Decentralized Phygital Identifier Systems for Digital Passports in Circular Construction: A Design Science Evaluation

Author(s):
Byers, Brandon; Emmenegger, Pascal; Hunhevicz, Jens Juri; Schumm, Daria; Heisel, Felix; Hall, Daniel; De Wolf, Catherine

Publication date:
2025

Originally published in:
Construction Innovation, https://doi.org/10.1108/ci-02-2025-0074

Decentralized Phygital Identifier Systems for Digital Passports in Circular Construction: A Design Science Evaluation

Abstract

Purpose: Circular construction promotes the reuse of building components, yet a key challenge is to reliably link long-term information with physical products. This study investigates (1) how to implement a decentralized identifier system linking physical products to their digital data, and (2) the design requirements necessary to evaluate these systems within circular construction.

Design/Methodology/Approach: A pragmatist sequential multi-methods approach is applied, integrating technical prototyping, performance evaluation, and stakeholder validation. The study explores different identifiers (decentralized identifiers (DIDs) and tokens) and data carriers (QR codes and NFC chips). A mobile application prototype is developed and tested for operational efficiency, cost-effectiveness, and usability.

Findings: QR codes outperform NFC chips in ease of use and efficiency, while DIDs offer higher interoperability compared to token-based identifiers. Blockchain technologies ensure long-term data integrity but introduce cost and complexity trade-offs. Stakeholder feedback highlights the importance of accessibility, user interface clarity, and legacy system interoperability for successful adoption.

Research Limitations & Implications: The study is exploratory, with validation conducted in controlled environments rather than field testing. Future work should test long-term performance in real-world reuse scenarios. Nonetheless, the findings have broad implications for research, practice, and society by guiding the development of robust traceability systems that enhance building component reuse and tracking for construction practices.

Originality: This research contributes to circular construction by systematically evaluating decentralized identifiers for tracking building components. It provides empirical insights into various technological configurations and establishes a foundational design framework to link digital product passports with physical products in circular supply chains.

Keywords: circular economy, circular supply chain, design science, blockchain, tokenization, decentralized identifier

1. Introduction

Circular construction emphasizes the reuse and repurposing of construction materials and building components through multiple uses or life cycles, thus reducing waste and increasing material efficiency. This is increasingly important for practitioners and researchers as 30-40% of total waste worldwide is construction and demolition waste and environmental concerns are rising as resources become more scarce (López Ruiz et al., 2020). Reuse keeps materials at highest utility and value, preserves embodied carbon, and prevents emissions from new production (Heisel and Hebel, 2022). However, one of the critical challenges hindering these efforts is a lack of reliable long-term information on the original attributes and life-cycle information on the products (Wijewickrama et al., 2021). This problem is exacerbated by the long life cycles of buildings, the distributed stakeholders, and the decentralized information ecosystem found in the architecture, engineering, construction, owner, and operator (AECOO) industry.

The industry is increasingly focused on how to connect digital information to physical products across one or several use cycles (Anumba et al., 2021). Often, construction documentation becomes lost after project handover and is not updated during operations and maintenance or renovations. Similarly, as efforts on reusing building components increase, the information transfer between owners and project stakeholders is often disrupted. The link between building products and digitized information is regularly broken. The increase of research on reality capture for the built environment and the rise of end-of-life building audits indicate the lack of available information on the built environment (Byers et al., 2024b). These problems beg the question of how to design a resilient, permanent, and accessible link between entities in the physical world and their digital representations.

Supply chain track and trace (T&T) problems often suggest blockchain as a solution (Wang et al., 2020; Li et al., 2021). The primary features of blockchain technologies addressing these issues are related to its robustness through the immutability, decentralization, and transparency of the distributed ledger technology. Indeed, there are several use cases across industries that have been successfully deployed (Kayikci et al., 2022). Nevertheless, there are still ambiguities around the optimum architecture of a T&T system as a blockchain is not functionally the same as traditional database systems and storing large amounts of data is often inefficient and expensive (Hunhevicz et al., 2022). If a blockchain system is to be used to store building product information throughout time (i.e., life cycles) and space (i.e., projects and stakeholders) a simple yet robust solution needs to be developed.

Some solutions use a private and permissioned blockchain solution, which inhibits future unknown users of the data from participating in the information ecosystem (Kifokeris and Koch, 2022). Other solutions may store all data on a blockchain despite its inefficiency (Sheng et al., 2020), several proposed solutions do not even mention the storage architecture (Chiacchio et al., 2022) or keep the information only within an NFC chip (Shibano et al., 2022), and many will only store a URI on a standard distributed file system like InterPlanetary File System without managing the change of information over time (Tao et al., 2021). In summary, not enough research examines the connection between the data store and the physical product in the unique AECOO context.

An under-researched key aspect of robust connections are the identifiers that link the physical product to the information store. The importance of this is evident when looking at open standards such as GS1, which provide such identifiers as a core service (GS1, 2021). As shown in Section 2, blockchain has the potential to help build more robust decentralized identifier systems for AECOO. Therefore, this paper narrows the focus to two unique decentralized product identification systems (blockchain tokens and decentralized identifiers (DIDs)) to bridge the physical components to the digital information for tracking a *phygital* asset in circular construction. This is important for manufacturers and asset owners to ensure long-term and distributed access to product information to increase their circularity and market value in the future. European Union (2024) stipulates that used construction products will be subject to the same DPP rules as new products, thereby strengthening the significance of this study in a European context.

1.1. Research Questions and Scope

Current research addresses only specific aspects of T&T in circular construction, neglecting the broad spectrum of design possibilities and the decision-making processes necessary for evaluating design alternatives. These design considerations are influenced by the stakeholder, application, and stage in the product life cycle. Moreover, the evaluation criteria are often restricted and not explicitly defined, typically focusing on the computational performance of the prototype or stakeholder perceptions of its usefulness. A more comprehensive understanding of how to effectively connect a product to its relevant data is required, necessitating the extraction of a general design pattern.

A robust and well-functioning T&T approach is key to circularity in the built environment, enabling a unique product history to inform future reuse of the product (Honic et al., 2024). Section 2 builds an argument for why a decentralized technology stack architecture would be useful in the context of circularity and have reviewed existing approaches. This paper introduces a conceptual model of T&T technology stack used to guide design decisions that include the hardware, identifier, software, user interface, and data storage (Figure 1).

In addition, a key aspect of a robust T&T technology stack is the unique identifier for building components that allow external information to be associated with the products while reducing reliance on third-party services for hosting or providing access over time. If information is retained on the components, it can enable new future uses and thus add value to the products, rather than being indiscriminately destroyed and wasted.

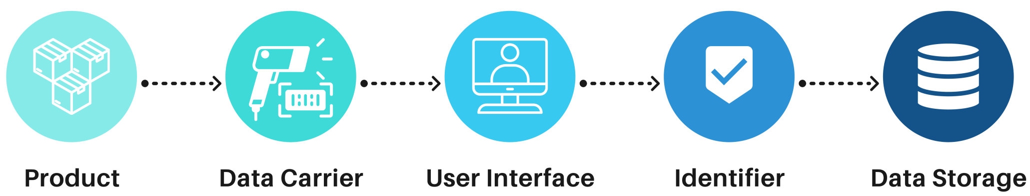


Figure 1: Proposed Track and Trace Technology Stack Connecting the Physical Construction Product to its Digital Representation.

Source: Created by the authors.

Therefore, the scope of this work is primarily on the throughline between the data carrier, user interface, and identifier. This is framed as the connection between unique construction components and a digital data store before a building is deconstructed. A specific focus is on decentralized identifiers in the context of blockchain-based T&T solutions in the built environment, in particular the promise of tokens and DIDs (see Sections 2.2 and 2.4). Testing the physical interface between the data carrier and the product is excluded from the scope of this work. The ideal data storage is also not examined as the chosen store meets the set functional requirements. Additionally, this work does not focus on bulk construction materials or building identification, but on discretized components and products in the built environment.

In short, although there are suggestions for and limited examples of using decentralized technologies for product tracking in circular economies, there is no formal exploration into *how* this should be done. Nor is there a comparison of identifiers between data carriers for circular construction supply chains. Therefore, this research aims to address the following two research questions to produce design knowledge in this domain:

1. How to implement a decentralized identifier system to connect physical products to their digital data store?

2. What design requirements should be used to assess this system in the context of circular construction?

2. Background

T&T plays an important role in enabling circular economies within AECOO by tracing material flows and linking physical products with their associated digital data. In this context, passports serve as structured, digital data sets that describe key attributes of materials and building components. Material passports (MPs) typically focus on information specific to the built environment—detailing material properties, quantities, and the potential for reuse or recovery at material, component, or building scales (Honic et al., 2019a, 2024). In contrast, digital product passports (DPPs) adopt a more expansive, cross-sectoral approach; they provide comprehensive product-related information including the origin, durability, composition, repair, reuse, and end-of-life handling, underpinned by regulatory frameworks such as the European Union Circular Economy Action Plan (Honic et al., 2024). This work focuses on *construction products*, that is defined in the European Union as any formed item, formless item, or kit for incorporation into construction works (European Union, 2024).

However, there is a lack of standardization across regions in the definition of these terms, their applicability, and their digital and physical infrastructure. Technical requirements proposed for digital product passports include interoperability, availability and timeliness, and portability of unique product identifiers (Neligan et al., 2023). Previous work suggests an asset administrative shell for digital product passports to include the identification, description and characteristics, and environmentally relevant information (Neligan et al., 2023). Nevertheless, the traceability of products helps facilitate the repurposing, reuse, and closing the loop of components (Morseletto, 2020; Liu et al., 2022).

In this section, the background and application of T&T in other industries are provided in Section 2.1. Next, more specific existing research of blockchain for T&T within AECOO is reviewed (see Section 2.2). Then the motivation and potential of blockchain for a circular economy are reviewed (see Section 2.3). This is followed by a review of the identifier problem (see Section 2.4) that support the scope of this paper from Section 1.1.

2.1. Track and Trace Origins

The origin of *track and trace* is decades old and has roots in the supply chain and logistics fields. Kelepouris et al. (2006) reported on T&T requirements in the aerospace industry and defined *tracking* as the ability to determine the current state of an asset (the present to the future) and *tracing* as the ability to determine previous states (the past to the present). Similarly, van Dorp (2002) provides a review of definitions of T&T that largely relate to understanding product history along its supply chain from cradle to grave.

Emphasis is given by van Dorp (2002) that along the product and material flow, the item coding, information architecture, and planning must also be bi-directional. Kelepouris et al. (2006) also state that an effective ID solution is critical within the aerospace industry. van Dorp (2002) describes unique product identification as what is assigned to products that have been subjected to unique processing conditions. Work in the aerospace industry proposes a set of user requirements and system requirements to be considered for T&T (Kelepouris et al., 2006). User requirements could include information on item identification, document and asset tracking, information system updates, part maintenance history, operations efficiency, and automatic certificate generation. The three proposed metrics used to judge these requirements are accuracy, completeness, and timeliness. In a model of requirements for textiles and clothing, Alves et al. (2022) proposes six functionalities: create, read, communicate, aggregate, consult/trace, and analyze.

There is a strong body of literature reviewing blockchain applications for T&T and supply chains, but much of this work focuses on industries outside of the AECOO context, such as agriculture, pharmaceutical, automobile, aerospace, and textiles (Sunny et al., 2020; Alves et al., 2022; Kelepouris et al., 2006). These applications focus on using blockchain to reduce counterfeits, remove false information, and keep products within specification (Sunny et al., 2020). An example from pharmaceutical supply chains explores the use of non-fungible tokens (NFTs) for T&T because NFTs have properties of authenticity, ownership, uniqueness, and interoperability (Chiacchio et al., 2022).

2.2. Blockchain for Track and Trace in AECOO

Increasingly, researchers are examining how blockchain technologies can address AECOO challenges. For instance, some frameworks demonstrate improved logistical performance in construction through blockchain-based data management (Wang et al., 2020). However, these studies often use identifier systems limited to internal applications and lack interoperability. Similarly, Brandín and Abrishami (2021) propose another framework for integrating building information modeling, Internet of Things (IoT), and blockchain, where the blockchain records metadata, final-agreement transactions, and handover information. There was no discussion on the architecture of the storage and the RFID identifier was added as another field into the Building Information Model (BIM) as metadata.

A blockchain prototype for construction logistics was tested with Swedish stakeholders (Kifokeris and Koch, 2022). The problem space defined in their context included unconnected accounting between suppliers and contractors, the contractor's internalized logistics planning (thus facilitating a lack of interoperability), and an unclear role of the transporters. The prototypes were tested on-site and feedback on the design included: no data tampering, a good streamlined platform, a somewhat higher degree of trust, the difficulty of adoption due to technical upskilling, adding a notification function, and accommodating additional roles in the supply-chain (Kifokeris and Koch, 2022).

Researchers Shibano et al. (2022) use a combination of NFC chips and zero-knowledge proofs (ZKPs) on Ethereum for an Android application prototype for wood traceability. ZKPs are used for the historical state of the products, and the consumer verifies the original data from the prover on the NFC chip. This approach is unique in its application of ZKPs, but not positioned among existing artifacts, not defined in a discrete problem and solution space, nor confirmed by practitioners.

van Groesen and Pauwels (2022) develop, test, and validate a QR code and blockchain prototype for tracking prefabricated assets through a controlled simulation. Functional requirements include data transfer between the blockchain, an immutable log on chain, smart contracts to compare asset states and contract requirements, and stakeholder payments (van Groesen and Pauwels, 2022). This work was thorough in design, implementation, and analysis, but focuses on asset tracking and payment transfers through the supply chain, not on product identification and information access.

The applied problem space varies from ensuring tamper-proof tracking to performing automated transaction payments in supply chains to focusing on cross-jurisdictional waste management. Wang et al. (2021) state one of the design principles for a blockchain-enabled supply chain should include sharing product data on the blockchain to establish transparency and tracking. The solution space varies from using ZKPs and NFTs for waste passports to tokens for authentication and payments.

Overall, there are several existing prototypes for how blockchain can be used for T&T solutions in a supply chain, but there are limitations in the research. Specifically, little work was found on the problems with the identifier bridging between the digital and physical environments. This problem is important both within and beyond the scope of circularity and is one of the key aspects of facilitating the T&T of physical goods. The best blockchain solution to store information long-term does not work if the connection to the physical component breaks.

2.3. *Blockchain for a Circular Economy*

Traditional data storage systems (e.g., corporate servers or cloud services) risk the long-term accessibility of critical information when support is withdrawn, a challenge for existing collaborative software in AECOO (Tao et al., 2021). In addition, when considering longer time scales, most data storage happens via magnetic storage systems, which are prone to decay over time. Often service providers will duplicate the information for redundancy, but this is computationally and environmentally inefficient and also does not alleviate the problem of long-term data access.

Decentralized technologies are promising for transparency and traceability in circular supply chains (Brandín and Abrishami, 2021; Rejeb et al., 2023). Blockchain, one possible decentralized technology, establishes confidence in the transactional exchange between parties over the internet through transparent rules in a distributed network of computers (De Filippi et al., 2020). The main opportunity of blockchain for T&T lies in recording and handling the transactional relationships of supply chains. The properties of a blockchain are tamper-proof and ensure transparent transactions. To what extent these properties are enforced depends on the chosen blockchain type (Hunhevicz and Hall, 2020). If a public blockchain is chosen, the decentralized (no single party has control) and distributed (multiple storage locations holding a copy) nature of the technology stack can ensure data availability independent from single providers.

Specific work on circular economy applications includes research from Gligoric et al. (2019) on developing a SmartTag from printed sensors, GS1 barcode standards, and data matrices. Traceability information can be stored with different approaches, via centralized databases (good for internal data), documents transmitted between partners, or on the physical element itself via RFID or barcode (Kelepouris et al., 2006). Blockchain tokens and IoT have previously been proposed for circular supply chains for both food (Kim et al., 2018) and textiles (Alves et al., 2022). GS1 identification standards GS1 (2021) are suggested to be adopted and stored on the Ethereum chain for the product.

Centobelli et al. (2022) propose a “Triple Retry” for integrating the strengths of blockchain (trust, traceability, and transparency) with circular supply chain processes (recycle, redistribute, and remanufacture) by providing a platform framework and proof of concept with Hyperledger Fabric. They collected data from industry interviews, operations shadowing, and a validation workshop, though it is unclear how the identification system worked with specific waste items (Centobelli et al., 2022).

Previous work examined the integration of issuing NFTs per topological component of a building from the design software, which may induce operations on material ownership, trading, and material passport generation (Dounas et al., 2021). Researchers from the University of Hong Kong have produced an artifact through design science research for a blockchain-based construction waste material passport for cross-jurisdictional trading (Lu et al., 2023; Wu et al., 2023). The problem space resulting from their research interviews included issues with user-friendly tools, lack of cross-jurisdictional platforms, and challenges with information opacity and duplicity (Wu et al., 2023). The prototypes were tested through a simulation environment and the system was evaluated using the following criteria: information completeness, collision resistance, information transparency (timeliness and readability), latency, and accuracy of immutability damage detection (Wu et al., 2023).

Work from Hunhevicz et al. (2023) proposes a Web3-based access protocol for building material passports. In their prototype, the material passport data is stored in decentralized storage and access is granted by issuing tokens to permitted users through a decentralized application and connecting to a wallet. The architecture is proposed and prototypes are developed but the application is not situated in a defined problem space or solution space, nor are evaluation criteria proposed. Similarly, Incorvaja et al. (2022) develop a blockchain application prototype for building product tracking with multiple stakeholders. Emphasis is given to the unique identification of products, and all related material passport data is chosen to be stored on-chain. Evaluation criteria primarily consist of transaction costs and the prototype is not verified with practitioners.

There is a clear precedent and interest within academia in using blockchain and decentralized technologies for addressing T&T within a circular economy context. Yet, there are limited prototypes, and they often have a narrow focus on the solution. As some previous work focuses on parts of the solution stack, there is no research on the problem of unifying and using the identifier as a bridge between the varying digital and physical environments.

2.4. The Identifier Problem

Kelepouris et al. (2006) state “it is critical to assign a unique tracking identity to each item that needs to be tracked and traced for the aerospace industry.” Typical unique identifier systems face specific challenges such as centralized management and control, privacy concerns, limited semantic context, and interoperability challenges (Sporny et al., 2022). Yet, for the future of a digital circular economy, a universal and robust identifier solution is critical (Neligan et al., 2023). Therefore, two identifier technologies with promise are blockchain tokens and decentralized identifiers (DIDs).

An emerging field in identity management is the exploration of DIDs and verifiable credentials (VCs) for decentralized and self-sovereign identity. A DID and VC are essential components of operational decentralized identity. Similarly to a unique identifier (UID), a DID is a unique identifier that also enables the verification of a DID subject (e.g., a human, company, or thing) independently of centralized registers or authorities, and can be created by the DID subject (Soltani et al., 2021; Sporny et al., 2022). DIDs associate a DID subject with a related DID document, which contains data that describe the DID subject. A DID document represented in a machine-readable JSON format, contains public keys, metadata, cryptographic mechanisms used for verification, and service endpoints for authentication or authorization of the DID subject (Sporny et al., 2022). To guarantee tamper resistance, a claim is wrapped in a VC container, which provides cryptographic proof of a claim (e.g., a digital signature), enabling verifiers to check its correctness (Sporny et al., 2024). A ZKP is typically used to disclose only a selected part of a claim, which is known as selective disclosure.

Some features of decentralized identity that are beneficial for human identification, may not prove advantageous in a system where data privacy is of little concern. Nevertheless, it also provides an opportunity to shift the reliance on centralized infrastructure, avoid vendor lock-in, and overcome fragmented data silos that tend to obstruct the connectivity necessary in circular construction (Wijewickrama et al., 2021). Ensuring the data is neutral (i.e., does not belong to a service provider), decentralized, and accessible despite the deprecation of the services that typically store the data is important for applications in AECOO.

Although these were initially applied to human actors (Pinto et al., 2022), there is increasing application to IoT devices (Ngo et al., 2023; Fedrecheski et al., 2020), and supply chain and assets management (Taleka et al., 2023). In the IoT domain, the use of DIDs and VCs is suggested to mitigate single points of failure, provide owner-centric data management, and ensure interoperability by following standardized and open approaches (Fedrecheski et al., 2020). The application of DIDs and VCs for supply chain and asset management is largely unexplored, with limited works considering their use. However, DIDs and VCs can provide greater trust between stakeholders (Taleka et al., 2023), enable information and services discoverability (Zhao et al., 2023), and facilitate supply chain transparency (Sghaier Omar and Basir, 2020).

To ensure the provenance of supply chain information, the consistent identity of the tracked items is important (Wang et al., 2021). This is further contextualized in construction applications with the proposal of Smart Construction Objects from Niu et al. (2016) that state the underlying properties for smart objects require a unique identity that is made available to other objects or systems. In a case study research of a smart prefabricated facade, an ifcXML file possesses an IfcIdentifier, which consists of an ApplicationIdentifier labeled "SmartCarServer001," presumably lacking universality or unique interoperability with other systems (Niu et al., 2016). The importance of the identifier is implied, but not designed or discussed in an extension of the work into smart construction objects as blockchain oracles, which use unique IoT devices to track and record data onto a shared blockchain (Lu et al., 2021). The research reviewed for this work showcases that the identifier between the physical product and digital information systems in circular construction supply chains is an understated problem concerning blockchain and T&T for AECOO.

2.5. Methodological Gaps in Existing Research

Despite the numerous calls and several studies on T&T and blockchain for product and material passports, several gaps remain. Primarily, most prototypes are limited to small-scale demonstrations or designed only for certain products (Shibano et al., 2022; Kifokeris and Koch, 2022). Designing solutions that comply with emerging legal frameworks like the EU proposals is rarely addressed (Honic et al., 2024). Studies often overlook interoperability and data format challenges (Brandín and Abrishami, 2021; Götz et al., 2020). Few prototypes demonstrate an ability to update product information across the lifecycle (Brandín and Abrishami, 2021; van Groesen and Pauwels, 2022). Prototypes developed rarely collect user feedback (Lu et al., 2021), and, lastly, data carrier integration with building products is often ignored (Cocco et al., 2022). These gaps highlight the potential contribution of a decentralized, interoperable, and persistent product passport solution that bridges the physical to digital connection.

3. Research Methodology

The work aims to produce design knowledge through an instantiation of a decentralized T&T prototype connecting physical and digital components. This work adopts a pragmatist paradigm and uses qualitative, exploratory methods (Fellows and Liu, 2022). Given the nascent nature of this work, this research is exploratory and broadly uses qualitative methods. Specifically, this paper adopts a sequential multi-method research methodology consisting of the development of an artifact, performance comparisons, and validation through surveys, resulting in future design criteria (Figure 2).

3.1. Problem Space Definition

The set of methods used follows a design science research (DSR) approach using inductive reasoning for the conclusions. DSR consists of three pillars: the problem

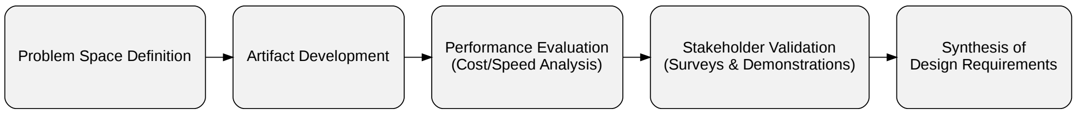


Figure 2: Research Design of the Multi-Method Approach

Source: Created by the authors.

space, solution space, and evaluation (Vom Brocke et al., 2020). The problem space for the artifact design was positioned as a building at the end of use, where the components needed to be tagged before deconstruction. The datasheets of the building components are available as a set of documents but are not linked to the individual components, which is particularly important as the building becomes disassembled. The scenario was described to those evaluating the prototypes. For DSR evaluation, this follows an artificial ex post method by using a role-playing simulation and lab experiment (Venable et al., 2012).

3.2. Artifact Development and Evaluation

The first research question on how to implement a decentralized identifier system is addressed by reviewing existing research on other similar prototypes exploring product passports, track and trace, and blockchain provenance. The artifacts are grounded and aligned with the few existing design artifacts works in this space (Elghaish et al., 2023; Wu et al., 2023). The technical prototyping through artifact design and development was then performed. In this work, several variations of the artifacts were developed based on data carriers and identifiers, which allows for simultaneous and comparative evaluation. Next, a performance comparison of the speed and costs (in ETH and USD) of actions was conducted for each variation. To address the second research question, the system design requirements are partially derived from previous work (Byers et al., 2024a). These requirements are further supplemented with other design requirements for similar systems in research and then validated with feedback gathered from both researchers and practitioners.

3.3. Artifact Validation

Due to hardware requirements, the validation for the prototype variations were through recorded videos for remote practitioners and direct testing for local users. The participants were a combination of researchers and practitioners who work in the fields of digitalization and circular construction. The objective was to target US and

European practitioners who work in circular construction domains. The validation approach was constrained because the artifact explores the hardware component (i.e., NFC chips and QR codes) and was not tested in an active deconstruction and reuse state. Nevertheless, through critical review by the stakeholders, observations and analyses still contribute to design knowledge.

4. Results

The total set of findings includes the developed design requirements for the prototype, the development process, and the responses from users on the applicability of the artifact and future design iterations.

4.1. Artifact Design Dimensions

Results reported in a survey from previous work demonstrate the relative importance of various views on data in construction (Byers et al., 2024a). The responses with the percentage of respondents who stated it was very or extremely important include data persistence and storage over building lifecycles (100%), updating and adding data (90%), trust and data authenticity (83%), data interoperability (80%), data access between stakeholders (77%), and costs (73%) (Byers et al., 2024a). These criteria were used to guide the prototyping of the artifacts.

The design requirements for the solution space were developed from three locations: literature, similar DSR projects, and general requirements for the T&T Stack (Figure 1). Additional criteria for the artifact were derived from data reported from the survey in supplement to typical operations of create, read, update, and destroy. Nonfunctional criteria used for the decentralization aspect of the prototypes included accessibility via a common device, data availability for 100 years (studies on building lifespans range from 50-100 years (Omrany et al., 2020)), use of common data formats, and the integration of data carriers (Table I).

The T&T Stack necessitates several design decisions, which resulted in different iterations of the artifact. The research aims to explore the role of the identifier and data carrier in the stack specifically so the other modules may be swapped to meet the minimum criteria. The decisions for each part of the stack are discussed below and shown in Figures 3 & 4.

4.1.1. Data Carrier

The data carrier is a critical part of the connection to the physical world. Similar technologies could be used such as automatic identification and data capture devices and IoT devices (e.g., RFID). Yet, these technologies face challenges with

Table I: Functional and Nonfunctional Criteria

Functional Criteria	**Nonfunctional Criteria**
1. Allow users to create passports 2. Allow users to read passports and modification history 3. Allow passport owners to update their passports 4. Allow passport owners to destroy their passports	1. Accessibility via common device 2. System and data availability for 100 years 3. Use of common data formats 4. Integration of data carriers

Source: Created by the authors.

longevity and integrity, especially if additional power is needed for operation. Additional work conducts a quantitative analysis of the performance between QR codes, NFC chips, and traditional direct product marking for simple circular construction supply chain tasks (Byers et al., 2025). The results showed a statistically significant increase in efficiency and user-friendliness for QR codes and NFC chips over direct product marking; therefore, these are the two data carriers chosen for the artifact development.

Additionally, a prototype was developed in part for a custom hardware-locked NFC chip (HaLo) developed by Arx Research (Arx Research, 2023). The developers discuss the problem with using traditional NFC chips for the secure and permanent identification of an asset, namely that NFC chips often use easily duplicated unique identifiers, or use symmetric key cryptography (Arx Research, 2023). The challenge with symmetric keys is that the key could be leaked through hacking or bugs and also rely on a centralized API for the authentication (Simmons, 1979). Similar to transaction signatures from hardware wallets, the HaLo chip uses asymmetric cryptography to produce message signatures, enabling unique and secure on-chain authentication. Assuming the preserved physical integrity of the chip and the application to read it, this also helps facilitate the long-term provenance of the identifier.

4.1.2. User Interface

The user interface was developed as a native mobile application. Mobile devices were preferred due to their commonly built-in NFC technology and cameras to read

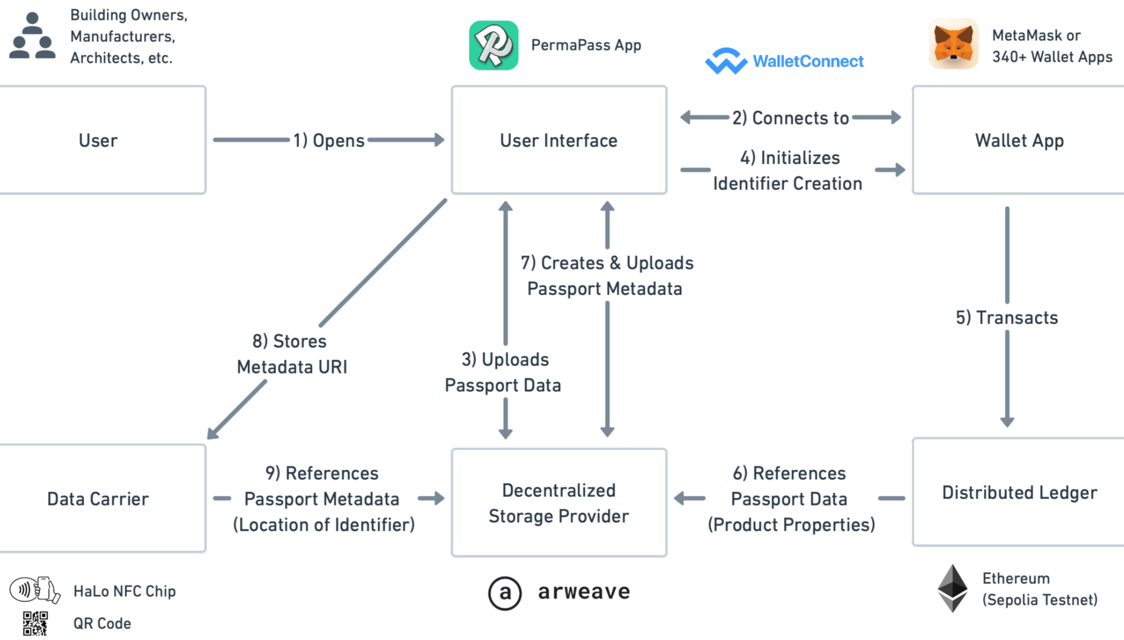


Figure 3: System Architecture for Creating a Passport

Source: Created by the authors.

QR codes, which are essential to connect to data carriers. A native application was chosen over a browser-based solution to facilitate wallet connections and interactions with NFC and camera interfaces. The application was built using React Native and tested on iOS devices through TestFlight. The user interface can be seen in Figure 5.

For guidance on designing the UI, van Welie et al. (2001) discuss design patterns by referencing the work in *A Pattern Language* from Alexander et al. (1977) who extracted design patterns from the built environment. van Welie et al. (2001) state that a UI should be positioned within a problem, provide a solution, and have a context, similar to the pillars of design knowledge proposed by Vom Brocke et al. (2020). The designed artifact focused on the simplest possible interface that directs the user at each step without superfluous functionality.

4.1.3. Identifier

Conventional identification systems face challenges in centralization, limited semantic context, and poor interoperability. To overcome these issues in the circu-

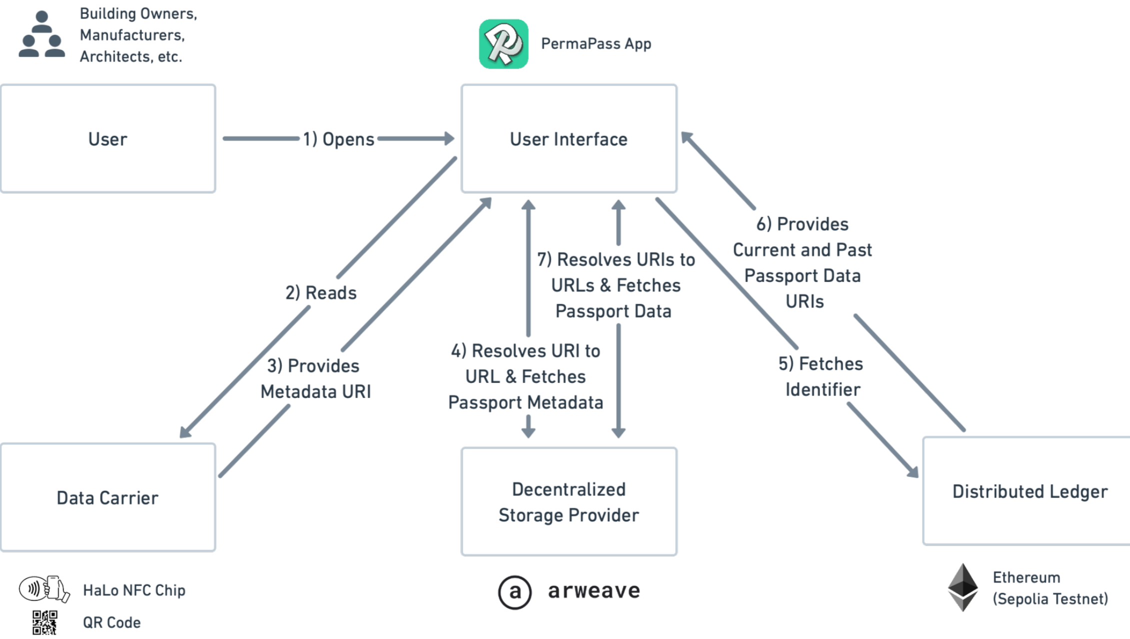


Figure 4: System Architecture for Reading a Passport

Source: Created by the authors.

lar construction context, DIDs and blockchain-based tokens were examined. These mechanisms offer unique, immutable, and verifiable links between physical products and their digital records, enabling self-sovereign control without reliance on central authorities.

The Ethereum ecosystem was chosen as the blockchain to store and manage the identifiers due to its support for the Solidity programming language, which simplifies custom smart contract coding. It offers various utility libraries and smart contract standards for NFTs and DIDs, including a DID method specification, which accelerates prototype development.

For the token prototype connected to the QR code, the traditional ERC-721 standard for NFTs was used. A novel Ethereum token standard, ERC-5791: Physical Backed Tokens (PBT), was used with NFC chips (2pmflow et al., 2022). This standard extends ERC-721 by connecting an NFT to an NFC chip with self-certifying capabilities. Interactions with PBTs require prior verification of the chip's authenticity (i.e., a message signature). This allows the chip to perform self-attestations through an asymmetric public-private key pair. Consequently, the need for central servers to mediate between the chip and the reader in traditional NFC chips is removed.

DIDs were also chosen as a relatively new identifier mechanism that does not depend on any central authority for identity verification. Decentralization refers to creating, controlling, and managing identities, rather than storage of identity data. Therefore, DIDs are recorded on a verifiable data registry that can be a blockchain or alternative service. The developed prototypes used DIDs hosted on Ethereum using the `did:ethr` method specification and Veramo's resolver library for resolving DIDs into a DID document.

4.1.4. Data Storage

Several different data storage applications can be used, including centralized databases or cloud servers. Alternative decentralized data stores can be found in (IoTeX Research). To fit the long-term data availability requirement in Table I, Arweave was selected for data storage because it is a decentralized storage network offering permanent data storage, unlike IPFS or Ceramic. By paying a one-time upfront fee, which contributes to an endowment for indefinite storage costs, Arweave guarantees data storage for at least 200 years.

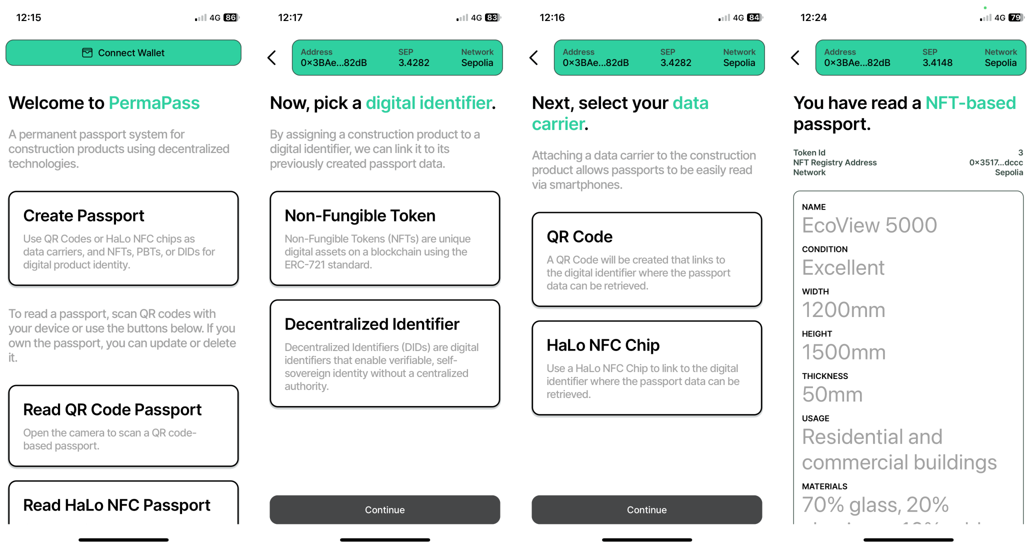
4.2. Artifact Implementation and Comparison

The final artifact is a mobile native application called PermaPass (Figure 5), which allows for four combinations of the T&T Stack, and smart contracts for managing NFTs, PBTs, and DIDs. The app was tested on iOS and the smart contracts were deployed to the Sepolia testnet to simulate the Ethereum mainnet environment. The source code can be found on github (*https://github.com/pemmenegger/permapass*). The mobile application permits ease of distribution and interaction albeit limits portability. This work explores a larger solution space in its design exploration of two data carriers and two identifiers. This approach allows for the evaluation of artifacts in parallel.

4.2.1. Technical Implementation

The PermaPass app serves as the user interface, orchestrating the prototype's user-initiated functionalities (Figure 3). It uses WalletConnect's software development kit to enable connections with any common wallet app, with MetaMask used for the demonstration. A wallet connection is required to cover gas fees when executing state-changing blockchain transactions (i.e., creating, updating, and destroying passports).

Every identifier is stored and managed by a specific smart contract:



(a) Home Screen

(b) Choose a Digital Identifier

(c) Choose a Data Carrier

(d) Read a Product Passport

Figure 5: Selected Screenshots from the PermaPass Artifact

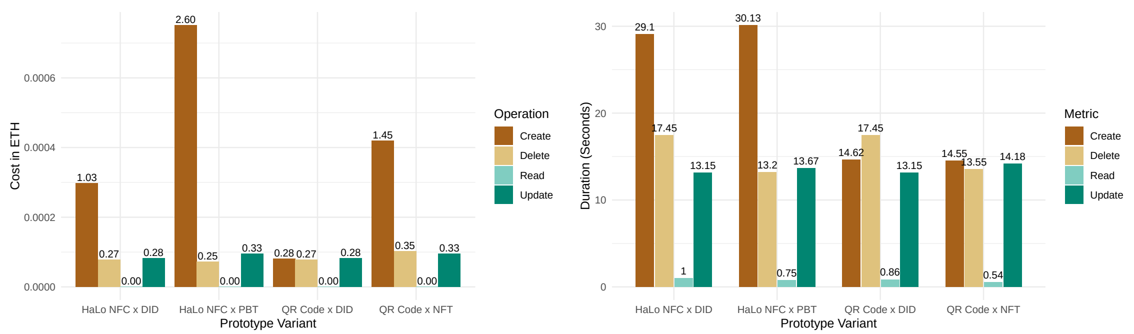
Source: Created by the authors.

- *NFTRegistry* contract for NFTs, implementing the ERC-721 standard.
- *PBTRegistry* contract for PBTs, implementing the ERC-5791 standard.
- *DIDRegistry* contract for DIDs, based on Veramo's DID registry contract for Ethereum.

Each smart contract manages URIs that point to the passport data stored externally on Arweave. An example URI is `ar://CUtrvwfXjjuoePjkpqSDA1C-4KP1QpMxmusXUvNnmXA`, which consists of the Arweave URI scheme (ar://) and the Arweave transaction ID (CUtrvwfXjjuoePjkpqSDA1C-4KP1QpMxmusXUvNnmXA). Listing 1 shows an example of passport data that can be retrieved by fetching the URI. This can be done using the official Arweave gateway via the URL `https://arweave.net/CUtrvwfXjjuoePjkpqSDA1C-4KP1QpMxmusXUvNnmXA`. Using URIs instead of URLs allows the user interface to select its preferred Arweave gateway or easily switch gateways in the future if a particular gateway becomes unavailable. To track passport data modifications, the contracts manage both current and past URIs. For NFTs and PBTs, the tokens contain the current URI, while past URIs are retrieved using blockchain events. For a DID, each URI is sequentially added to the service type “ProductPassport” within the DID document.

```
{
  "name": "EcoView 5000",
  "condition": "Excellent",
  "width": "1200mm",
  "height": "1500mm",
  "thickness": "50mm",
  "materials": "70% glass, 20% aluminum, 10% rubber",
  "carbonFootprint": "8 kg eCO2",
  ...
}
```

Listing 1: Example of Passport Data



(a) Operational Cost Comparison (with USD shown above each bar)

(b) Operational Speed Comparison (with seconds shown above each bar)

Figure 6: Cost and Processing Speed Comparison of Prototypes

Source: Created by the authors.

To connect an identifier with a data carrier, passport metadata is used, as depicted in Listing 2. This metadata includes the identifier formatting (NFT, PBT, or DID) and the globally unique location data of the identifier. The location data consists of the `chainId`, representing the Ethereum Virtual Machine-based chain ID (e.g., 11155111 for Sepolia), the `address` of the deployed identifier smart contract on this blockchain, and a locally unique ID for the identifier within the contract. For NFTs and PBTs, this ID is communicated by the `tokenId`, while for DIDs, a `DID` key with the DID as its value serves this function. The PermaPass app composes passport metadata, which is also uploaded to Arweave. Due to the limited memory capacity of data carriers, storing passport data directly on them is impractical. Instead, only the Arweave URI pointing to the passport metadata is encoded as a QR code. For security reasons related to self-certification, the memory of HaLo NFC chips is immutable. Therefore, the retrievable chip address is linked to the passport metadata URI on-chain. For this purpose, an additional smart contract was developed and deployed on Sepolia.

```
{
  "type": "nft";
  "chainId": 11155111;
  "address": "0xebf4455180945bc730363fa01cb39a4a54666439";
  "tokenId": 3;
}
```

Listing 2: Example of Passport Metadata

4.2.2. Prototype Workflow

Figure 3 summarizes the workflow of passport creation. More detailed sequence diagrams for this process can be found in the Appendices (Figures A.2, A.3, A.4). The process begins with users opening the PermaPass app (1), connecting to their wallet app (2), and uploading a JSON file of their passport data. The PermaPass app uploads this JSON file to Arweave, which responds with a transaction ID (3). The app converts this transaction ID to an Arweave URI, which is used to initiate the creation of the identifier using the deployed smart contracts. Since creating identifiers on a blockchain is state-changing, users must confirm the process within their wallet apps to cover gas fees (4 & 5). Once created, the identifier holds the Arweave URI pointing to the passport data (6). The PermaPass app then composes the passport metadata JSON, uploads it to Arweave, and converts the transaction ID to the passport metadata Arweave URI (7). This URI is stored on the data carrier by encoding it as a QR code or linking the NFC chip's address to the URI via an additional smart contract call (8 & 9). Finally, the connected wallet address becomes the owner of the identifier, i.e., the passport owner.

Reading passports, as illustrated in Figures 4, 7, & A.5, is the reverse process of passport creation. The metadata URI is retrieved from the data carrier (2 & 3) and metadata is resolved using Arweave (4). Once the location of the identifier's deployed smart contract is known, the current and past passport URIs can be retrieved (5 & 6). Finally, the PermaPass app resolves all passport URIs to plain passport data and shows the user's current passport data and its historical modifications (7). Since reading data does not incur gas fees, users are not required to be connected to a wallet app. Therefore, the PermaPass app reads smart contract data using its own Ethereum account.

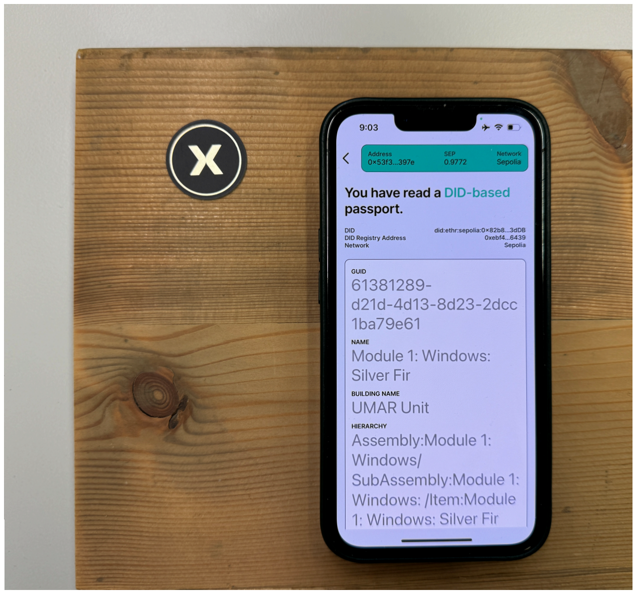


Figure 7: Image of the application after reading the HaLo data carrier (left) attached to a wooden component

Source: Created by the authors.

The passport can be updated or destroyed after being read if the connected wallet address is the passport owner. Passport updates are implemented by updating the passport data URI on Arweave using the identifier's smart contract (Figure A.1). The destruction of the passport functions by transferring the passport's ownership to the zero address. Consequently, the passport can still be read but can no longer be updated or destroyed.

4.2.3. Comparison of Prototypes

The variations were also tested and compared for their performance, specifically, the time to complete the actions stated in the functional requirements and the costs of each of the actions reported in ETH and USD (Figure 6). Processing speed includes Sepolia transaction and Arweave interaction times. Costs solely refer to Sepolia transaction gas fees, since a free Arweave Node (Irys Node 2) was used for uploading prototype data to Arweave. The computations were run 12 times at 5-minute intervals between 17:00 - 18:00 CEST on June 14, 2024. The mean values are shown in Figure 6. Sepolia ETH has no real value because it is a test net but it was converted to USD based on the Ethereum mainnet rate of USD 3,481.87 per 1 ETH as of June 14, 2024.

4.3. Survey Results

Table II: Demographics of Survey Participants

Domain	**Gender**	**Country**	**Years Experience**	**Interaction**
Industry	Male	US, CA, EU	12	Online
Industry	Male	CH	5	Online
Industry	-	Global	20+	Online
Academia	Male	CH	9	In-person
Academia	Female	CH	4	In-person
Academia	Male	US	3	In-person
Academia	Female	CH	1	In-person
Academia	Female	CH	1	Online
Industry	Female	EU	8	Online
Industry	Male	CH	2	Both
Academia & Industry	Female	DE	1	Online

Source: Created by the authors.

The resulting decentralized product passport artifacts are evaluated for how effective they were in achieving design objectives, and what design features were yet to be realized. The application was developed for iOS devices so the sampling of users to download the application on their device is limited. Additionally, due to more stringent restraints for releasing the application on the public application store, it is kept in developer mode and users must also have a blockchain wallet to mint and hold the passports. Lastly, after the virtual or in-person demonstration, the practitioners completed a survey reviewing the prototypes (Table A.1). The breakdown of the users is shown in Table II.

Researchers van Welie et al. (2001) suggest that usability criteria for user interface design should include efficiency, effectiveness, and satisfaction. Figure 8 shows user feedback on the variations of the prototype and Figure 9 shows feedback on the effectiveness of the prototype in general.

Following the collection of the survey, the results were analyzed on the resulting design knowledge from the deployment of the prototypes. Design knowledge has three main components, the problem space, the solution space, and the evaluation (Vom Brocke et al., 2020). The first main axis is the *projectability* of the problem

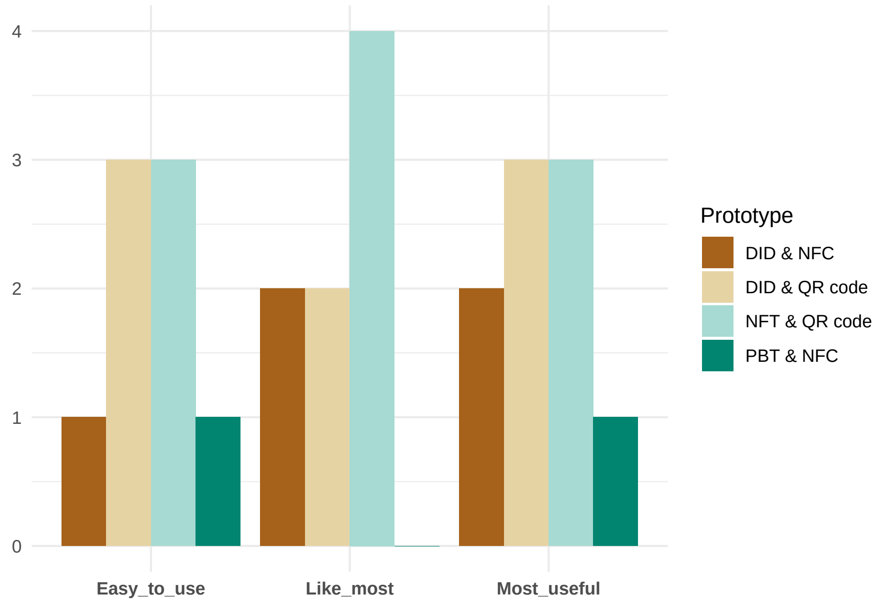


Figure 8: Relative Comparison between the Prototype Variations.

Source: Created by the authors.

space, which is how well the research context aligns with other similar projects in the knowledge base and the applicability of the domain. The next dimension is the solution space and the *fitness* of the artifact. Fitness describes the maturity of the solution by addressing more of the problem space in more effective ways, higher fitness provides higher normative power situated in a problem. Lastly, *confidence* is used to describe the designated evaluations used for the design knowledge, including the rigor of evaluation to minimize the risk of applying the design knowledge. The assessment of the design knowledge categories from the survey is reported below.

Problem Space: the *projectability* received a score of 3.44/5.0

Solution Space: the *fitness* received a score of 3.11/5.0

Evaluation: the *confidence* received a score of 2.67/5.0

One of the questions asked about what other problems the prototypes could be useful for, further examining the *projectability* of the problem. Several respondents mentioned that the prototypes can also be used for general T&T problems in other

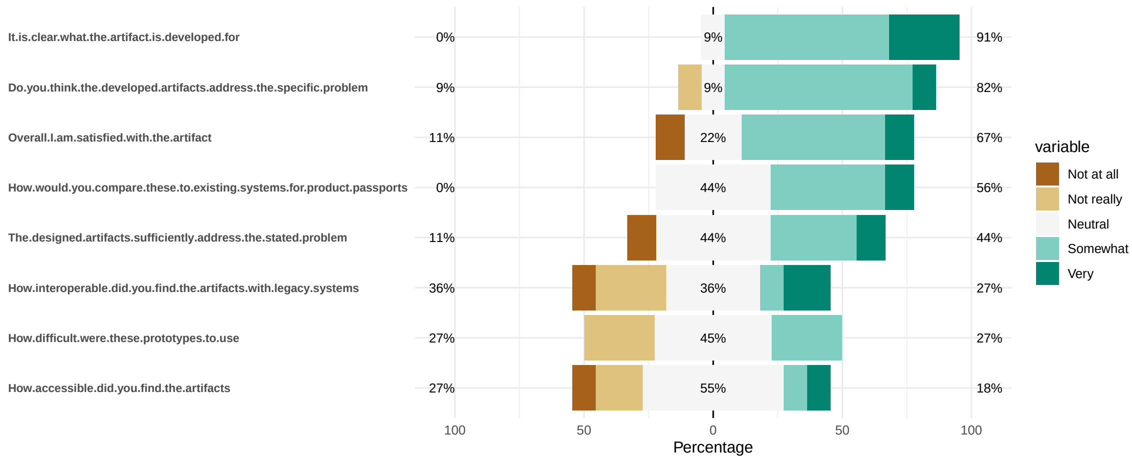


Figure 9: Survey Responses for the Prototypes.

Source: Created by the authors.

industries. One user responded these prototypes may be used to facilitate the valuation of real estate for the financial value of an overall portfolio. Similarly, there were suggestions for material trading applications. One user mentioned applications in traditional construction site logistics, and two other users mentioned the prototypes may also be used for recording operations, maintenance, and life-cycle information, but should include the traceability of previous owners of the product passports. Also mentioned was the application of the product passports for estimating the total embodied carbon of projects (aggregation functions). Overall, the artifact was reported to meet the design intentions. The accessibility and user interface of the prototypes could be improved, and interoperability with legacy systems remains to be fully proven, but the review was favorable (Figure 9).

In the open questions, one response suggested including the success rate as additional evaluation criteria for the prototypes to be a market indicator for the pragmatism of the prototype. The responses also included suggestions to conduct trials with companies. The prototypes tested in person experienced some bugs in the connection to the hardware and wallets, this was emphasized in the feedback. One response suggested considering data trustworthiness and sourcing in addition to the general readability of the data without needing a specific application. Four respondents wanted to see more on the connection of the data carriers to the product and testing the durability and applicability of that connection. One comment received was on the gas costs and questioned whether that may inhibit scalability. Lastly, there were comments on scaling the UI for different levels of digital literacy, especially concerning the references to technologies like blockchain and decentralized identifiers.

5. Discussion

The objective of this research was to develop and test a prototype that used a decentralized identifier to link the physical product to its digital data. The research found that the broader problem space is not clear, influenced by vague calls for a circular economy, policy for digital product passports, T&T systems from tangential industries, and unclear business models (De Wolf et al., 2024). Because of this, the solution space also varies. Nevertheless, literature repeatedly claims that blockchain has the potential to facilitate a T&T approach for the reuse of building components and construction material (Wang et al., 2020; Li et al., 2021). To better develop artifacts for this aim, more confident evaluation criteria should be developed.

Two identifier systems were explored, DIDs and Ethereum tokens. DIDs were chosen because of their lightweight architecture but high functionality and interoperability through different resolver systems. Using blockchain technology for storing product passport URI and metadata adds costs but brings the added benefits of distributed storage and immutability. Tokens have the ease of transferability and direct connection to market mechanisms. Additionally, this work helps lay the foundation for the tokenization of real world assets.

This work reviewed existing DSR artifacts in a similar space and discussed their contributions and shortcomings (see Section 2). The artifacts developed in this work differ from them by focusing more on the integration of the data carrier and the identifier. Existing DSR artifacts often use closed ecosystems, third-party storage, or centralized identifiers, all subject to failure in highly distributed and long-term scenarios. According to the evaluation from the survey, the projectability of the problem space is medium-high for transferability to similar problems. The developed solution has only a medium level of fitness, indicating the moderate production of broader design constructs and not specifically addressing a defined problem. Lastly, the confidence of the evaluation criteria was also only rated medium, indicating the metrics might not have been clear enough nor of high enough confidence for fully assessing the prototypes.

5.1. Interpretation of Results

The processing speed and costs will vary across time, but the relative comparison illustrates the general difference in performance. Similar comparisons can be found in the prototypes developed by Incorvaja et al. (2022), which showed transaction costs that ranged from 0.0014 ETH to 0.0039 ETH ($3.42 - $9.52 USD as calculated in the publication in 2022). The results from this experiment show the highest value for creating a passport with the HaLo NFC and PBT variant at 0.000751 ETH ($2.60 USD as calculated previously) and the lowest value for updating the token-based passports at 0.000082 ETH ($0.28 USD) without testing ownership transfer. Reading the passports has no cost and does not require a wallet connection. For passport creation and reading, the processing speed and costs with HaLo NFC are significantly higher than with QR codes due to the additional smart contract calls needed for linking passport metadata.

An observation from the survey is that users did not take much interest in digital infrastructure or the identifier when using the application. In general, the feedback focused mostly on the user experience and less on the functionality. This is likely because at the time of testing the users did not need to perform any actual transactions and were not reliant on such artifact features. This highlights the difficulty of extracting design knowledge without positioning solutions against the problem space. Many blockchain prototypes and legacy T&T systems typically work in the short term and the problem of long-term and decentralized storage explored in this work is ephemeral and difficult to test directly. The nature of blockchain storage does not allow for updating information directly, so developing a system that updates where the identifier points to it became relevant to focus on linking data and data stores (Figure 3).

By expanding from these learnings, a proposed set of design requirements can be synthesized for future researchers to use and verify. The criteria are based on the literature review of other DSR artifacts, literature review from other industry T&T solutions, previous surveys in the literature (Byers et al., 2024a), and feedback from the validation of this study. The suggested design requirements fall under three main axes: functional, non-functional, and user.

Functional: create, read, update, trace, delete, archive

Non-functional: linked open data formats; long-term storage (more than 50 years); unique identity; connection to data carrier; data accuracy, completeness, and timeliness

User: provide clear instructions, easy access management, open reading, data analysis and export

Additional Considerations: privacy controls (encryption), open-source, non-proprietary, certifiable, incentive and transfer mechanisms, compatibility with digital twins, integration with central data registries (aggregate)

5.2. Connection to Existing Systems

Product passports and T&T technologies are purported to enable a circular economy by endowing identity, providing information persistence, and therefore adding value to existing materials and components (Çetin et al., 2021; De Wolf et al., 2024). The European Commission announced digital product passports as a mandatory cross-sectoral digital infrastructure by 2026 to increase transparency on product supply chains, help consumers make sustainable choices, and provide new business opportunities (Honic et al., 2024; ISO; European Union, 2024). Given this regulatory push, there are many ongoing research and industry efforts related to tracking and tracing products, as well as product passports. The connection to these existing systems needs to be further explored from both a technical and regulatory perspective.

For the AECOO industry, previous research on the quantification of building component reuse and recycling was focused on material passports and often connected to BIM programs and platforms (Honic et al., 2019b). Industry standard DPP providers such as Madaster or OneClickLCA implement export functionalities using the .ifc format to facilitate the connection between BIM models in various software formats and DPP platforms and formats. However, the exchange is generally one-way, and the connection often breaks with the export of the model, which works against the requirements of transparency, accessibility and editing, data ownership, and information persistence. The promise of digital twins connected further with IoT devices aims to address these challenges, but are nascent and not fully implemented at a material component level. Additionally, many proposals of digital twins for reuse in construction only consider the 3D geometry Zboinska and Göbel (2025). Mêda et al. (2021) review digital twins, digital building logbooks, and digital data templates for circular construction. Their work proposes incremental maturity levels of a digital twin based on the level of dynamic data connection and automated decision making. For purposes of product lifecycle management explored in this work falls under the label of a "digital shadow" due to its as-built nature.

The explored decentralized design in this study also comes with potential tensions with emerging European DPP governance models. Regulation (EU) 2024/3110 calls for product passports that use unique identifiers managed by economic operators from regulatory oversight, in addition to the use of standard data carriers for machine-readable accessibility (European Union, 2024). Regulated data schemas may lend themselves to interoperability due to ease of data exchange, but simultaneously inhibit flexible data types that could be managed with the examined systems in this work. In addition, European Union (2024) mandates that a construction digital product passport system must remain accessible for ten years by an economic operator without disproportionate costs; this is supported by the data found in this experiment for the design of the data hosting system.

Similarly, GS1's EPCIS 2.0 standards recommend using managed identifiers under their defined governance, which contrasts with the design in this study that does not rely on central authorities, institutional verification, and enables self-issued identity claims (GS1, 2022). This potential discrepancy may introduce further interoperability nuance, to cohere a decentralized and universal system with a centrally managed system (e.g., GS1 GTIN codes). The EPCIS standard focuses heavily on the data sharing framework. Hybrid models with decentralized control and centralized verification may resolve these tensions while enhancing scalability, increasing system resilience, and enabling distributed data ownership and identity creation (García et al., 2024).

This work proposed a T&T stack in Figure 1 to be explored when designing solutions for decentralized product passports. Other researchers have been exploring additional approaches to decentralization in circularity and construction, such as decentralized data marketplaces (Bucher and Hall, 2022). At its core, uniquely identifying construction products is the first step for exploring future possibilities such as material marketplaces and trading ownership rights to materials as introduced in previous work on the Self-Sovereign Identity of Things. However, ensuring the discrete naming and nature of the reuse of building products is essential for these mechanisms.

Borrowing from the Linked Open Data rating developed by Tim Berners-Lee, the developed prototypes achieve four out of five stars (Berners-Lee, 2009). This is because the building product information stored through these prototypes is available as machine-readable structured data, in a non-proprietary format, and uses open standards from W3C (through DIDs) (Solita and Gaia Consulting, 2022). The subsequent step would be to link the product data to other data (e.g., the original supplier data or government building permitting data).

5.3. Research Challenges and Limitations

There are several limitations to this research, including the sampling approach and the location of experts for validating the artifact. For global generalization of results, testing should be representative of the geography and demography of potential users to limit bias in reporting. Therefore, the problem and solution space defined in this paper is subject to modification by additional research.

This approach is also constrained because a field validation would require not just the installation of the tags, but would necessitate the moment when the product information is needed for a reuse application or similar. This stands to be the work of future studies that could use an action research or case study approach. Testing the prototypes and design knowledge with multiple contexts or stakeholders (such as at the manufacturer or near the end of the building life) may help increase the ability to generalize the findings, the projectability of the problem space, and the fitness of the solution space. In addition, research needs to be developed to test the longevity of the solution to support the design requirements.

From a security perspective, the artifact is vulnerable at multiple levels: data carrier, identifier, and data storage. QR codes are susceptible to duplication and transfer, allowing counterfeit products to exploit them. Similarly, HaLo NFC chip-based passports are not immune to fraud. Attackers could link a new chip to existing passport metadata or physically steal and reattach a genuine chip to counterfeit products. The identifier and data storage components depend on the security and availability of the Ethereum and Arweave networks, introducing potential risks. In addition, smart contracts are prone to vulnerabilities caused by coding errors, which are more challenging to fix than centralized software systems.

The prototype also has limitations in achieving complete decentralization. The developer of the user interface has access and power to exchange the smart contracts used, thus, manipulating identities is possible from a user perspective. A mechanism to distribute control for publishing updates to the user interface would be important to incorporate. Similarly, the iOS application store and distribution of any wallet application are centralized, which could result in a single point of failure.

Lastly, access controls and privacy are challenges not fully addressed in the prototypes. Passports can be read without restrictions using the user interface. Even with restrictions, the public nature of Sepolia allows for the collection of all Arweave URIs to access the unencrypted data stored on Arweave.

5.4. Future Research Directions

This is exploratory research, meaning the results can and should be used to generate hypotheses for future testing. A better understanding of the problem space enables more specific theories and research questions to be explored. The scope of the solution space can be modified by focusing on certain global regions and examining proposed legal frameworks based on specific products. The qualitative testing and empirical results of this research might help inform regulatory development for construction contexts in the future, yet more research should be conducted. Some additional research directions are listed below.

- The prototypes should be tested as case studies along points in circular construction supply chains where such T&T systems would be used to determine how they impact the processes. Potential points of interest are starting with the manufacturer of construction products, or architects and building owners when a building is at the end of use.

- A review of existing policy, regulations, and legal standards across different regions may modify the criteria for potential design architectures or unveil the potential impact of such T&T systems on society.
- A cost-benefit analysis or economic viability study of product passports should be conducted to determine cost thresholds for implementing a T&T system. This could help identify scaling challenges for different building products.
- A systematic review of specific identifier mechanisms from different open web standards, blockchain token standards, and decentralized identities and their suitability for product passports. Additional work should review different scenarios for adopting blockchain and when it would be appropriate to use on-chain or off-chain solutions for what level of data storage.
- A further study on VCs for robust claims verification about construction documentation. Additionally, investigating the role of privacy and addressing an additional consideration of privacy controls with the help of selective disclosure.
- An investigation of the reliability and longevity of decentralized storage, and its suitability to support the need for long-term product passport data storage.

6. Conclusion

The research questions of this work asked how to connect physical products to their digital data store in a robust manner and what requirements should be used to develop decentralized prototypes. Four variations of prototypes were developed using design science research methods and were validated with surveys by researchers and practitioners in the space. The designated problem the design artifacts were positioned in was a hypothetical end-of-life of a building, where the materials needed to be tagged for deconstruction and distribution. The prototypes were found to be largely favorable and met the intentions defined for the solution space. There were some bugs and challenges in the implementation, but the QR codes were found to be more favorable than the NFC chips, and the DIDs were found to outperform the tokens.

The design requirements were synthesized based on the results of the prototyping and validation in combination with existing literature to guide future research into the design space. In addition, due to the exploratory nature of the work, future research directions and hypotheses were proposed for further testing. The work is not without limitations, primarily in that the validation approach was not in a full reuse scenario that tracked the components. To further transition this work to practice, the technical prototypes are under continued technical development. Pilot studies are the next step under controlled conditions to examine the specific attributes to modify. Lastly, the cultural and business contexts need to be further examined to elucidate incentives for implementation and understand economic viability.

This is the first known work by the authors to explore DIDs and alternative token standards within the AECOO context and circular supply chains. Beyond the theoretical contribution of the T&T stack, the results of the study further expand the T&T design space by proposing new methods to uniquely identify products. The design knowledge produced in this work was found to have medium projectability of the problem, medium fitness of the solutions, and medium confidence of the evaluation, grounding the resulting artifact within existing design knowledge. Future research on product passports in construction and decentralized T&T solutions can reference the findings of this work to position their results for improved prototyping. These steps will help evolve the technology to a more mature technology readiness level, which can advance industry adoption.

Within AECOO, manufacturers and asset owners can benefit from the practical contributions of this work, as the proposed robust identifiers, component hardware verification, and long-term storage could ensure access to product information to facilitate future circular economy activities, including the reuse and reselling of materials. These results are more broadly significant for society as they further the design knowledge of a decentralized product passport system as a less-discussed alternative to current institutional and centralized approaches. This is important, particularly as the EU rolls out recommendations for digital product passports and more global companies are interested in adopting circular economy practices. Finally, the results also support the objectives of better supply chain transparency of the existing building stock, to decouple raw material extraction from societal growth.

Acknowledgments

The authors have many people to thank for the completion of this work. To begin, the authoring team recognizes that the prototypes were developed largely out of Master Thesis work conducted under the supervision of Professor Burkhard Stiller (University of Zurich) and Professor Catherine De Wolf (ETH Zurich). Preliminary results were presented at the Blockchain in Construction Research Workshop hosted by the Construction Blockchain Consortium at TU Delft and the authors thank the attendees for the feedback received. Similarly, thanks go to the anonymous testers of the application for their patience and interest in the work. Lastly, the authors would like to thank Arx and Cameron Robertson for samples of their HaLo chips and support during development.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to improve the readability of some of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

2pmflow, locationtba, Cameron Robertson, cygaar, Brian Weick, 2022. ERC-5791: Physical Backed Tokens. URL: https://eips.ethereum.org/EIPS/eip-5791.

Alexander, C., Ishikawa, S., Silverstein, M., 1977. A Pattern Language: Towns, Buildings, Construction. Oxford University Press.

Alves, L., Ferreira Cruz, E., Lopes, S.I., Faria, P.M., Rosado da Cruz, A.M., 2022. Towards circular economy in the textiles and clothing value chain through blockchain technology and IoT: A review. Waste Management & Research 40, 3–23. URL: https://doi.org/10.1177/0734242X211052858, doi:10.1177/0734242X211052858. publisher: SAGE Publications Ltd STM.

Anumba, C.J., Akanmu, A., Yuan, X., Kan, C., 2021. Cyber—physical systems development for construction applications. Frontiers of Engineering Management 8, 72–87. URL: https://doi.org/10.1007/s42524-020-0130-4, doi:10.1007/s42524-020-0130-4.

Arx Research, 2023. The Hidden Expiration Date in NFC Chipped Goods. URL: https://mirror.xyz/arx-research.eth/jgJG3vygw9GbwZtpnxeXE1toZQq4nIjCfCJink55u-c.

Berners-Lee, T., 2009. Linked Data - Design Issues. URL: https://www.w3.org/DesignIssues/LinkedData.html.

Brandín, R., Abrishami, S., 2021. Information traceability platforms for asset data lifecycle: blockchain-based technologies. Smart and Sustainable Built Environment 10, 364–386. URL: https://doi.org/10.1108/SASBE-03-2021-0042, doi:10.1108/SASBE-03-2021-0042. publisher: Emerald Publishing Limited.

Bucher, D., Hall, D., 2022. New Ways of Data Governance for Construction? Decentralized Data Marketplaces as Web3 Concept just around the Corner, in: Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering, Aarhus University. p. 1872. URL: https://www.research-collection.ethz.ch/handle/20.500.11850/560904, doi:10.7146/aul.455.c224. accepted: 2022-09-08T11:21:53Z.

Byers, B.S., Hunhevicz, J.J., Honic, M., Wolf, C.D., 2024a. Exploring Tokenized Product Passports for Circular Construction Supply Chains, European Council on Computing in Construction. pp. 0–0. URL: https://ec-3.org/publications/conference/paper/?id=EC32024_265, doi:10.35490/EC3.2024.265.

Byers, B.S., Raghu, D., Olumo, A., De Wolf, C., Haas, C., 2024b. From research to practice: A review on technologies for addressing the information gap for building material reuse in circular construction. Sustainable Production and Consumption 45, 177–191. URL: https://www.sciencedirect.com/science/article/pii/S2352550923002920, doi:10.1016/j.spc.2023.12.017.

Byers, B.S., Stengele, K., De Wolf, C., 2025. Data Carriers for Circular Construction Supply Chains: an Exploratory Quantitative Analysis. Journal of Cleaner Production , 145053URL: https://www.sciencedirect.com/science/article/pii/S0959652625004032, doi:10.1016/j.jclepro.2025.145053.

Centobelli, P., Cerchione, R., Vecchio, P.D., Oropallo, E., Secundo, G., 2022. Blockchain technology for bridging trust, traceability and transparency in circular supply chain. Information & Management 59, 103508. URL: https://www.sciencedirect.com/science/article/pii/S0378720621000823, doi:10.1016/j.im.2021.103508.

Chiacchio, F., D'Urso, D., Oliveri, L.M., Spitaleri, A., Spampinato, C., Giordano, D., 2022. A Non-Fungible Token Solution for the Track and Trace of Pharmaceutical Supply Chain. Applied Sciences 12, 4019. URL: https://www.mdpi.com/2076-3417/12/8/4019, doi:10.3390/app12084019. number: 8 Publisher: Multidisciplinary Digital Publishing Institute.

Cocco, L., Tonelli, R., Marchesi, M., 2022. A System Proposal for Information Management in Building Sector Based on BIM, SSI, IoT and Blockchain. Future Internet 14, 140. URL: https://www.mdpi.com/1999-5903/14/5/140, doi:10.3390/fi14050140. number: 5 Publisher: Multidisciplinary Digital Publishing Institute.

De Filippi, P., Mannan, M., Reijers, W., 2020. Blockchain as a confidence machine: The problem of trust & challenges of governance. Technology in Society 62, 101284. URL: https://www.sciencedirect.com/science/article/pii/S0160791X20303067, doi:10.1016/j.techsoc.2020.101284.

De Wolf, C., Byers, B.S., Raghu, D., Gordon, M., Schwarzkopf, V., Triantafyllidis, E., 2024. A 5D Digital Circular Workflow: Digital Transformation Towards Matchmaking of Environmentally Sustainable Building Materials through Reuse from Disassembly. URL: https://www.researchsquare.com/article/rs-4349460/v1, doi:10.21203/rs.3.rs-4349460/v1. iSSN: 2693-5015.

van Dorp, K., 2002. Tracking and tracing:a structure for development and contemporary practices. Logistics Information Management 15, 24–33. URL: https://doi.org/10.1108/09576050210412648, doi:10.1108/09576050210412648. publisher: MCB UP Ltd.

Dounas, T., Jabi, W., Lombardi, D., 2021. Topology generated non-fungible tokens: blockchain as infrastructure for a circular economy in architectural design. 2. URL: https://rgu-repository.worktribe.com/output/1335050/topology-generated-non-fungible-tokens-blockchain-as-infrastructure-for-a-circular publisher: Association for Computer-Aided Architectural Design Research in Asia.

Elghaish, F., Hosseini, M.R., Kocaturk, T., Arashpour, M., Bararzadeh Ledari, M., 2023. Digitalised circular construction supply chain: An integrated BIM-Blockchain solution. Automation in Construction 148, 104746. URL: https://www.sciencedirect.com/science/article/pii/S0926580523000067, doi:10.1016/j.autcon.2023.104746.

European Union, 2024. Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 laying down harmonised rules for the marketing of construction products and repealing Regulation (EU) No 305/2011 (Text with EEA relevance). URL: http://data.europa.eu/eli/reg/2024/3110/oj/eng. legislative Body: EP, CONSIL.

Fedrecheski, G., Rabaey, J.M., Costa, L.C.P., Calcina Ccori, P.C., Pereira, W.T., Zuffo, M.K., 2020. Self-Sovereign Identity for IoT environments: A Perspective, in: 2020 Global Internet of Things Summit (GIoTS), pp. 1–6. URL: https://ieeexplore.ieee.org/document/9119664, doi:10.1109/GIOTS49054.2020.9119664.

Fellows, R.F., Liu, A.M., 2022. Research Methods for Construction. 5th ed., John Wiley & Sons.

García, I.I., Muñoz-Escoí, F.D., Aroca, J.A., Peñuela, F.J.F.B., 2024. Digital Product Passport Management with Decentralised Identifiers and Verifiable Credentials. URL: http://arxiv.org/abs/2410.15758, doi:10.48550/arXiv.2410.15758. arXiv:2410.15758 [cs].

Gligoric, N., Krco, S., Hakola, L., Vehmas, K., De, S., Moessner, K., Jansson, K., Polenz, I., van Kranenburg, R., 2019. SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers. Sensors 19, 586. URL: https://www.mdpi.com/1424-8220/19/3/586, doi:10.3390/s19030586. number: 3 Publisher: Multidisciplinary Digital Publishing Institute.

van Groesen, W., Pauwels, P., 2022. Tracking prefabricated assets and compliance using quick response (QR) codes, blockchain and smart contract technology. Automation in Construction 141, 104420. URL: https://www.sciencedirect.com/science/article/pii/S092658052200293X, doi:10.1016/j.autcon.2022.104420.

GS1, 2021. GS1 Global Traceability Compliance Criteria Standard. URL: https://www.gs1.org/docs/traceability/GS1_Global_Traceability_Compliance_Criteria_For_Food_Application_Standard.pdf.

GS1, 2022. EPCIS Standard. URL: https://ref.gs1.org/standards/epcis/.

Götz, C.S., Karlsson, P., Yitmen, I., 2020. Exploring applicability, interoperability and integrability of Blockchain-based digital twins for asset life cycle management. Smart and Sustainable Built Environment ahead-of-print. URL: https://doi.org/10.1108/SASBE-08-2020-0115, doi:10.1108/SASBE-08-2020-0115.

Heisel, F., Hebel, D.E., 2022. Building Better - Less - Different: Circular Construction and Circular Economy: Fundamentals, Case Studies, Strategies. Birkhäuser. URL: https://www.degruyter.com/document/doi/10.1515/9783035626353/html, doi:10.1515/9783035626353.

Honic, M., Kovacic, I., Rechberger, H., 2019a. Concept for a BIM-based Material Passport for buildings. IOP Conference Series: Earth and Environmental Science 225, 012073. URL: https://dx.doi.org/10.1088/1755-1315/225/1/012073, doi:10.1088/1755-1315/225/1/012073.

Honic, M., Kovacic, I., Sibenik, G., Rechberger, H., 2019b. Data- and stakeholder management framework for the implementation of BIM-based Material Passports. Journal of Building Engineering 23, 341–350. URL: https://www.sciencedirect.com/science/article/pii/S2352710218309392, doi:10.1016/j.jobe.2019.01.017.

Honic, M., Magalhães, P.M., Van den Bosch, P., 2024. From Data Templates to Material Passports and Digital Product Passports, in: De Wolf, C., Çetin, S., Bocken, N.M.P. (Eds.), A Circular Built Environment in the Digital Age. Springer International Publishing, Cham. Circular Economy and Sustainability, pp. 79–94. URL: https://doi.org/10.1007/978-3-031-39675-5_5, doi:10.1007/978-3-031-39675-5_5.

Hunhevicz, J.J., Bucher, D.F., Soman, R.K., Honic, M., Hall, D.M., De Wolf, C., 2023. Web3-based role and token data access: the case of building material passports, European Council on Computing in Construction. pp. 0–0. URL: https://ec-3.org/publications/conference/paper/?id=EC32023_217, doi:10.35490/EC3.2023.217.

Hunhevicz, J.J., Hall, D.M., 2020. Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. Advanced Engineering Informatics 45, 101094. URL: https://www.sciencedirect.com/science/article/pii/S147403462030063X, doi:10.1016/j.aei.2020.101094.

Hunhevicz, J.J., Motie, M., Hall, D.M., 2022. Digital building twins and blockchain for performance-based (smart) contracts. Automation in Construction 133, 103981. URL: https://www.sciencedirect.com/science/article/pii/S0926580521004325, doi:10.1016/j.autcon.2021.103981.

Incorvaja, D., Celik, Y., Petri, I., Rana, O., 2022. Circular Economy and Construction Supply Chains, in: 2022 IEEE/ACM International Conference on Big Data Computing, Applications and Technologies (BDCAT), pp. 92–99. doi:10.1109/BDCAT56447.2022.00019.

IoTeX Research, . Decentralized Physical Infrastructure Networks - A Modular Infrastructure Thesis. Technical Report.

ISO, . ISO/DIS 59040(en), Circular economy — Product circularity data sheet. URL: https://www.iso.org/obp/ui/en/#iso:std:iso:59040:dis:ed-1:v1:en.

Kayikci, Y., Gozacan-Chase, N., Rejeb, A., Mathiyazhagan, K., 2022. Critical success factors for implementing blockchain-based circular supply chain. Business Strategy and the Environment 31, 3595–3615. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/bse.3110, doi:10.1002/bse.3110. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/bse.3110.

Kelepouris, T., Theodorou, L., McFarlane, D., Thorne, A., Harrison, M., 2006. Track and trace requirements scoping. Aerospace-ID Technologies White Paper Series .

Kifokeris, D., Koch, C., 2022. The Proof-of-Concept of a Blockchain Solution for Construction Logistics Integrating Flows: Lessons from Sweden, in: Dounas, T., Lombardi, D. (Eds.), Blockchain for Construction. Springer Nature, Singapore. Blockchain Technologies, pp. 113–139. URL: https://doi.org/10.1007/978-981-19-3759-0_7, doi:10.1007/978-981-19-3759-0_7.

Kim, M., Hilton, B., Burks, Z., Reyes, J., 2018. Integrating Blockchain, Smart Contract-Tokens, and IoT to Design a Food Traceability Solution, in: 2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), pp. 335–340. doi:10.1109/IEMCON.2018.8615007.

Li, C.Z., Chen, Z., Xue, F., Kong, X.T.R., Xiao, B., Lai, X., Zhao, Y., 2021. A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction. Journal of Cleaner Production 286, 125391. URL: https://www.sciencedirect.com/science/article/pii/S0959652620354378, doi:10.1016/j.jclepro.2020.125391.

Liu, Q., Trevisan, A.H., Yang, M., Mascarenhas, J., 2022. A framework of digital technologies for the circular economy: Digital functions and mechanisms. Business Strategy and the Environment 31, 2171–2192. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/bse.3015, doi:10.1002/bse.3015. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/bse.3015.

Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., Yeh, A.G.O., 2021. Exploring smart construction objects as blockchain oracles in construction supply chain management. Automation in Construction 129, 103816. URL: https://www.sciencedirect.com/science/article/pii/S0926580521002673, doi:10.1016/j.autcon.2021.103816.

Lu, W., Peng, Z., Webster, C., Wu, L., 2023. Developing a construction waste material ‘passport’ for cross-jurisdictional trading. Journal of Cleaner Production 414, 137509. URL: https://www.sciencedirect.com/science/article/pii/S0959652623016670, doi:10.1016/j.jclepro.2023.137509.

López Ruiz, L.A., Roca Ramón, X., Gassó Domingo, S., 2020. The circular economy in the construction and demolition waste sector – A review and an integrative model approach. Journal of Cleaner Production 248, 119238. URL: https://www.sciencedirect.com/science/article/pii/S0959652619341083, doi:10.1016/j.jclepro.2019.119238.

Morseletto, P., 2020. Targets for a circular economy. Resources, Conservation and Recycling 153, 104553. URL: https://www.sciencedirect.com/science/article/pii/S0921344919304598, doi:10.1016/j.resconrec.2019.104553.

Mêda, P., Calvetti, D., Hjelseth, E., Sousa, H., 2021. Incremental Digital Twin Conceptualisations Targeting Data-Driven Circular Construction. Buildings 11, 554. URL: https://www.mdpi.com/2075-5309/11/11/554, doi:10.3390/buildings11110554.

Neligan, A., Schleicher, C., Engels, B., Kroke, T., 2023. Digital Product Passport as Enabler for the Circular Economy: Relevance and practicability for companies. Technical Report. Institut der deutschen Wirtschaft (IW). Köln. URL: https://circulareconomy.europa.eu/platform/sites/default/files/2024-02/IW-Report_2023-Digitaler-Produktpass-englisch.pdf.

Ngo, T.T.T., Dang, T.A., Huynh, V.V., Cong Le, T., 2023. A Systematic Literature Mapping on Using Blockchain Technology in Identity Management. IEEE Access 11, 26004–26032. URL: https://ieeexplore.ieee.org/abstract/document/10068205, doi:10.1109/ACCESS.2023.3256519. conference Name: IEEE Access.

Niu, Y., Lu, W., Chen, K., Huang, G.G., Anumba, C., 2016. Smart Construction Objects. Journal of Computing in Civil Engineering 30, 04015070. URL: https://ascelibrary.org/doi/10.1061/%28ASCE%29CP.1943-5487.0000550, doi:10.1061/(ASCE)CP.1943-5487.0000550. publisher: American Society of Civil Engineers.

Omrany, H., Soebarto, V., Sharifi, E., Soltani, A., 2020. Application of Life Cycle Energy Assessment in Residential Buildings: A Critical Review of Recent Trends. Sustainability 12, 351. URL: https://www.mdpi.com/2071-1050/12/1/351, doi:10.3390/su12010351. number: 1 Publisher: Multidisciplinary Digital Publishing Institute.

Pinto, F., Ferreira da Silva, C., Moro, S., 2022. People-centered distributed ledger technology-IoT architectures: A systematic literature review. Telematics and Informatics 70, 101812. URL: https://www.sciencedirect.com/science/article/pii/S0736585322000454, doi:10.1016/j.tele.2022.101812.

Rejeb, A., Appolloni, A., Rejeb, K., Treiblmaier, H., Iranmanesh, M., Keogh, J.G., 2023. The role of blockchain technology in the transition toward the circular economy: Findings from a systematic literature review. Resources, Conservation & Recycling Advances 17, 200126. URL: https://www.sciencedirect.com/science/article/pii/S2667378922000633, doi:10.1016/j.rcradv.2022.200126.

Sghaier Omar, A., Basir, O., 2020. Decentralized Identifiers and Verifiable Credentials for Smartphone Anticounterfeiting and Decentralized IMEI Database. Canadian Journal of Electrical and Computer Engineering 43, 174–180. doi:10.1109/CJECE.2020.2970737.

Sheng, D., Ding, L., Zhong, B., Love, P.E.D., Luo, H., Chen, J., 2020. Construction quality information management with blockchains. Automation in Construction 120, 103373. URL: https://www.sciencedirect.com/science/article/pii/S0926580520309535, doi:10.1016/j.autcon.2020.103373.

Shibano, K., Nakajima, T., Mogi, G., 2022. Wood traceability system using blockchain and zero-knowledge proof. URL: http://arxiv.org/abs/2211.11136, doi:10.48550/arXiv.2211.11136. arXiv:2211.11136 [cs].

Simmons, G.J., 1979. Symmetric and Asymmetric Encryption. ACM Comput. Surv. 11, 305–330. URL: https://doi.org/10.1145/356789.356793, doi:10.1145/356789.356793.

Solita, Gaia Consulting, 2022. Digital Product Passport. Technical Report. Technology Industries of Finland. Finland. URL: https://www.stjm.fi/wp-content/uploads/2022/10/Digital-Product-Passport-A4-v010.pdf.

Soltani, R., Nguyen, U.T., An, A., 2021. A Survey of Self-Sovereign Identity Ecosystem. Security and Communication Networks 2021, e8873429. URL: https://www.hindawi.com/journals/scn/2021/8873429/, doi:10.1155/2021/8873429. publisher: Hindawi.

Sporny, M., Longley, D., Chadwick, D., Steele, O., 2024. Verifiable Credentials Data Model v2.0. URL: https://www.w3.org/TR/vc-data-model-2.0/. publication Title: W3C Candidate Recommendation Draft.

Sporny, M., Longley, D., Sabadello, M., Reed, D., Steele, O., Allen, C., 2022. Decentralized Identifiers (DIDs) v1.0. URL: https://www.w3.org/TR/did-core/. publication Title: W3C Recommendation.

Sunny, J., Undralla, N., Madhusudanan Pillai, V., 2020. Supply chain transparency through blockchain-based traceability: An overview with demonstration. Computers & Industrial Engineering 150, 106895. URL: https://www.sciencedirect.com/science/article/pii/S0360835220305829, doi:10.1016/j.cie.2020.106895.

Taleka, M., Makkithaya, K., V G, N., 2023. A Blockchain-Based Credentials for Food Traceability in Agricultural Supply Chain, in: 2023 IEEE International Conference on Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER). doi:10.1109/DISCOVER58830.2023.10316706. pages: 24.

Tao, X., Das, M., Liu, Y., Cheng, J.C.P., 2021. Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design. Automation in Construction 130, 103851. URL: https://www.sciencedirect.com/science/article/pii/S0926580521003022, doi:10.1016/j.autcon.2021.103851.

Venable, J., Pries-Heje, J., Baskerville, R., 2012. A Comprehensive Framework for Evaluation in Design Science Research, in: Peffers, K., Rothenberger, M., Kuechler, B. (Eds.), Design Science Research in Information Systems. Advances in Theory and Practice, Springer, Berlin, Heidelberg. pp. 423–438. doi:10.1007/978-3-642-29863-9_31.

Vom Brocke, J., Winter, R., Hevner, A., Maedche, A., 2020. Special Issue Editorial –Accumulation and Evolution of Design Knowledge in Design Science Research: A Journey Through Time and Space. Journal of the Association for Information Systems 21, 520–544. URL: https://aisel.aisnet.org/jais/vol21/iss3/9/, doi:10.17705/1jais.00611.

Wang, Y., Chen, C.H., Zghari-Sales, A., 2021. Designing a blockchain enabled supply chain. International Journal of Production Research 59, 1450–1475. URL: https://doi.org/10.1080/00207543.2020.1824086, doi:10.1080/00207543.2020.1824086. publisher: Taylor & Francis _eprint: https://doi.org/10.1080/00207543.2020.1824086.

Wang, Z., Wang, T., Hao Hu, Hu, H., Hao Hu, Gong, J., Ren, X., Xiao, Q., 2020. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Automation in Construction 111, 103063. doi:10.1016/j.autcon.2019.103063. mAG ID: 2997365797.

van Welie, M., van der Veer, G.C., Eliëns, A., 2001. Patterns as Tools for User Interface Design, in: Vanderdonckt, J., Farenc, C. (Eds.), Tools for Working with Guidelines, Springer, London. pp. 313–324. doi:10.1007/978-1-4471-0279-3_30.

Wijewickrama, M.K.C.S., Rameezdeen, R., Chileshe, N., 2021. Information brokerage for circular economy in the construction industry: A systematic literature review. Journal of Cleaner Production 313, 127938. URL: https://www.sciencedirect.com/science/article/pii/S0959652621021569, doi:10.1016/j.jclepro.2021.127938.

Wu, L., Lu, W., Peng, Z., Webster, C., 2023. A blockchain non-fungible token-enabled 'passport' for construction waste material cross-jurisdictional trading. Automation in Construction 149, 104783. URL: https://www.sciencedirect.com/science/article/pii/S0926580523000432, doi:10.1016/j.autcon.2023.104783.

Zboinska, M.A., Göbel, F., 2025. Digital tool integrations for architectural reuse of salvaged building materials. Automation in Construction 170, 105947. URL: https://www.sciencedirect.com/science/article/pii/S0926580524006836, doi:10.1016/j.autcon.2024.105947.

Zhao, H., Paik, H., Wang, Q., Chen, S., 2023. SID: Service Identification and Discovery Framework for Decentralised Supply Chains, in: 2023 IEEE International Conference on Software Services Engineering (SSE), pp. 1–9. doi:10.1109/SSE60056.2023.00012.

Çetin, S., De Wolf, C., Bocken, N., 2021. Circular Digital Built Environment: An Emerging Framework. Sustainability 13, 6348. URL: https://www.mdpi.com/2071-1050/13/11/6348, doi:10.3390/su13116348. number: 11 Publisher: Multidisciplinary Digital Publishing Institute.

Appendix A. Appendix

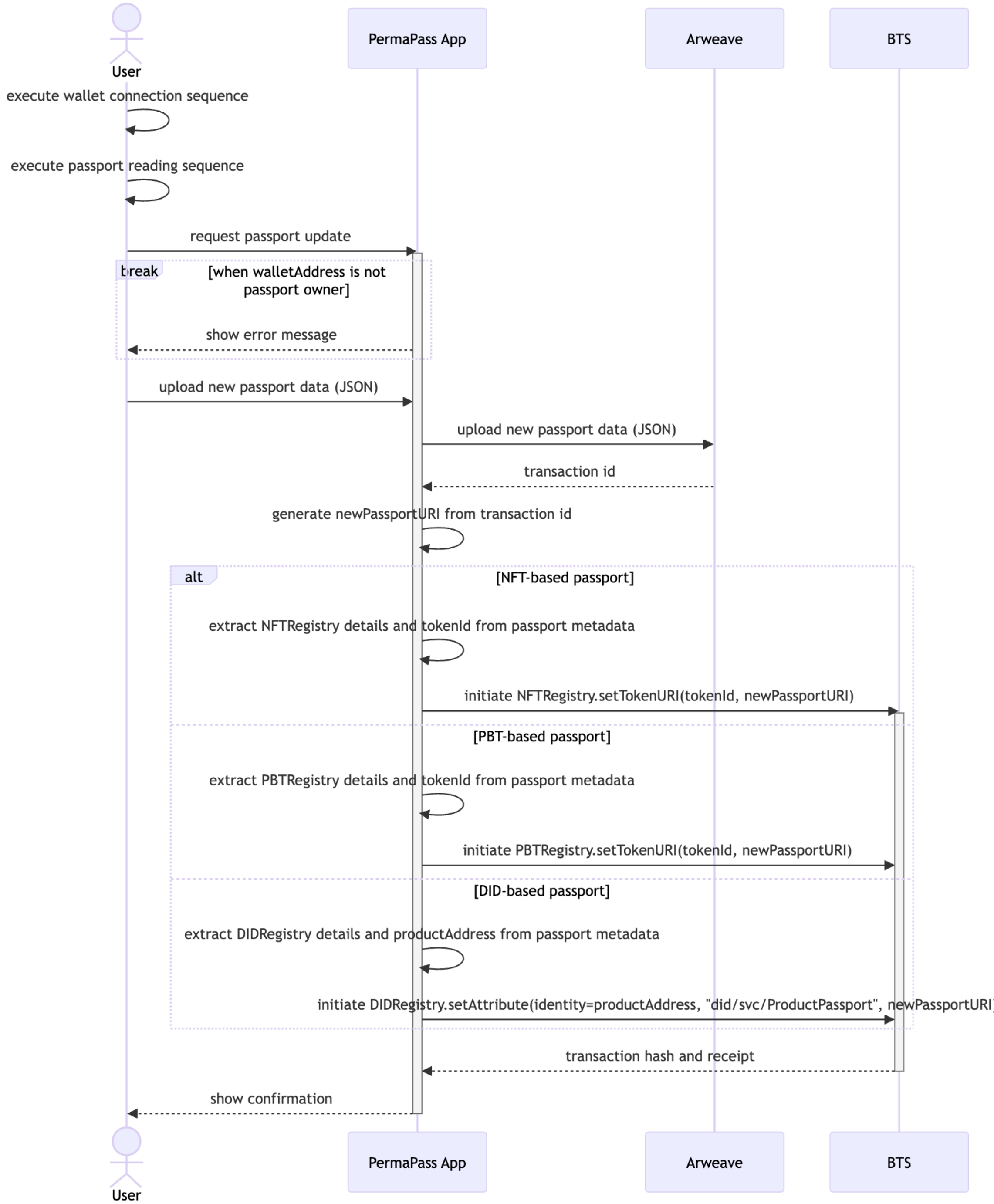


Figure A.1: Sequence Diagram of Updating a Passport.

Source: Created by the authors.

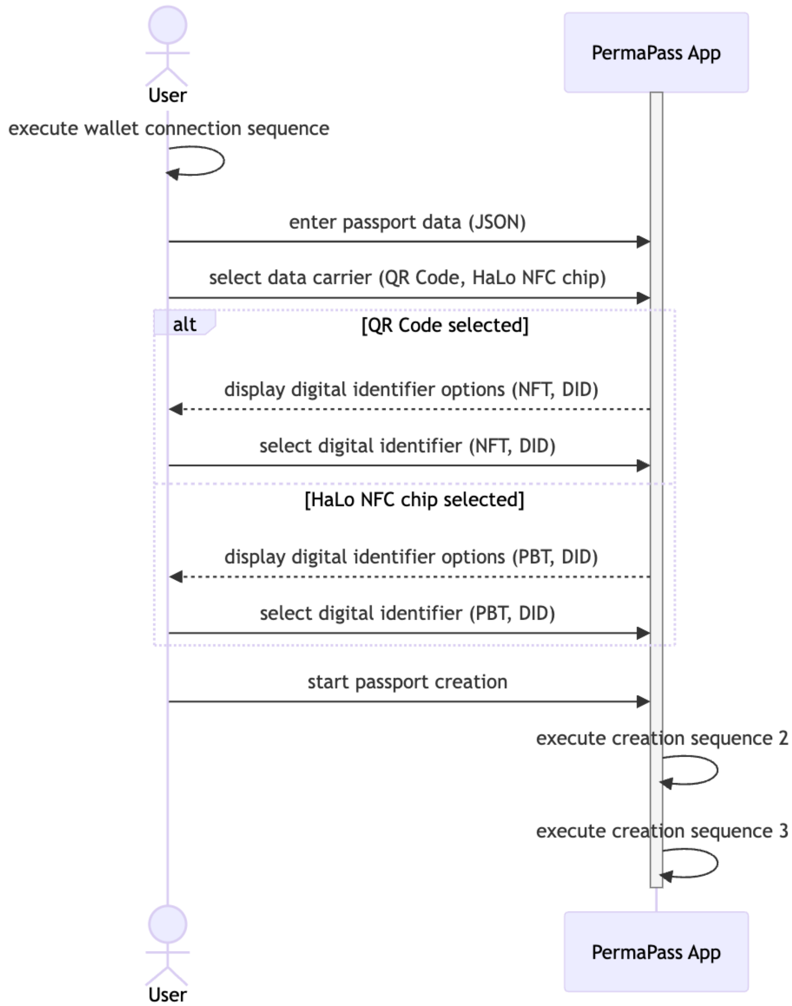


Figure A.2: Sequence Diagram of Creating a Passport (Part 1 of 3).

Source: Created by the authors.

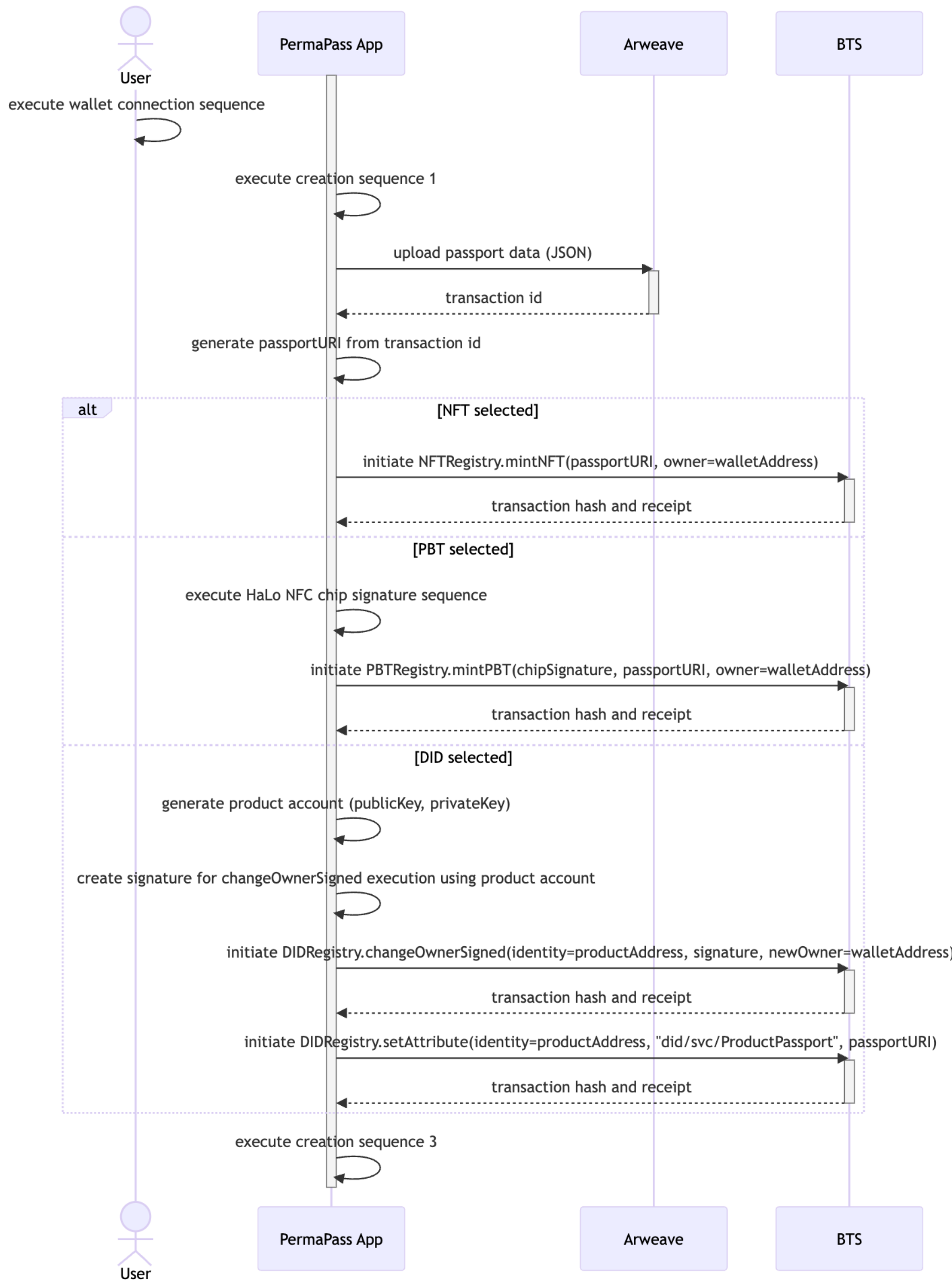


Figure A.3: Sequence Diagram of Creating a Passport (Part 2 of 3).

Source: Created by the authors.

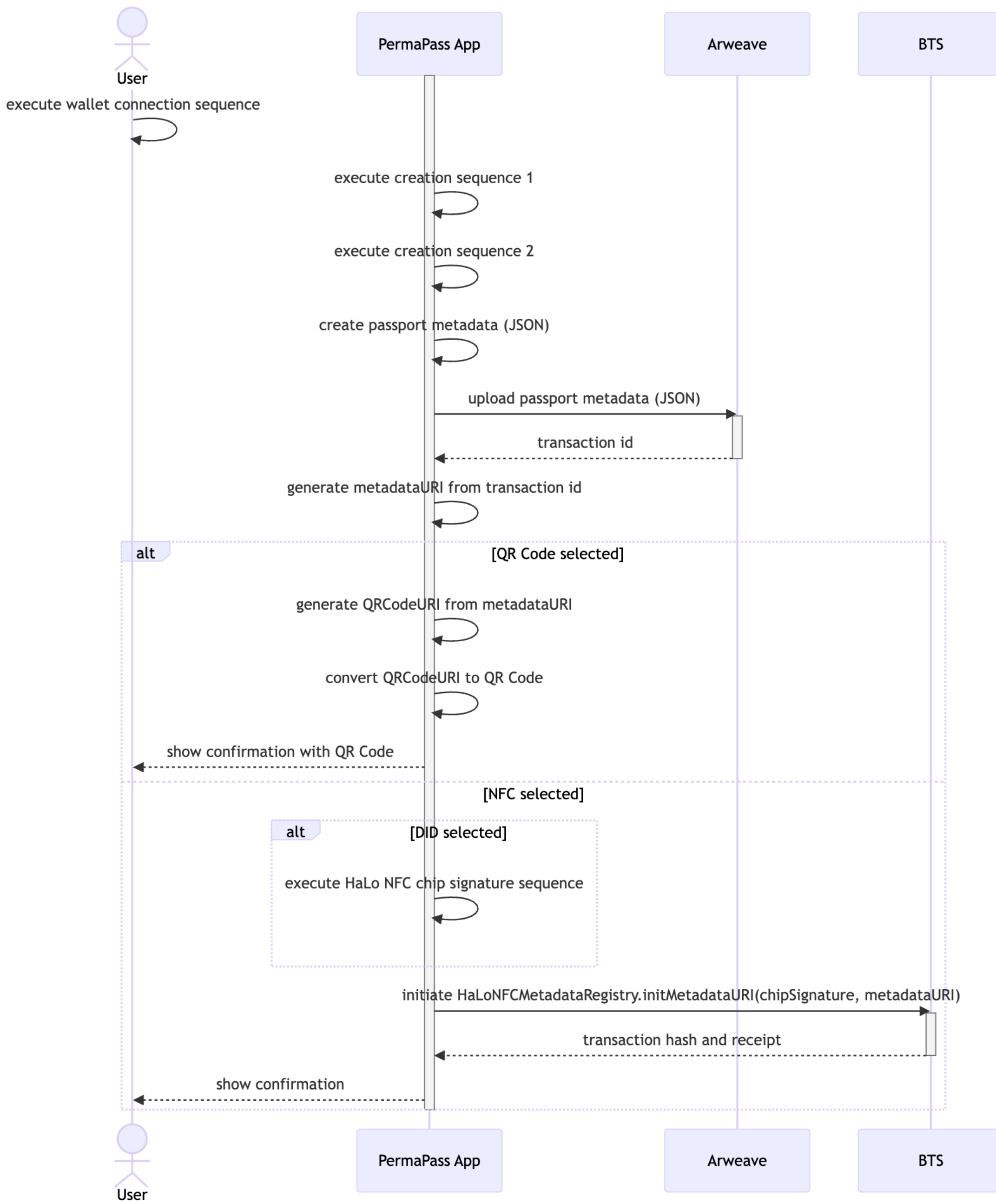


Figure A.4: Sequence Diagram of Creating a Passport (Part 3 of 3).

Source: Created by the authors.

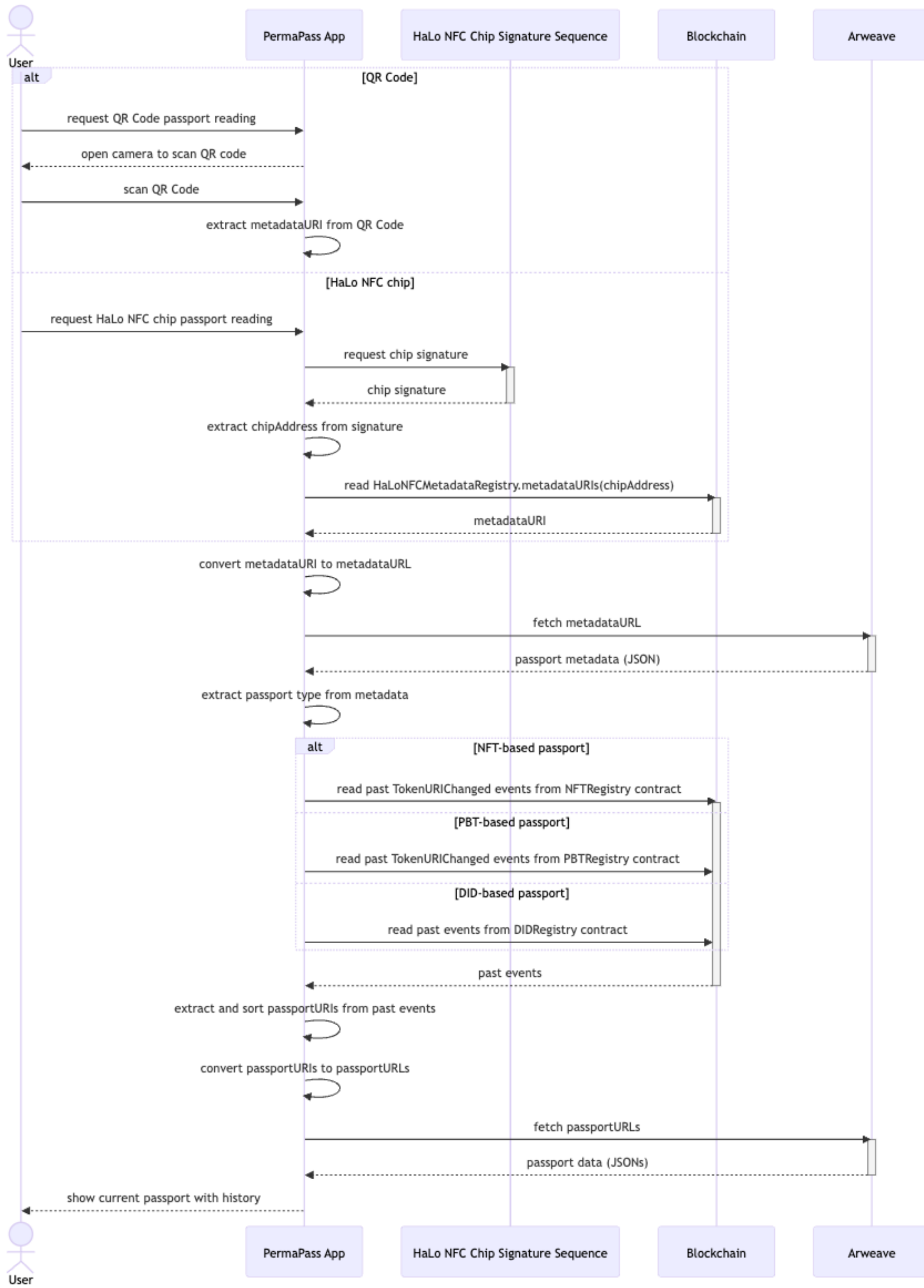


Figure A.5: Sequence Diagram of Reading a Passport.

Source: Created by the authors.

Table A.1: List of Survey Questions Issued via Survey

	Questions	Details
1	What type of company or institution do you work in?	*(Open-Ended)*
2	What is your position?	*(Open-Ended)*
3	What gender do you identify as?	*(Multiple Choice)*
4	What country or countries do you work in?	*(Open-Ended)*
5	How many years of experience do you have?	*(Open-Ended)*
6	Did you get to interact with the prototype in person, or only through video demonstration?	*(Multiple Choice)*
7	Do you see this as a relevant current problem?	*(Likert Scale)*
8	It is clear what the artifact is developed for	*(Likert Scale)*
9	How "projectable" is this problem space?	*(Likert Scale)*
10	What other problems do you think these prototypes could be useful for?	*(Open-Ended)*
11	Do you think the developed artifacts address the specific problem?	*(Likert Scale)*
12	How difficult were these prototypes to use?	*(Likert Scale)*
13.a	Which of these prototypes do you like the most?	*(Multi-Select)*
13.b	Which of these prototypes do you think is most useful?	*(Multi-Select)*
13.c	Which of these prototypes do you find easy to use?	*(Multi-Select)*
14.a	Did these prototypes sufficiently allow creating new PP?	*(Multi-Select)*
14.b	Did these prototypes sufficiently allow reading PP?	*(Multi-Select)*
14.c	Did these prototypes sufficiently allow managing read access?	*(Multi-Select)*
14.d	Did these prototypes sufficiently allow updating PP?	*(Multi-Select)*
14.e	Did these prototypes sufficiently allow deleting PP?	*(Multi-Select)*
14.f	Did these prototypes sufficiently allow reading the history?	*(Multi-Select)*
15	How accessible did you find the artifacts?	*(Likert Scale)*
16	How interoperable did you find the artifacts with legacy systems?	*(Likert Scale)*
17	How would you compare these to existing systems for product passports?	*(Open-Ended)*
18	The designed artifacts sufficiently address the stated problem	*(Likert Scale)*
19	Overall, I am satisfied with the artifact	*(Likert Scale)*
20	How "fit" would you describe the solution?	*(Likert Scale)*
21	How "confident" are you in the evaluation criteria from the previous section in assessing if the artifact addresses the stated problem?	*(Likert Scale)*
22	What other evaluations (not mentioned) should be used to assess the artifacts in this problem context?	*(Open-Ended)*
23	What other design attributes do you think are important for designing a decentralized product passport?	*(Open-Ended)*
24	Any feedback on improving the prototypes?	*(Open-Ended)*
25	Any general feedback?	*(Open-Ended)*

Source: Created by the authors.