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GOVERNING CONSTRUCTION MATERIAL REUSE AS A BLOCKCHAIN COMMONS: OSTROM'S DESIGN PRINCIPLES AND EU DIGITAL PRODUCT PASSPORTS

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Abstract

Scotland's construction industry operates at a circularity rate of just 1.3%, exemplifying a wider EU governance failure: the Construction Products Regulation and Ecodesign for Sustainable Products Regulation mandate Digital Product Passports (DPPs) for construction materials, assuming linear supply chains, with no governance for reclaimed material re-entry. This paper applies Ostrom's principles for commons governance to a blockchain-based marketplace for construction material reuse. Using hybrid methods, we present a deployed prototype architecture of seven smart contracts, built on VeChainThor and implemented as the TRACE platform (trace.adventurous.systems), designed for EU DPP compliance while implementing commons governance for material reuse's institutional context.

Introduction

The construction industry is responsible for approximately 37% of global CO^2 emissions and consumes roughly half of all extracted materials worldwide (UNEP, 2022). In Scotland, despite ambitious circular economy targets, the construction sector achieves a circularity rate of only 1.3% (Zero Waste Scotland, 2024)—a figure that reflects a broader EU-wide challenge, as the governance infrastructure for material reuse does not yet exist in any member state. The vast majority of demolition materials are downcycled or landfilled rather than reused in their original form. Beyond an environmental failure this is a governance failure: the institutional infrastructure required to coordinate material reuse across fragmented stakeholders does not exist.

Two converging policy developments create both urgency and opportunity. First, the EU's revised Construction Products Regulation (CPR), which entered into force on 7 January 2025, mandates Digital Product Passports for construction products, requiring structured digital records of material composition, environmental performance, and compliance data (European Commission, 2024a). Second, the Ecodesign for Sustainable Products Regulation (ESPR, EU 2024/1781) establishes the broader DPP framework, specifying JSON-LD data formats, GS1 Digital Link identifiers, and tiered access controls for consumers, professionals, and regulators (European Commission, 2024b). Construction product DPPs are expected to become mandatory between 2029 and 2032 through phased harmonised standards.

However, these regulations are designed for linear supply chains: a manufacturer produces a product, declares its performance, and places it on the market with a CE marking and accompanying DPP. The regulatory framework offers no model for what happens when a construction material is deconstructed from a building, assessed for condition, and re-enters circulation through a community-run reuse hub. Who issues the DPP for a reclaimed steel beam? Under what authority? With what quality assurance mechanisms? How are disputes resolved when the 'manufacturer' is a volunteer-run charity?

We argue that this governance vacuum is precisely the institutional challenge that Elinor Ostrom's (1990) design principles for managing common-pool resources can address. Construction materials available for reuse constitute a shared resource that is rivalrous (one builder's use of a reclaimed beam excludes another's) and partially excludable (access requires knowledge of availability and logistics coordination). The community of reuse hubs, suppliers, and buyers face classic commons dilemmas: how to maintain quality without central authority, how to share information without exploitation, and how to distribute costs and benefits fairly across heterogeneous participants.

This paper presents findings from the TRACE (Transforming Resources and Advancing Circular Economy) project, which develops a blockchain-based digital marketplace for construction material reuse hubs. We address the following research question: *How can Ostrom's design principles for commons governance inform the design of EU DPP-compliant blockchain infrastructure for construction material reuse?*

Related work

Ostrom's design principles and digital commons

Ostrom's (1990) eight design principles for successful commons governance—clearly defined boundaries, congruence between appropriation and provision rules, collective-choice arrangements, monitoring, graduated sanctions, conflict-resolution mechanisms, minimal recognition of rights to organise, and nested enterprises—were originally derived from analysis of natural resource commons. Subsequent work has extended these principles to digital contexts. Schweik and English (2012) applied the framework to open-source software communities. Fuster Morell (2014) adapted it to online creation communities. Most relevant to this research, Rozas et al. (2021) systematically mapped Ostrom's principles to six blockchain affordances: tokenisation, self-enforcement and autonomy of rules, decentralisation of authority, transparency, and codification of trust through cryptographic mechanisms. The Mozilla Foundation's practical framework (Ruhaak et al., 2021) further operationalised Ostrom for data commons governance.

EU digital product passports for construction

The EU's DPP framework represents the most significant regulatory development in construction product information management in decades. The revised CPR (EU 2024/1305) folds DPPs into the CE marking workflow, requiring Declarations of Performance and Conformity to be digitally accessible alongside environmental data including Global Warming Potential, which becomes mandatory from 2026 (European Commission, 2024a). The ESPR (EU 2024/1781) establishes horizontal DPP requirements: machine-readable structured data (JSON-LD aligned with Schema.org), persistent unique product identifiers (GS1 GTIN with serial-level granularity via GS1 Digital Link), QR code or NFC data carriers, tiered access controls, and mandatory third-party backup storage (European Commission, 2024b). Environmental product data must align with EN 15804+A2 standards for lifecycle assessment.

Critically, these regulations assume a manufacturer-to-market linear chain. The ESPR designates the 'economic operator'—typically manufacturer or importer—as responsible for creating and maintaining the DPP (European Commission, 2024b). For reclaimed materials, this responsibility chain breaks: the original manufacturer may no longer exist, the material's properties may have changed through use and ageing, and the entity placing the reclaimed material on the market is typically a small reuse hub or social enterprise with limited resources for conformity assessment. This institutional gap is the specific problem our research addresses.

Blockchain for construction material traceability

Blockchain applications in construction have focused primarily on material traceability and supply chain transparency. Dounas et al (2021) and Lombardi (2022) provided the first comprehensive treatment of non fungible tokens on blockchain based smart contracts for building components for construction, covering smart contracts, non-fungible tokens for building components. Circularise (Amsterdam) and ReCheck (Netherlands) have implemented blockchain-based material identity systems, while the EU BAMB (Buildings as Material Banks) project explored material passport concepts. However, these implementations share a common limitation: they treat blockchain as a technical ledger for recording provenance, without addressing the governance question of who has authority to assert material properties, how quality disputes are resolved, and how collective decisions about standards and parameters are made. Circularise, for example, records material data but relies on manufacturer self-declaration, leaving the governance vacuum unchanged when no manufacturer exists. BAMB developed material passport schemas without addressing the institutional infrastructure required to issue, verify, and dispute those passports in a commons setting. This gap—between technical traceability and institutional governance—is precisely what this research addresses through the Ostrom framework.

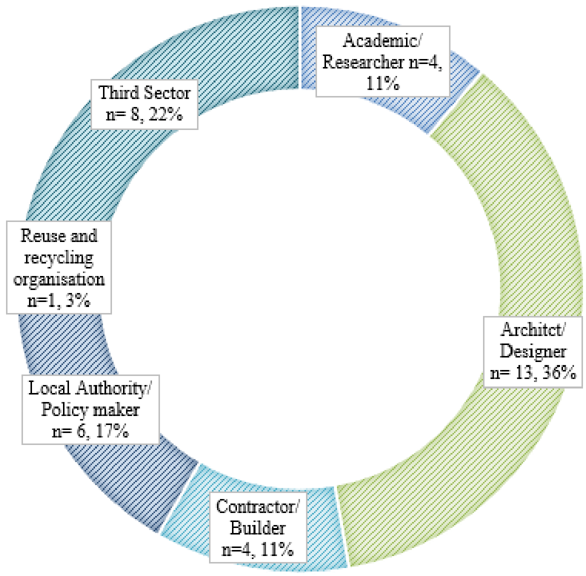

Figure 1: distribution of stakeholders' professional backgrounds

Methodology

Oversized This research follows a Design Science Research (DSR) methodology (Hevner et al., 2004) structured through a Design Thinking process (Stanford d.school, 2010). The current paper reports on the Empathise, Define, and Ideate phases, with the prototype architecture now implemented and deployed as the TRACE platform on VeChainThor.

Data collection

Four participatory workshops were conducted with 36 stakeholders across six categories: architects (n=6), third-sector organisations (n=7), local authorities (n=6), academics (n=5), contractors (n=6), and reuse organisations (n=6). Workshops were organised around four thematic areas: (1) materials and practical use, (2) trust and quality, (3) information and decision-making, and (4) process and experience. Each workshop used Microsoft Teams with Miro whiteboards for collaborative data capture. Discussions were recorded and transcribed with participant consent.

Analytical framework

Data was analysed using a hybrid deductive-inductive framework. The primary method followed Gioia et al.'s

(2013) approach: first-order codes captured participant language, second-order themes represented researcher-interpreted patterns, and aggregate dimensions mapped to theoretical constructs. An Ostrom Institutional Analysis and Development (IAD) overlay was applied to code for action arenas, rules-in-use, biophysical conditions, community attributes, and outcomes. This dual-layer analysis enabled systematic translation from stakeholder insights to governance requirements to prototype specifications.

Findings

Thematic analysis revealed three critical governance gaps that consistently surfaced across all stakeholder categories and all four thematic areas: (1) assurance mechanisms—the absence of verification pathways for reclaimed material quality; (2) logistics infrastructure—the lack of coordination systems for material availability and movement; and (3) information systems—the absence of structured digital records comparable to those available for new construction products. These gaps map systematically onto Ostrom's design principles, as presented below.

Boundaries and material viability (P1)

Stakeholders identified clear material viability hierarchies. Mineral-based materials (stone, slate, granite), brick and masonry, and structural timber were considered most viable for reuse due to durability and professional familiarity. Concrete, moisture-sensitive timber, and specification-specific steel were cited as most challenging. Participants consistently demanded clear boundary definitions: what materials qualify for reuse, under what conditions, and with what documentation. In Ostrom's terms, the resource system requires clearly defined boundaries before appropriation rules can function.

Monitoring and trust infrastructure (P4)

Trust emerged as the dominant concern across all stakeholder groups, particularly intensified by the post-Grenfell regulatory environment. Participants emphasised that reclaimed materials must be supported by documentation comparable to new-material technical data sheets. Third-party verification, recognised certification schemes, and professional expertise were identified as essential. Current checking practices rely on a combination of document-led assurance (certificates, warranties), expert-led assessment (structural engineer reports, visual grading), and operational boundary-setting (focusing on lower-risk applications). The absence of systematic monitoring mechanisms was identified as the primary barrier to scaling reuse beyond informal, relationship-dependent exchanges, in some cases with public procurement as a stimulus for circular practices.

Information asymmetry and collective choice (P3)

Decision-critical information identified by stakeholders included precise specifications (quantity, dimensions, cost, performance data), testing and certification evidence, and traceability data establishing provenance. A significant finding was the distinction between essential information (compliance and risk data) and desirable information (embodied carbon data, material history). Stakeholders from all categories expressed that current information sourcing is informal and relationship-dependent, particularly for smaller projects, while regulated buildings require substantially higher documentation standards. This asymmetry maps to Ostrom's collective-choice arrangements: stakeholders need voice in determining what information standards are required at what levels.

Congruence and cost distribution (P2)

A persistent temporal mismatch emerged: the costs of material documentation and quality assurance are borne at the point of reclamation, while the benefits accrue at the point of reuse—potentially months or years later. Third-sector organisations expressed concern that documentation costs could create barriers for smaller hubs operating on minimal budgets. Participants identified that a viable system must distribute costs proportionally to benefits derived, aligning with Ostrom's congruence principle.

Prototype architecture: implementation and design

Based on the governance requirements derived from stakeholder analysis, Ostrom mapping, and EU DPP technical specifications, we have implemented a prototype architecture comprising seven smart contracts integrated through a commons governance layer. The prototype is deployed as the TRACE platform (trace.adventurous.systems), built on VeChainThor—an EVM-compatible enterprise blockchain with built-in fee delegation (enabling users to interact without holding cryptocurrency), multi-clause batch transactions, and an energy-efficient proof-of-authority consensus model aligned with sustainability goals. The architecture follows a 'thin on-chain, rich off-chain' philosophy: the full material passport data resides in a conventional database (PostgreSQL) as structured JSON-LD, while the blockchain stores content hashes for integrity verification, ownership records, marketplace escrow logic, and governance votes. The frontend is implemented as a Progressive Web App (Next.js 14), accessible at trace.adventurous.systems, with a QR code scanner enabling public passport verification without any blockchain knowledge.

EU DPP-compliant material passport layer

The material passport data model is designed from the ground up for ESPR and CPR compliance. Each passport is structured as JSON-LD aligned with Schema.org and GS1 Web Vocabulary, carrying: a globally unique GS1 GTIN identifier with serial-level granularity; a GS1 Digital Link URI resolvable via QR code scanning; environmental data structured per EN 15804+A2 (including Global Warming Potential); and tiered access controls separating public, professional, and regulatory data views as mandated by the ESPR.

For reclaimed materials entering circular reuse, the core DPP schema is extended with fields capturing: the source building and deconstruction context, condition assessment scores (structural, aesthetic, environmental), photographic evidence, estimated remaining useful life,

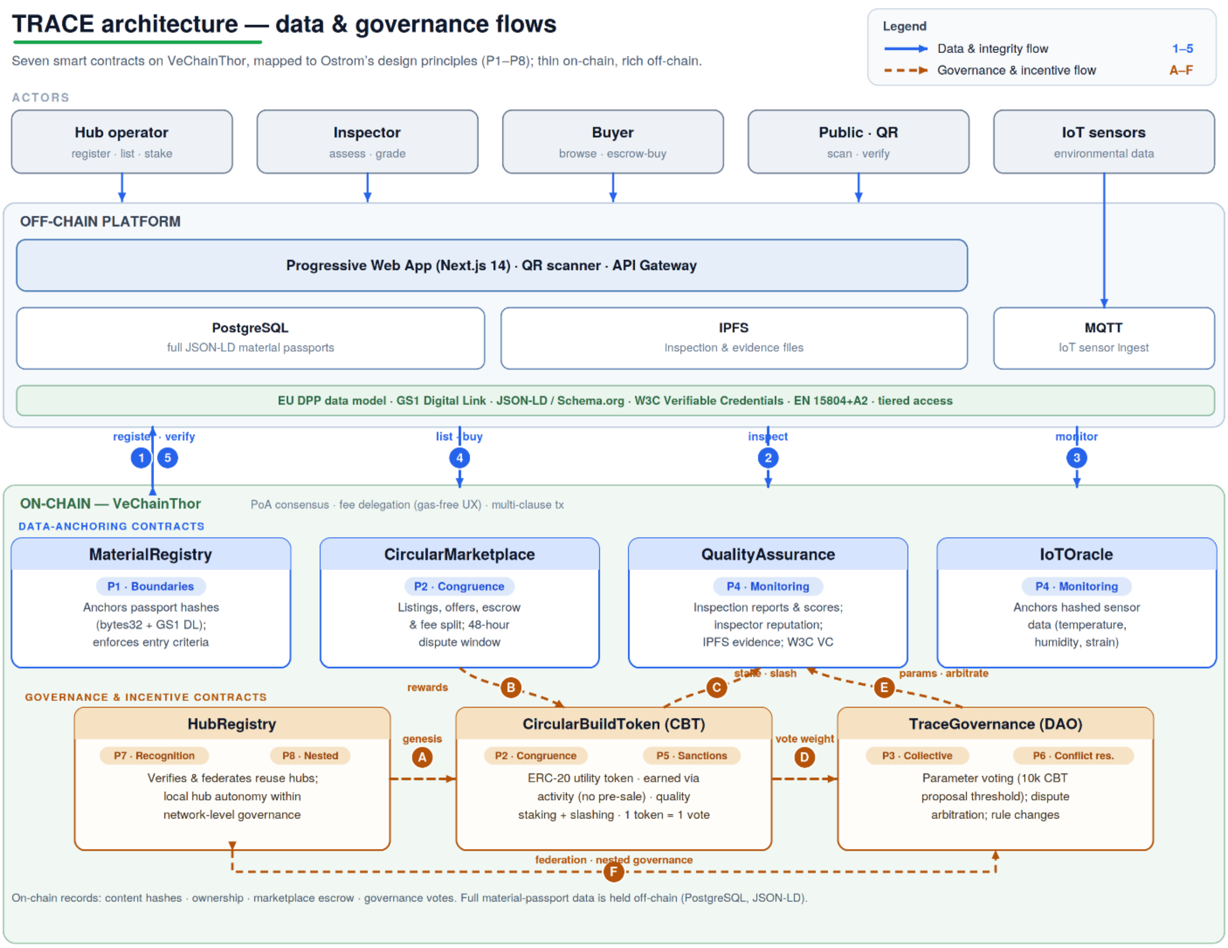

Figure 2: Implemented software architecture (deployed at trace.adventurous.systems)

and critically, the carbon savings achieved by reusing versus manufacturing new—data not captured by the standard DPP framework but essential for circular economy accounting. The extended schema also explicitly captures material-specific technical performance data referenced to applicable standards (EN 1995 for timber, EN 1992 for concrete, EN 1993 for steel), measured residual properties, and recommended use-class constraints, since reclaimed materials must continue to satisfy performance requirements in their new application context. Quality certifications are issued as W3C Verifiable Credentials (VCDM 2.0), enabling cryptographic verification of inspector qualifications and assessment results without requiring trust in a central authority. This directly addresses the ESPR's requirement for conformity assessment while providing a decentralised alternative to the manufacturer-issued Declaration of Performance that does not exist for reclaimed materials.

Smart contract modules

Seven smart contracts implement the on-chain governance layer, each mapped to specific Ostrom principles and DPP requirements (Table 1):

MaterialRegistry (P1: Boundaries) anchors material passport hashes on-chain, providing tamper-evidence for off-chain JSON-LD data. Each registered material receives a unique bytes32 identifier linked to its GS1 Digital Link URI. The contract enforces entry criteria—minimum documentation requirements that must be met before a material can be registered—implementing the boundary definitions demanded by stakeholders.

CircularMarketplace (P2: Congruence) manages listing creation, offer handling, escrow, and fund release with configurable fee distribution. A 48-hour dispute window after delivery confirmation provides buyer protection. Fee structures are adjustable through governance to ensure costs remain proportional to benefits, addressing the temporal mismatch identified in workshops.

CircularBuildToken (CBT) is an ERC-20 utility token serving as the governance and incentive mechanism. CBT is not a payment currency; material purchases settle in fiat via conventional payment rails. CBT provides governance weight (one token, one vote), quality staking (hubs stake CBT against material quality claims, with slashing for disputes), and activity rewards (minted for registering complete passports, completing transactions, and providing quality reviews). The initial CBT supply is bootstrapped through a genesis allocation to verified founding hubs (Stirling Reuse Hub and network partners), with subsequent supply minted exclusively through verified on-platform activity—there is no pre-sale or speculative allocation. This design ensures governance weight is earned through participation rather than purchase, directly implementing Ostrom's congruence principle at the token level. The staking mechanism implements Ostrom's graduated sanctions (P5): first disputes result in partial CBT slashing; repeated violations escalate to hub suspension.

QualityAssurance (P4: Monitoring) records inspection reports on-chain with inspector reputation tracking. Each report stores material ID, multi-dimensional quality scores, and an IPFS reference to the full inspection documentation. Inspector reputation accumulates from successful (undisputed) inspections, creating an emergent quality assurance system that does not depend on a single certifying authority—essential for reclaimed materials where no manufacturer exists to issue conformity declarations.

IoTOracle (P4: Monitoring, automated) receives hashed sensor data from environmental monitoring systems (temperature, humidity, structural strain), providing on-chain evidence that storage conditions were maintained. For the prototype, QR code scanning serves as the primary physical-digital bridge, with IoT sensor integration as a secondary capability.

TraceGovernance (P3: Collective Choice, P6: Conflict Resolution) implements a Decentralised Autonomous Organisation for platform parameter voting, dispute arbitration, and community rule changes. A proposal threshold of 10,000 CBT ensures only committed participants can propose changes, while all token holders can vote. This provides the structured collective-choice and conflict-resolution mechanisms that stakeholders identified as absent from current informal reuse practices.

HubRegistry (P7: Recognition of Rights, P8: Nested Enterprises) manages the federation of reuse hubs. Each hub registers on-chain with its operator address and metadata hash, receives platform verification, and operates semi-autonomously within the network. This addresses the regulatory gap where reuse hubs are not recognised as 'economic operators' under the CPR: the HubRegistry creates a parallel institutional recognition system governed by the commons rather than by the state.

Bridging the regulatory gap

The architecture specifically addresses the institutional gap between EU DPP regulations and circular economy practice through three mechanisms. First, *DPP issuance for reclaimed materials*: where the ESPR assigns DPP responsibility to the manufacturer or importer, the TRACE system assigns it to the verified reuse hub, with quality assurance distributed across the inspector network rather than concentrated in a single entity. Second, *conformity assessment through commons governance*: where the CPR requires manufacturer-issued Declarations of Performance, the TRACE system substitutes blockchain-anchored quality assessments issued as W3C Verifiable Credentials by reputation-scored inspectors, governed by DAO-set standards. Third, *federated authority*: where EU regulations assume national market surveillance authorities, the TRACE system implements Ostrom's nested enterprises principle, with local hub autonomy operating within network-level governance—a structure that could complement rather than replace regulatory oversight.

Discussion

The mapping presented in Table 1 reveals a systematic correspondence between Ostrom's governance requirements, stakeholder-identified gaps, EU DPP technical requirements, and blockchain smart contract capabilities. This is not coincidental: the EU DPP framework and Ostrom's principles both address the fundamental challenge of governing shared information resources, but from different institutional perspectives. The EU approach is top-down and regulatory, designed for hierarchical supply chains with identifiable responsible entities. Ostrom's approach is bottom-up and institutional, designed for polycentric governance where authority is distributed across self-organising participants.

The circular economy's material reuse context sits awkwardly between these two models. Materials that have been deconstructed and re-enter circulation require the structured data and consumer protection that EU DPP regulations provide, but they lack the institutional infrastructure (manufacturer, importer, notified body) through which those regulations are implemented. Our findings suggest that Ostrom-governed blockchain infrastructure can fill this gap—not as a replacement for regulatory oversight, but as a complementary institutional layer that enables reuse hubs to issue EU-compliant material passports through a collectively governed, reputation-based system. It is important to be clear on regulatory positioning: the TRACE system does not claim to issue legally binding DPPs under current EU law, where formal authority remains with recognised economic operators. Rather, it demonstrates the institutional and technical architecture that a future regulatory adaptation—such as recognition of 'verified reuse hub' as an economic operator category under CPR delegated acts—would need to build upon. This is consistent with the EU's own approach to DPP implementation, which explicitly anticipates stakeholder-driven standard development through delegated acts. Construction companies managing material reuse independently of hubs would interface with the same schema and smart contract layer, with the HubRegistry federation providing the interoperability layer between actors.

Several limitations must be acknowledged. First, while the prototype is now deployed and operational at trace.adventurous.systems, empirical evaluation at scale remains ongoing; the Stirling Reuse Hub pilot currently underway will provide the first rigorous assessment of adoption, usability, and governance effectiveness in practice.

Table 1: Mapping of Ostrom's design principles to stakeholder evidence, EU DPP requirements, and implemented blockchain features (TRACE platform).

Ostrom Principle	Workshop Evidence	Governance Gap	EU DPP Requirement	TRACE Smart Contract
P1: Boundaries	Material viability hierarchies; demand for clear grading standards	No defined criteria for reuse eligibility	Unique product identifier (GTIN); product classification	MaterialRegistry: entry criteria, passport hash anchoring
P2: Congruence	Cost-benefit temporal mismatch; small hub burden	Documentation costs borne at reclamation, not reuse	Proportionate compliance based on product risk	CBT token: rewards proportional to contribution; fee distribution
P3: Collective choice	All groups want voice in quality standards	No forum for stakeholder input on reuse standards	Delegated acts developed via stakeholder consultation	GovernanceDAO: parameter voting, proposal system
P4: Monitoring	Trust as dominant barrier; post-Grenfell anxiety	No systematic quality verification for reclaimed materials	Conformity assessment; Declaration of Performance	QualityAssurance: inspector reports, reputation; IoTOracle
P5: Graduated sanctions	Need for accountability without excluding marginal suppliers	No penalty mechanism for quality misrepresentation	Market surveillance; penalties for non-compliance	CBT staking/slashing: graduated penalties for disputes
P6: Conflict resolution	Current disputes resolved informally; need structure	No arbitration mechanism for reuse transactions	National market surveillance authorities	GovernanceDAO: arbitration workflow, evidence-based resolution
P7: Recognition of rights	Regulatory uncertainty; building control unfamiliarity	Reuse hubs not recognised as 'economic operators' under CPR	Economic operator registration; EOID	HubRegistry: on-chain hub verification and federation
P8: Nested enterprises	Local vs regional coordination needs; independence desired	Siloed hub operations; no network coordination	Interoperability between DPP systems across sectors	HubRegistry: federated architecture; cross-hub protocols

Second, the regulatory compatibility we describe is architectural (schema compliance, identifier standards) rather than legal—formal recognition of blockchain-issued DPPs under EU law remains an open question. Third, the digital literacy requirements of blockchain interaction present barriers for some reuse hub staff, particularly older volunteers. The prototype addresses this through a 'blockchain-invisible' design where the user interface abstracts away wallet management and on-chain transactions. Fourth, the physical-digital verification gap persists: a blockchain record cannot independently verify that a reclaimed beam has the structural properties claimed. The quality assurance system mitigates but does not eliminate this fundamental limitation.

The broader implication extends beyond construction. As EU DPP requirements expand across product categories through 2030, every sector with significant secondary material flows—textiles, electronics, furniture—will face the same institutional gap: regulation designed for manufacturing supply chains applied to contexts where products re-enter circulation through informal or community-based channels. The commons governance approach demonstrated here may offer a transferable institutional model.

Conclusion

This paper has presented a theoretically grounded approach to governing construction material reuse as a digital commons, bridging Ostrom's design principles with the EU's emerging Digital Product Passport regulatory framework through blockchain smart contracts. Our contribution is twofold. First, we provide empirical evidence from 36 stakeholder workshop participants that the governance challenges of construction material reuse map systematically onto Ostrom's eight design principles, identifying assurance, logistics, and information systems as the three critical gaps. Second, we present a deployed seven-contract prototype architecture, implemented on VeChainThor and accessible at trace.adventurous.systems, that is simultaneously EU DPP-compliant (JSON-LD, GS1 Digital Link, W3C Verifiable Credentials, EN 15804+A2) and commons-governed (DAO voting, reputation-based quality assurance, graduated sanctions, federated hub architecture).

The key finding is that EU DPP regulations and Ostrom's governance principles are not competing frameworks but complementary layers: the regulations define *what* data a material passport must contain, while Ostrom's principles define *how* the institutional infrastructure for issuing and governing those passports should be organised in contexts—such as material reuse—where the regulatory assumption of a responsible manufacturer does not hold.

The TRACE prototype is now deployed and operational at trace.adventurous.systems, with ongoing pilot evaluation at Stirling Reuse Hub providing empirical assessment of whether blockchain-enabled commons governance can deliver the trust, traceability, and coordination that stakeholders identified as prerequisites for scaling construction material reuse in Scotland and beyond.

Figure 3 presents the public landing page of the running platform. The deployed system operationalises the architecture described above through a deliberately blockchain-invisible interface: a visitor can browse the materials marketplace, register or list reclaimed materials, or scan a passport QR code to verify a material's integrity against its on-chain hash—none of which requires a cryptocurrency wallet or any blockchain knowledge. The landing page foregrounds the three commitments that distinguish the platform—EU Digital Product Passport compliance, blockchain-anchored integrity on VeChainThor, and circular-economy traceability of deconstruction origin, condition grade, carbon savings and reuse history—while the seven-contract governance layer of Figure 2 operates entirely beneath this surface. To our knowledge, this is among the first publicly accessible material-passport platforms to pair EU DPP-aligned data structures with an Ostrom-grounded commons-governance layer, and it constitutes the live system on which the Stirling Reuse Hub pilot is now being evaluated.

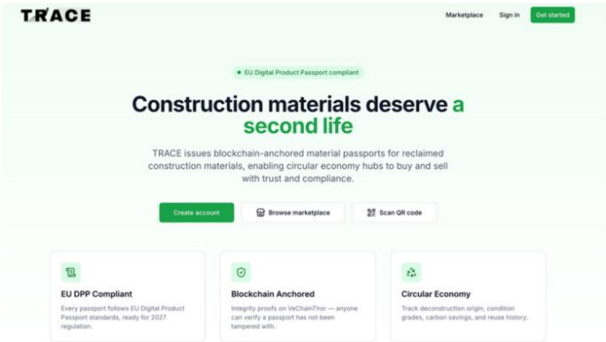

Figure 3: The deployed TRACE platform (trace.adventurous.systems): public landing page presenting EU DPP-compliant, blockchain-anchored material passports for reclaimed construction materials.

Acknowledgements

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