EXPLORING TOKENIZED PRODUCT PASSPORT FOR CIRCULAR CONSTRUCTION SUPPLY CHAINS

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Abstract

A token is a cryptoeconomic entity on a blockchain that can be used to digitally secure, represent, and trade assets. Existing research does not sufficiently explore the use of tokenization as digital representations of physical construction assets within the context of circular supply chains. Thus, this research explores why tokenization for circular construction may be helpful by employing a mixed methods approach via quantitative and qualitative analysis of expert surveys and a technical review of tokens. The contribution proposes scenarios of tokenization's potential for blockchain-based product tracking and product passports for AEC.

Introduction

The built environment is facing two major transformations: a circular economy transformation and a digital transformation, and both are critical paradigms that can target enhancing sustainability (Çetin et al., 2021). Digitization for the architecture, engineering, and construction (AEC) industry is known to be slow because of general resistance to changing processes and adopting new technologies. Changing our built environment from a linear to a circular model is also inhibited by resistance to changing processes, resistance to upfront added costs, and information deficits (Byers et al., 2024).

In the built environment, implementing a circular economy primarily deals with the complexity of the supply chain. This includes the procurement and specification of materials, involving numerous participants, and the certification of material quality. Circular construction supply chain (CCSC) compared to typical construction supply chains also include connecting the materials from disassembly in one life cycle to a use case for additional life cycles as well as preserving information on the materials over time (Wijewickrama et al., 2021). Additional challenges include the presumed added costs of component reuse, though it appears this depends primarily on local regulation, culture, and precedent (Mollaei et al., 2023). Other challenges for reusing materials include product liability and the producer's responsibility for the circulation of the materials at the end of use, particularly if the original information on them is unknown (Farooque et al., 2019). Therefore, research is growing on how to track construction products over time, what information to track, and where to store it. Blockchain technology is considered useful for tracking and tracing information in supply chains and construction (Wang et al., 2020; Qian and Papadonikolaki, 2020). Though there is an overlap of tracking product information with the concept of Digital Product Passports (DPPs) European Commission (2022), there is insufficient work on their application for AEC. In particular, the use of tokenization to represent circular supply chain assets with a tokenized product passport (TPP) seems a promising concept. TPPs may help ensure data continuity and availability through multiple stakeholders and life cycles. Yet, this application is nascent and there is a gap in research and practice. Therefore, this research addresses the question: *why would tokenization be useful for product passports for a circular built environment?* The paper begins with a background on relevant concepts, states the methods used, analyzes survey responses, provides a technical review of token features, proposes resulting applications of tokens, and finally discusses existing challenges and future work.

Background

To contextualize the research objective of this work, some background is provided on product passports, blockchain tokens, and existing applications in both academia and industry.

Product Passports

Recent legislation in the EU pushes for Digital Product Passports (DPPs), which will be used to inform product supply chains and environmental impact (Çetin et al., 2023; Honic et al., 2024; European Commission, 2022). Within AEC, Material Passports (MP) are similar to DPPs and describe characteristics of materials in products regarding their constituents, recyclability, and reuse potential, which have been found to support circularity (Honic et al., 2021) and reuse (Byers and De Wolf, 2023). While MPs and building logbooks apply to the built environment, DPPs are a cross-sectoral concept shaped by the regulatory framework "setting eco-design requirements for sustainable products" of the European Commission (2022). A report from the Wuppertal Institute by Jansen et al. (2022) reviews 76 corporate, policy, and research initiatives for DPPs. Though several of these initiatives do look at buildings, many are focused on batteries, textiles, machinery, and automotive products and discuss the challenges of heterogeneous industries and stakeholders. Interestingly, nine of these implemented blockchains for immutability, transparency, and decentralization along the supply chain.

Blockchain Tokenization

Blockchain technology is a type of distributed ledger technology (DLT) that is run over a decentralized set of computer nodes and ensures secure and transparent peer-to-peer transactions without intermediaries. Blockchain's potential application for construction is well-researched (Li et al., 2019), including supply chain and lifecycle applications (Scott et al., 2021).

This paper concentrates on Ethereum, which is among the most widely used blockchains, chosen for its capabilities in handling smart contracts, offering distributed computing solutions, and having a robust developer community. Tokens can be programmed through smart contracts, which are executable code stored on the blockchain that can interact with and define transaction logic. Smart contracts are used to specify token features (e.g., destroyable, ownable, metadata, etc.), supply count, and transfer mechanisms. On a blockchain, tokens provide a critical role as a medium of exchange and a way to represent digital or real-world asset ownership. Tokens have already been integrated into various digital ecosystems (e.g., gaming, decentralized markets of digital goods, and real estate fractionalization) reshaping industries through innovative business models on new forms of ownership and transactions (Sazandrishvili, 2020).

Because tokens are produced through smart contracts and are customizable, token standards are used to ensure interoperability and secure implementation through standardized building blocks in the network. In the Ethereum ecosystem, this standardization happens through an Ethereum Request for Comment (ERC). An ERC is a proposed protocol for suggesting a new standard defining rules and specifications for tokens or smart contracts to be adopted by individual developers and projects. The most common token standards are ERC-20 and ERC-721. ERC-20 establishes a fungible token that is tradable and dividable into discretized shares. ERC-721 is a non-fungible token (NFT) that is tradeable, non-divisible, and used to represent unique values. Tokens often consist of links within the metadata to the storage of data too large to be stored on-chain as shown in Figure 1. A token, often constituted as a JSON-LD entity, combines principles of the semantic web with interoperability and is readable by both humans and machines.

The general benefits of tokenization are greater liquidity, global access, reduced intermediaries, faster transactions, increased transparency, and immutability. The associated challenges are legal, regulatory compliance and uncertainty, cybersecurity, and absence of public sector involvement (Tian et al., 2020; Sazandrishvili, 2020). This is similar to the report from McKinsey & Company that discusses the impact of tokenization including improved capital efficiency; democratization of access; operational cost savings; enhanced compliance, auditability, and transparency; and, cheaper infrastructure (Banerjee et al., 2023).

```json
"name": "DT4C2 MP NFT",
"symbol": "NFTPro",
"description": "NFT of a material passport of a truss for exchange in
the course Digital Transformation for Circular Construction at ETH",
"seller_fee_basis_points": 100,
"image": "https://www.arweave.net/
E3o1gs0MN450vaFzDJ1lgaYLvuJW-4AfyGiwyzs-rU8?ext=PNG",
"attributes": [
  {
    "trait_type": "wood truss",
    "value": "physical asset"
  },
  {
    "trait_type": "material passport",
    "value": "circular construction"
  }
],
```

Figure 1: Example of a Material Passport NFT as a JSON

Tokenization Applications

In the context of using tokens within markets, Ferrara et al. (2022) states, "tokens of digital assets are indeed defined as digital objects in which the relevant information are stored to guarantee a single, unique matching between asset and token." The work proposed two processes for using blockchain in digital markets of physical assets: tokenization and legitimacy of ownership. Additional research from Weingärtner (2019) states the advantage of tokens is they facilitate the self-sovereignty of data and proposes three types: payment tokens (currency), utility tokens (rights or services), and assets or security tokens (represents a share).

A report from the consulting firm EY discusses tokenization of real-world assets for the transparency and improved traceability and trust in the chain of ownership. (EY, 2020). Tokens can be considered software with a unique asset reference connected to properties or legal rights. The report discusses three token standards and their ideal implementation: ERC-20 for transferring value between users, ERC-1400 for transferring asset or security tokens requiring a certificate, and ERC-721 for transferring ownership of a specific asset.

A recent position paper on the value of tokens for AEC provides a slightly modified token classification noting that the applications are either economic or technical: utility (governance), security (object representation), pegged (stablecoins), and direct (payments) (Kifokeris et al., 2023). The paper provides recommendations for a classification of tokenization opportunities by thematic area (e.g., circularity), and the associated benefits, challenges, issues, and opportunities.

Tezel et al. (2021) explored blockchain implementation in construction and suggested three primary supply chain management models: project bank accounts, reverse auction-based tendering, and asset tokenization for financing (crowdfunding). Wu et al. (2023) developed a prototype of an NFT-based construction waste material passport using a design science research approach. The prototype was built using Hyperledger, a private and permissioned blockchain. Additional research overlaps the concepts of smart construction objects and blockchain oracles for recording information around the construction processes on a blockchain (Lu et al., 2021).

Within the context of AEC, tokens have often been

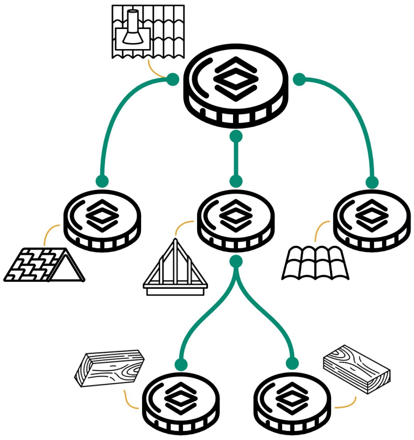

Figure 2: Visualization of Nested Token Hierarchy Representing Nested Component Assembly

proposed as an incentivization mechanism between stakeholders (Kouhizadeh et al., 2022). However, work from Dounas et al. (2021) proposed a system of organizing topology graph representation of a building as Ethereum tokens. Research from Hunhevicz et al. (2023) demonstrates a prototype of using tokens for Web3-based data access roles for material passports. Earlier work from 2019 proposes a framework for supply chain traceability based on tokenizing the bill of materials and component IDs (Dasaklis et al., 2019). Different tokens for source materials, elemental tokens, and compound tokens can be used to build up a tree structure of the data, emulating the similar hierarchy of assemblies in construction. Figure 2 symbolically represents this relationship of nested tokens for an assembly.

Boston Consulting Group and Arianee (2023) created a report on DPP tokenization that provided five main utilities: access to product information, a certificate of authenticity and ownership, a product lifecycle management tool, a customer relationship management tool, and a virtual replica of a physical object. Additionally, the three main proposed architectures are centralized DPPs, permissioned blockchain DPPs, and tokenized DPPs. Though in the short term, and for low-value products, tokenized DPP adoption is not as advantageous as other solutions, it is expected to provide much greater value in the long-term and for high-value products.

Methods

This paper is an exploratory paper on the overlap between tokenization and CCSC, therefore a mixed-methods approach was used including the exploratory data analysis of a survey of researchers and practitioners and a technical review of token features relevant to CCSC. The survey was issued to explore interest and elicit context on current challenges, perceptions, and suggestions for blockchain in CCSC. A more detailed description of the survey distribution and analysis is found in the respective section. In addition, technical standards were reviewed to better understand what features tokens can offer for product passports within AEC. Lastly, the mixed-methods approach combines the findings from each step into proposed scenario applications for tokenized product passports.

Survey on Exploring TPPs

Survey Approach and Overview

The survey distributed had 30 questions to gauge proximal knowledge on product passports for CCSC, technical requirements, and blockchain and tokenization applications. The survey was built online using Qualtrics and distributed via email through a convenience sampling of experts known by the authors with relevant experience in at least two of the three topics: sustainable construction, blockchain technologies, and circular economy. The submissions were analyzed anonymously using the language *R*. A total of 30 respondents completed the survey, though not all respondents answered every question. This paper shows the analyses of the most relevant questions for this work. The anonymized responses are a published dataset (https://doi.org/10.3929/ethz-b-000656624) and the code for the analysis can be found on github: https://github.com/cea-eth/TPP-EDA.

The format of the questions included five-point Likert-response, multi-select multiple-choice questions, and open-response questions. The open-response questions were analyzed using a natural language processing technique called latent Dirichlet allocation (LDA) for topic modeling. LDA is a generative probabilistic model for extracting similar topics over multiple documents (in this case, the documents are individual survey responses). The set of words for each extracted topic and the frequency of the topic are plotted and then interpreted by the authors for their meaning.

The respondents were asked to report in which countries they have projects. The highest reported country was Switzerland with 24% (nine responses), then the US tied with the UK with 13% (five responses), two responses in the Middle East, one response in Asia-Pacific, and the rest of the responses (n=16) were across Europe. About 40% of the respondents have 1-5 years of experience, about 23% have 5-10 years of experience, and 37% have greater than 10 years of experience. Of all the respondents, twelve work in academia, two for a government entity, and the rest within the private industry (in a combination of AEC firms, startups, and consultants).

Responses on DPP and Product Tracking

Of the 30 responses, four stated they were slightly familiar or not familiar with product passports, and two were left blank. Yet, 40% stated it is “Extremely Important” to track construction and building products over time, 40% stated it's “Very Important”, and 13% stated it's “Moderately Important”. The other two responses were blank.

Some of the questions asked were on potential issues related to data in the respondent's field and are displayed in Figure 3. The most striking results show a 100% positive

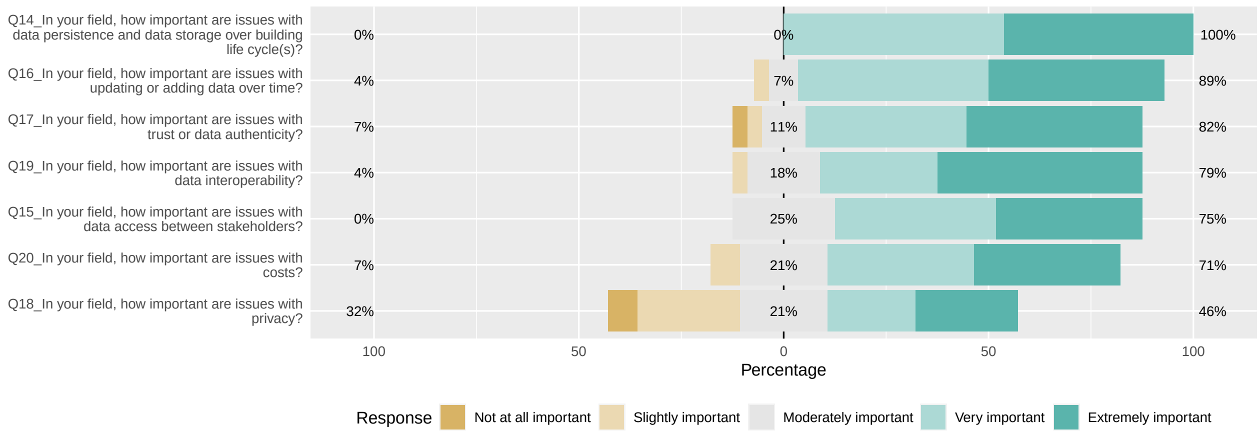

Figure 3: Responses on Importance of Issues on Data

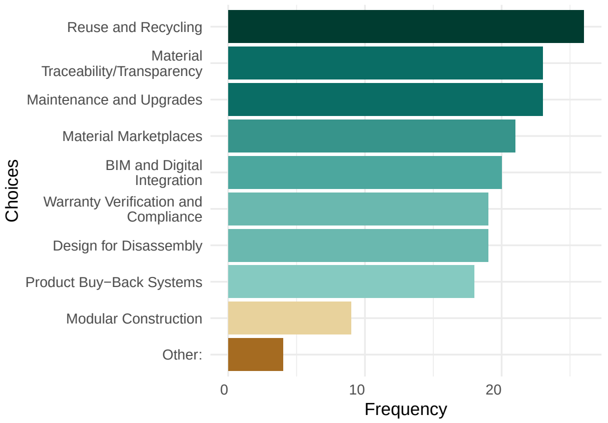

Figure 4: Responses on Ideal Use Cases for Product Passports

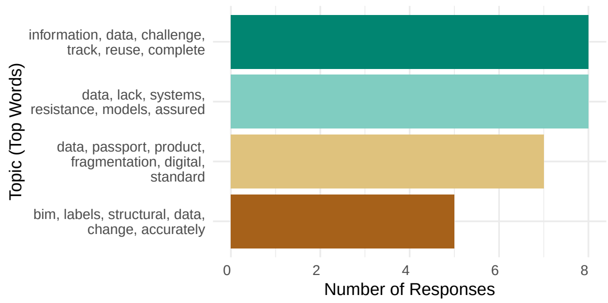

Figure 5: LDA Topics on the Challenges Inhibiting Product Passports for AEC

response for the importance of data persistence and storage over the building life cycle, and about one-third state issues with data privacy are only slightly or not important at all.

Among the various phases of the traditional product lifecycle, the three selected as having the greatest potential for implementing a product passport are B1-B3: Use, Maintenance, and Repair; B4-B5: Replacement and Refurbishment; and C1-C4: End of Life Stage. These responses are validated by another question on potential use cases for product passports shown in Figure 4.

The results from the LDA topic modeling on the problems and challenges inhibiting the use of product passports in AEC are shown in Figure 5. The y-axis shows the words in the topics produced from the model and the x-axis is their frequency found in responses. There are two topics on the challenges found eight times from the responses. The first topic is on the challenge of having complete information for tracking and reuse, the other major topic is on the resistance to data models and lack of assured data. Additional topics allude to challenges of product passport standardization and data fragmentation.

Responses on the Use of Blockchain and Tokenization

Figure 6 is a color-based correlation matrix from the Likert-based responses in the survey. The individual questions have been simplified to their topic and shown in the axes. A question has a perfect positive correlation with itself and is illustrated as dark green and a negative correlation is colored brown.

One of the questions asked the respondent how useful tokenizing product passports would be. The results from Figure 6 show that there is a slight positive correlation between tokenizing product passports and the questions asking about the applicability of blockchain and tokenization.

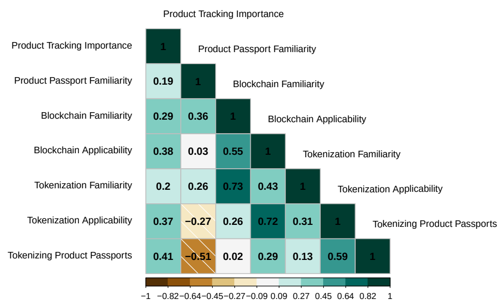

Figure 6: Correlation Matrix between Blockchain, Tokenization, Product Passports, and Product Tracking

Table 1: *Features of Tokens Relevant for Designing CCSC Systems*

Category	Token Features	Feature Description
Product Identification	Metadata Capacity	Amount of storage to hold product information
	Asset Linkage	Connecting the token to the product it represents
	Data Authenticity	Verification of unaltered product data
	Metadata Flexibility	Different types of data to be stored
Supply Chain Integration	Interoperability	Integration across platforms, actors, and file type
	Data Update Mechanism	Modifying data as the product moves or changes
	Queryable	Ease in searching for and retrieving token data
Lifecycle Management	Metadata Storage location	Considering on-chain or off-chain storage
	Composability	Combining and nesting tokens for assemblies or sub-products
Compliance & Privacy	Regulatory Compliance	Adhering to reporting regulations and other norms
	Data Privacy	Public or private chain for sensitive information
Business Proposition	Tradeability	Facilitating B2B/B2C transactions by token transfer
	Cost Efficiency	Evaluating overheads against its ROI
Product End-of-Life	Data Handling	Handling or burning of data at the end of its lifecycle
	Asset Linkage	Connecting the token to the product it represents

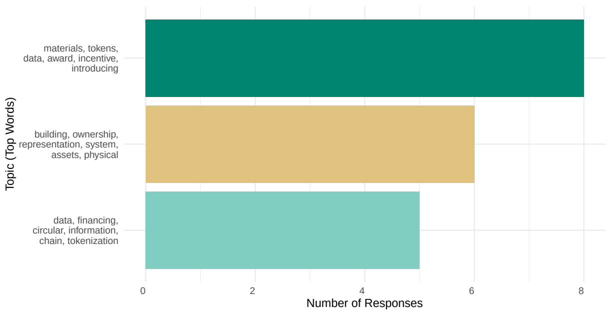

Figure 7: LDA Topics from the Potential Use Cases of Tokenization for AEC

Nevertheless, there is a slight negative correlation between the usefulness of tokenizing product passports and the familiarity level with product passports.
From the question of how might blockchain be used, the largest topic (n=13) extracted from the LDA was as the underlying technology for data transparency and tracking technology for building materials. From the question of how might tokenization be used for circular construction or circular supply chain management, only 19 responses were given as shown in Figure 7. Of those, the most frequent topic (n=8) discussed an application to introduce a system to award incentives for material information. Six responses discussed the topic of using tokens for ownership or representation of building assets. The third largest topic with five responses was on financing data for information in circular supply chains.

Review of Technical Token Features for CCSC

This section explores token standards for Ethereum and provides a table constructed from examined token standards that can be used to guide the applicability of a specific token for CCSC. Beyond ERC-20 and ERC-721, additional token standards have added functionality and potential relevance for this domain. Some are briefly listed below but this list is not exhaustive, which inspired the abstraction of token attributes from these ERC standards in Table 1.

- ERC-1155: Enables fungible and non-fungible tokens in one contract
- ERC-998: Composable NFTs that can own other NFTs and ERC-20 tokens
- ERC-6960: Dual Layer Tokens for asset classification, aiding in fractional and versatile ownership
- ERC-994: Delegated NFTs that register a geolocation of land and property
- ERC-5791: Physical-Backed Tokens representing physical item ownership and authenticity
- ERC-6551: Token-Bound Accounts are NFTs with unique Ethereum accounts for asset ownership and multi-chain application interaction
- ERC-5114: Soul-Bound Token, a non-transferable token permanently attached to a *soul* or address

Table 1 proposes features from various token standards that are relevant for applications to CCSC. The categories of token features should be considered by stakeholders interested in designing and implementing token-based systems. A similar classification approach was previously conducted on designing blockchain oracles for AEC (Dounas et al., 2023).

Resulting Scenarios

This section offers detailed scenarios for tokenized product passports, derived from a mixed-methods approach. The approach is a result from the analysis of token features, the review of relevant literature, and insights from the survey on blockchain's utility and use cases for CCSC. Tokens have broadly been shown to be used for asset representation, payment and incentive systems, or utilitarian and governance systems as defined in Kifokeris et al. (2023); Weingärtner (2019); Boston Consulting Group and Arianee (2023). The proposed scenarios examine the potential utility of tokens in CCSC by focusing on how tokens can serve as a means for representing objects. Proposing payment, incentive, or governance systems, although expressed from the survey results in Figure 7, is beyond the interest of this study.

These scenarios are not direct responses from the questionnaire but a synthesis of all results. Additionally, some token features are universally relevant for CCSC applications including Asset Linkage, Metadata Storage Location, Cost Efficiency, Data Authenticity, Composability, and Metadata Capacity.

Scenario 1) *Tokenize the Material DPP*: Drawing from industry proposals and the results from the survey, this scenario proposes a TPP system where each token acts as a representation for the DPP of the construction assets. The TPP can be connected directly to tracking hardware installed into the asset and used for streamlining compliance and transparency along the supply chain. Tokens could serve to create a unique digital identity for the provenance of each component, similar to Wu et al. (2023); Boston Consulting Group and Arianee (2023). According to DPP regulation, these tokens could facilitate accurate tracking and verification of the origin, composition, and recycling credentials of materials, which is essential for the integrity of a circular supply chain. Specific token features from Table 1 include: Regulatory Compliance, Queryable, and Interoperability.

Scenario 2) *Tokenize the Material Asset*: In this scenario, an asset tokenization platform for the CCSC can be developed for tokenizing the asset and supported by the results shown in Figure 7. Tokenizing a real-world asset reflects ownership within the real world and economic markets. Tokenized assets could allow the transparent traceability and management of material (EY, 2020) as well as their physical relationship to other materials (Dasaklis et al., 2019). An example of a preliminary implementation of this scenario and its integration with building modeling is proposed by Dounas et al. (2021). The token features from Table 1 important for this architecture include Tradeability, Metadata Flexibility, and Interoperability.

Scenario 3) *Tokenize the Material Ownership*: While the first scenario tokenizes the material information, the second scenario tokenizes the asset, and this third scenario utilizes tokens as a security for the ownership of the asset. This token security is a subset of asset tokenization that uses tokens to represent its value contractually, which can be reflected along the CCSC, particularly for material exchange, leasing, or purchasing in decentralized marketplaces (Hunhevicz et al., 2023; Ferrara et al., 2022). Though similar to the other scenarios, the financial and business considerations are more of an emphasis EY (2020); Boston Consulting Group and Arianee (2023). Using tokens as a mechanism for material asset securities also introduces new sustainable finance mechanisms for investing in circular economy solutions. Because of the legal and financial implications, the specific token features in the scenario include Regulatory Compliance, Tradeability, and Data Privacy from Table 1.

Discussion

One of the most interesting results from the survey is found in Figure 6, which shows a negative correlation between familiarity with product passports and the utility of tokenizing product passports. This implies either that those very familiar with product passports do not think there is much utility with TPPs, or that those who think there is high utility with TPP aren't very familiar with product passports. Nevertheless, there is a stronger positive correlation between TPP utility and those who believe tokenization has high potential for CCSC. These results align with Figure 7, where the most frequently mentioned topic was using tokens as incentives, not as representations of the asset itself. Although this supports the *direct* and *utility* cases found in Kifokeris et al. (2023), those cases are out of scope as this paper focuses on the *object representation* case.

Storing product passports on-chain ensures their accessibility and permanence for any stakeholder through time. This approach secures the data and also potentially enables new ecosystem interactions, such as unique wallets assigned to physical assets and the possibility for tokens to be held by non-human entities. The proposed scenarios for token usage are directional but grounded in existing research and survey findings. They require further development and verification through technical implementation and stakeholder engagement. Although this research primarily examines tokens on the Ethereum blockchain, other blockchains also employ tokens, which could be leveraged for DPP applications.

Challenges and Limitations

Blockchain in construction, in addition to product life cycle tracking, is a cyber-physical-social systems problem. To abate this challenge, the researched scenarios should be able to integrate first with existing systems for business-as-usual. Thus the use of a common data format and metadata schema is critical. Additionally, linking data in tokens to external servers is often critiqued because of the challenges associated with the maintenance of hosting externally.

This study is limited by not yet testing implementations of the proposed scenarios. For the survey, the respondents primarily work across Europe, with some in the UK and the US. Responses may vary based on geographical region. There is a natural selection bias from the method of approaching the respondents and cannot be taken as a generalizable state of knowledge. There are inherent limitations to using a questionnaire as it is more likely respondents will provide brief or no answers at all. The use of more exhaustive methods, like interviews or the Delphi method, may produce more informed responses.

Given the heterogeneity of experiences of the survey respondents, a deeper statistical analysis can be used for analyzing results. For instance, the results can be partitioned and analyzed separately based on the categories of responses (e.g., familiarity level with product passports, familiarity level with tokenization, or country of work).

Future Work

The survey included additional open-ended questions that were not covered in this study. Additional work can explore these other inputs from the respondents on hardware approaches, ideal stakeholders, and challenges and use cases. A few of the respondents noted the importance of analyzing the value-add of tokenizing product passports and an understanding of the environmental tradeoffs. These are valid concerns and though they are out of the scope of this study, stand as points for future work.

This work sets the exploratory and theoretical underpinning for future hypothesis development and research on qualitative implementation and quantitative testing of these new processes. Future efforts by the researchers will address the *how-to* for technical implementation and aim to quantify impacts. Further work will use a design science research approach for an exploration of TPP in a real building. The survey findings in this study will inform the goals and design of such a system.

Conclusions

This research investigated the application of tokenization for product passports in CCSC. The authors employ a mixed methods approach via a technical review and survey of experts to frame the potential value of tokenization in circular construction. The results extend the understanding of blockchain-based product tracking for AEC by focusing on the potential of using tokens for object representation of a product passport.

The academic literature confirmed general interest in blockchain and tokenization for product tracking, although with limited CCSC applications tested. Survey results supported the need for product tracking and blockchain for data transparency, while also noting challenges such as data gaps and system integration. Features extracted from various Ethereum tokens were explored for their potential relevance for product passports. Lastly, these results were combined for three proposed scenarios of tokenization within the CCSC: tokenizing the material DPP, tokenizing the material asset, and tokenizing the material ownership. Future research intends to expand upon this theoretical foundation by testing the specified scenarios. This study's findings suggest that tokens could serve as a comprehensive information repository, providing innovative application possibilities for CCSC.

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