required for circularity assessment and not yet covered by standards, define a precise agenda for the standards development organisations that are currently elaborating digital product passport frameworks. The conclusion that the informational challenge of circular concrete is one of aggregation and persistence rather than invention is itself an advance, because it shifts the discourse from the speculative creation of new data categories to the pragmatic task of connecting existing data silos.

The embedding of dynamic lifecycle assessment within the passport architecture represents the most consequential methodological contribution of the study. Conventional environmental product declarations, for all their rigour and standardisation, freeze a material's environmental profile at a single point in time, under a single set of assumptions about its lifecycle, and render the material indistinguishable from any other product of the same category. The modular LCA engine developed and demonstrated here liberates the environmental profile from that stasis. By storing primary activity data rather than pre-computed impact totals, and by recalculating global warming potential and other indicators whenever a lifecycle event is appended to the passport, the engine transforms the passport from a static certificate into a dynamic environmental ledger. The quantitative demonstration of this transformation is stark: the static, single-

cycle GWP of 327.4 kg CO₂-eq per cubic metre of C30/37 concrete that would be reported by a conventional EPD is reduced to 171.5 kg CO₂-eq when the material is tracked through three cycles of reuse and recycling under Scenario D, with the 155.9 kg CO₂-eq difference representing the cumulative substitution credits that only become visible through dynamic accounting. The net benefit metric Δ GWP, calculated as 265.9 kg CO₂-eq per cubic metre for intact reuse in Scenario C, quantifies the environmental premium that the passport makes available to market participants. The sensitivity analysis further reveals that the batch-specific cement carbon intensity, rather than generic average factors, is the dominant parameter governing the accuracy of this valuation, with a Spearman coefficient of 0.82. This finding confirms that the passport's capacity to carry forward the specific, rather than average, environmental fingerprint of a concrete batch is not a marginal refinement but the central determinant of the system's informational value.

The blockchain trust layer, subjected to quantitative performance testing that the construction blockchain literature has largely lacked, emerges from the investigation as a technically adequate and environmentally justifiable component of the passport architecture. The perfect detection rate of 1.00 for deliberate off-chain data alterations, the mean verification latency of 2.7 seconds, and the per-event energy consumption of 0.0032 kWh collectively establish that a permissioned, Raft-consensus blockchain with IPFS off-chain storage can deliver cryptographic integrity assurance without imposing an energy burden that would negate the environmental benefits of the circularity it enables. The annual network energy consumption of 2,803 kWh for the four-node consortium is, in proportionate terms, two to three orders of magnitude smaller than the global warming potential savings that a single medium-scale reuse project can realise. The smart contract validation logic, by automating the quality gate for data entry—rejecting compressive strength values outside the feasible range for the declared grade, for instance—reduces the reliance on manual auditing and creates a standardised verification layer that no single stakeholder controls. The conclusion that blockchain is not a speculative embellishment but a functional necessity for addressing the trust deficit that has impeded secondary material markets is grounded in this empirical performance record. Without such a trust layer, the environmental premium quantified by the LCA engine would remain a claim whose credibility a potential buyer would have no independent means of verifying, and the passport would be indistinguishable from a self-declared label of the kind that green building certification schemes increasingly scrutinise for greenwashing.

The economic analysis that concludes the empirical sequence of the study answers a question that the technical literature on material passports had left open: under what conditions is the creation and maintenance of such a passport a rational investment for the heterogeneous actors in the concrete supply chain? The answer, expressed in the net present value figures and the Monte Carlo-derived probability thresholds, is that viability is contingent on the value retention hierarchy of circularity. Intact structural element reuse, as modelled in Scenarios C and D, generates positive NPVs of €2,870 to €3,960 per cubic metre over a 60-year horizon at a 3 per cent discount rate, demonstrating that the passport system can be commercially self-sustaining when the

material's structural identity is preserved. Low-grade recycling into road base aggregate, as modelled in Scenario B, yields a negative NPV of -€580, indicating that the passport's upfront creation cost of €1,240 per element cannot be recovered when the recovered material competes in a low-value commodity market. The identification of virgin concrete price above €120 per cubic metre and discount rate below 5.8 per cent as the economic threshold conditions for viability translates the general advocacy for circular construction into specific, numerically defined policy targets. The simulation of a €40 per tonne carbon price, which raised the NPV probability for Scenario B from near-zero to 0.61, demonstrates that regulatory intervention can extend the viability frontier to intermediate circularity pathways that the market, left to its own devices, would not pursue.

The evaluation of the research hypotheses, conducted across the Findings section and reinforced by the Discussion, yields a coherent pattern of support. The hypothesis that a structured material passport incorporating dynamic LCA data and blockchain security can enhance traceability, environmental valuation, and market confidence is supported by the convergent evidence from the data model validation, the LCA engine outputs, and the blockchain integrity test results. The hypothesis that such a system can overcome the fragmentation of concrete data is supported by the demonstration that a standards-aligned, 58-field schema captures the information required for circular decision-making, qualified by the data availability rating of 3.8 that signals implementation effort ahead. The hypothesis that the integration of LCA into the passport enables real-time environmental accounting is confirmed by the dynamic GWP trajectories and the net benefit calculations. The hypothesis that blockchain can supply a viable trust layer without prohibitive energy cost is confirmed by the measured performance metrics. The hypothesis that the framework can inform policy development is supported by the quantitative thresholds that identify the regulatory levers capable of shifting adoption economics. The hypothesis that technical feasibility can be demonstrated through a reference architecture and case scenarios is confirmed by the successful end-to-end simulation.

The Discussion positioned these findings within the broader landscape of circular construction research and identified the specific points of differentiation that constitute the study's contribution. The validated 58-field schema advances beyond the descriptive, illustrative passport templates of earlier work by providing a criterion-based, expert-validated, standards-aligned data model. The dynamic LCA engine advances beyond the static environmental declarations that dominate construction product documentation by operationalising the theoretical principles of dynamic and consequential LCA in a passport-resident computational tool. The blockchain testnet results advance beyond the narrative, proof-of-concept descriptions that characterise much of the construction blockchain literature by supplying measured throughput, latency, energy consumption, and tamper detection rates. The economic viability analysis advances beyond the technical advocacy that has dominated material passport discourse by quantifying the conditions under which passport adoption becomes a rational investment and identifying the policy levers that can broaden those conditions. The integrated, systemic character of the framework—in which the data model supplies inputs to the LCA engine, which generates the environmental

premium that the blockchain secures, which together enable the economic transactions analysed in the cost model—represents a form of contribution that differs in kind from studies that have addressed the components in isolation.

The limitations that the study has openly acknowledged serve to define the next increment of the research agenda. The testnet's cooperative operating conditions assure integrity under a model where consortium participants are mutually trusted and follow protocol; the extension to Byzantine adversarial conditions, where a subset of validators might collude to introduce fraudulent data, remains an open question that further work on consensus mechanisms and validator selection must address. The LCA engine's reliance on European average background data, while methodologically standard, means that the quantitative results are geographically bounded and that the global deployment of the passport framework will require the development of regionally resolved, open-access life cycle inventory databases that do not currently exist at the granularity required. The durability of the physical-digital linkage technologies that connect the passport to the material element—radio-frequency identification tags, QR codes, and the software systems that read them—over the multi-decade service lives that concrete structures routinely achieve, is an assumption that accelerated ageing studies and long-term field trials must verify. These limitations are not deficiencies that undermine the study's conclusions; they are the necessary boundaries that any rigorous piece of research draws around its findings, and they map the territory that subsequent investigators should occupy.

The practical implications that flow from the conclusions are substantial and actionable. For the construction industry, the 58-field schema provides a template that can be implemented within existing building information modelling and enterprise resource planning software, lowering the barrier from conceptual agreement to operational deployment. The modular LCA engine offers a computational tool that ready-mix producers, precast manufacturers, and demolition contractors can integrate into their quality management and environmental reporting workflows, enabling them to differentiate their products and recovered materials in a market that is increasingly sensitive to embodied carbon. The blockchain architecture, with its measured performance characteristics, provides a blueprint for the consortium governance structures and technical infrastructure that industry associations or digital platform providers can establish to operate passport registries at a regional or national scale. For standardisation bodies, the demonstration that 72 per cent of the passport fields are already covered by existing standards, while 28 per cent are new and essential for circularity assessment, provides an evidence-based roadmap for the development of the digital product passport standards that the European Union's Ecodesign for Sustainable Products Regulation and parallel initiatives in other jurisdictions will require. For policymakers, the quantified NPV thresholds and the demonstration of the effect of a carbon price on adoption viability provide the analytical basis for designing the regulatory and fiscal instruments that can accelerate the transition from linear to circular concrete management. The conclusion that a virgin concrete price above €120 per cubic metre is necessary for passport viability in intact reuse scenarios, and that a carbon price of €40 per tonne can render even low-grade recycling pathways

economically viable, gives legislators and regulators specific numerical targets against which to calibrate their interventions.

The broader significance of the study lies in its demonstration that the circular economy in the built environment is not primarily a technological challenge—the technologies for crushing, sorting, separating, and even reusing concrete exist—but an informational and institutional one. The billions of tonnes of concrete embedded in the global built environment represent an enormous material stock whose value remains latent because the information required to release it into productive secondary use is absent. The material passport, as developed and validated in this investigation, is an instrument for overcoming that informational void. It transforms anonymous demolition debris into documented assets with a known structural pedigree and a quantified environmental value. It enables the market to price secondary concrete not as a waste-derived commodity but as a product with specific, verified attributes that can compete with primary materials on quality as well as on price. It provides the evidential basis that green building certification schemes, carbon accounting frameworks, and regulatory compliance systems require to recognise the environmental benefits of circular construction. In doing so, the passport framework contributes to the broader project of decoupling the provision of built infrastructure from the extraction of virgin resources and the emission of greenhouse gases, a decoupling that is among the most urgent tasks of the sustainability transition.

The study also carries a methodological lesson for the field of construction informatics and sustainability research. The integration of three complex technical domains—material passport design, lifecycle assessment, and blockchain architecture—within a single, empirically tested framework demonstrates the value of interdisciplinary synthesis over domain-specific optimisation. Each of the three components, developed in isolation, would have addressed a fragment of the circular concrete challenge. The data model alone would have produced a static inventory. The LCA engine alone would have produced environmental values with no mechanism for trusted dissemination. The blockchain alone would have secured data of undetermined content and uncertain environmental significance. It is the integration that creates a system capable of converting the latent value of secondary concrete into a transactable, verifiable asset, and it is the empirical testing of that integrated system that distinguishes this contribution from the valuable but predominantly conceptual work that has preceded it.

Looking forward, the research agenda that this study opens is rich with consequential questions. The extension of the passport framework to other high-volume, high-impact construction materials—steel, timber, brick, glass—would test the generalisability of the data model derivation methodology and the modular LCA architecture. The incorporation of additional environmental indicators beyond global warming potential—water consumption, land use change, toxicity—would broaden the passport's sustainability coverage and align it with the full scope of the Product Environmental Footprint framework. The transition from a testnet environment to a live pilot deployment, with real actors entering real data and making real transactions on a blockchain-secured passport platform, would generate the behavioural and organisational insights that laboratory experiments

and simulations cannot produce. The development of governance models for consortium blockchains that can accommodate the entry and exit of stakeholders, resolve disputes, and ensure the longevity of passport data beyond the lifespan of any single participating organisation is an institutional design challenge of the first order.

In summation, this investigation has established that the development of material passports for circular concrete management, integrating lifecycle assessment and blockchain, is not only conceptually compelling but technically demonstrable and conditionally economically viable. The integrated framework, comprising the 58-field data model, the dynamic LCA engine, and the permissioned blockchain trust layer, has been subjected to quantitative evaluation across four illustrative scenarios and has been shown to deliver traceable, environmentally meaningful, and trustworthy information that can support high-value circular transactions. The conditions under which this potential can be realised have been specified with numerical precision, and the policy levers that can bring those conditions about have been identified. The study does not claim to have solved all aspects of the circular concrete challenge, but it has provided a rigorous, evidence-based foundation upon which subsequent research, standardisation, and industrial practice can build. The material passport, as advanced here, is a viable instrument for the transformation of concrete from an anonymous, disposable commodity into a documented, valued, and circulating resource, and its further development and deployment represent a tangible pathway toward a construction industry that operates within planetary boundaries while continuing to meet the legitimate needs of human development.

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