

Research on a Business Modeling-Driven Construction Mechanism for Distributed Trustworthy Digital Product Passports (DPP)

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ABSTRACT

The Digital Product Passport (DPP), a core tool of the EU's "Ecodesign for Sustainable Products Regulation" (ESPR), aims to achieve digital management of products across their entire lifecycle and promote green supply chains. It mandates the recording and sharing of multi-dimensional, highly correlated comprehensive data, including product description, material composition, supply chain stages, environmental impact, circularity, reparability, and disposal information. In a multi-stakeholder collaborative and distributed environment, ensuring the atomicity of this complex data, maintaining its state consistency, performing efficient cross-domain verification, and achieving trustworthy bidirectional traceability present significant challenges for the current implementation of DPP. Existing research predominantly focuses on the functional application of blockchain technology, such as automated execution of smart contracts, yet generally lacks a deep analysis of DPP's multi-dimensional and interconnected business attributes. This often leads to a significant divergence between technological implementations and actual business requirements. Against this backdrop, this paper proposes a business modeling-driven construction mechanism for a distributed trustworthy DPP. This study deeply analyzes key business characteristics of DPP, such as multi-stakeholder collaboration, the assetization of core information (e.g., components and environmental attributes) as data, and the irreversibility of lifecycle event processes. Based on a formal modeling approach, this research constructs a meta-model for the distributed Digital Product Passport (DPP). This model centers on "DPP core data units" (the minimal information set carrying business semantics like product description, materials, and environmental footprint) and "state transition events" (marking critical lifecycle nodes such as production, maintenance, and recycling). It explicitly defines data operation boundaries, multi-stakeholder read-write permissions, and constraint rules to ensure the consistent association between product and event information, thereby laying the theoretical and business foundation for the subsequent technical architecture. Building upon the aforementioned business model, this paper designs an innovative blockchain implementation architecture that precisely maps DPP's business rules to underlying technological assurance mechanisms. The core contributions of this architecture are threefold: firstly, by mapping business rules to a blockchain state machine, it ensures the atomicity and global consistency of data updates; secondly, it integrates decentralized identifiers (DIDs) and verifiable credentials (VCs) to build an efficient and privacy-preserving distributed verification system; finally, leveraging the immutability inherent in blockchain, it achieves full lifecycle bidirectional traceability with strong business context. Theoretical analysis and experimental validation demonstrate that the mechanism proposed in this study effectively addresses the data trustworthiness and collaborative trust issues encountered when managing complex business content within a distributed DPP. It significantly ensures a high level of data consistency, substantially improves the efficiency of cross-domain verification, and noticeably optimizes the response time for traceability queries. This research provides a systematic design paradigm of "business model deeply driving technology selection," laying an important theoretical and methodological foundation for constructing distributed data infrastructures in complex business scenarios like DPP, which demand multi-dimensional information integration and high trustworthiness.

Keywords: DPP; Business Modeling; Blockchain; Distributed Environment; Atomicity; Consistency; Distributed Verification; Bidirectional Traceability