Human-Centric Digital Product Passports: Enabling Verifiable Information Sharing for Sustainable Consumption through Wallet-Based Identity Management and Zero-Knowledge Proofs

Matthias Babel
Branch Business and Information Systems Engineering of Fraunhofer FIT
matthias.babel@fit.fraunhofer.de

Claus Guthmann
University of Bayreuth
claus.guthmann@uni-bayreuth.de

Marc-Fabian Körner
FIM Research Center, University of Bayreuth
marc.koerner@fim-rc.de

Tobias Kranz
Branch Business and Information Systems Engineering of Fraunhofer FIT
tobias.kranz@fit.fraunhofer.de

Jens Strüker
Branch Business and Information Systems Engineering of Fraunhofer FIT, FIM Research Center, University of Bayreuth
jens.strueker@fit.fraunhofer.de

Abstract

Empowering end consumers with transparent product-related information is seen as a promising way to drive sustainable consumption choices and counter the global sustainability challenges. To foster this endeavor, Digital Product Passports (DPPs) are a potential solution to share product-specific data across supply chains, aiding informed consumer decisions and supporting sustainability. However, DPPs often involve the collection of sensitive information about supply chain actors and their processes. Hence, this paper aims to develop a DPP prototype that provides end-consumers with increased and verified information. We utilize wallet-based identities, non-fungible tokens (NFTs), and zero-knowledge-proofs (ZKPs) to design a DPP for the textile industry that facilitates the transfer of verifiable information, lowering information asymmetries between humans and organizations and equips value-chain stakeholders with a means to verifiably share data. Our study seeks to bridge the design gap for a human-centric DPP infrastructure in IS literature by developing a sample infrastructure.

Keywords: Digital Product Passport, Non-fungible Token, Zero-knowledge-proof, Sustainable Economy, Wallet-based Identity Management

1. Introduction

In the context of escalating global environmental challenges, there is a compelling need for both individuals and organizations to counter resource scarcity and increase efforts toward saving and protecting natural resources and pursuing responsible production and consumption practices to foster the development of a sustainable economy (UN, 2021). Thus, it becomes indispensable to have an unambiguous picture of the environmental impact of products and services to advance the supply and demand of sustainable goods and services and leverage their sustainable production (Heeß et al., 2024; Jensen et al., 2023). Therein, the empowerment of end consumers to make informed consumption and usage decisions in a system that primarily serves organizational relations plays a pivotal role in fueling the sustainable transition of the economy (Guillen et al., 2021.

Currently, organizations and consumers often lack access to adequate and reliable information regarding a product's environmental footprint and production process. Even when information is accessible, its credibility is often questionable due to the deceptive practices (e.g., greenwashing) of individual supply chain actors. This lack of reliable information is most evident at the stage of end-consumers, highlighting the prevalent information asymmetry between consumers and supply chain actors. At the first stage, organizations often lack detailed and reliable information on their production processes and a product's lifecycle. Second, because of reservations regarding data protection, only limited information about a product is communicated to the end consumer, exacerbating the information asymmetry between supply chain actors and individuals. However, empowering individuals with detailed and verified product-related information to make profound consumption decisions may have a significant potential to influence markets and drive organizations toward adopting more sustainable

URI: https://hdl.handle.net/10125/109373
978-0-9981331-8-8

practices and products (Plank & Teichmann, 2018). Leveraging the role of individuals requires a sound and reliable system that enables organizations and consumers to interact with each other equally, ensuring that consumers do not have to rely solely on the goodwill of organizations for the reliability and verifiability of the information provided.

The global digital transformation addresses this need by enabling the development of human-centric and end-user-empowering information systems (IS) as a cornerstone of a digital sustainable economy (Human et al., 2022; Kotlarsky et al., 2023). Therein, Digital Product Passports (DPPs) (European Commission, 2022; Götz et al., 2022) may serve as a common carrier of information throughout a supply chain, increasing the amount and quality of information organizations are willing to attach to a physical good (Gelhaar & Otto, 2020) and providing it to end-consumers. As such, DPPs may enable organizations that follow environmentally friendly practices to provide end-consumers with increased information on their product and production processes to facilitate more sustainable consumption decisions (Heeß et al., 2024; Munaro & Tavares, 2021).

Initial practical (e.g., Atma IO by Avery Dennison, SA Fluxy One, Spherity GmbH) and theoretical (e.g., Adisorn et al., 2021; Berger et al., 2022; Heeß et al., 2024) approaches for DPPs that leverage the capturing and sharing of product and sustainability data among supply chains actors already exist. However, one of the most significant challenges still revolves around the willingness of organizations to share product and process-related data, which may result from the fear of later uncontrollable spreading of supply chain-related data (Gelhaar & Otto, 2020; Scheider et al., 2023). When addressing this challenge and lowering the data asymmetry between organizations and end-consumers, it becomes indispensable to consider two angles within the design of a DPP infrastructure. First, empowering sustainable consumption decisions of end-consumers through a human-centric IS architecture for a DPP. Second, ensuring the protection and verifiability of the forwarded data (Heeß et al., 2024; Jansen et al., 2023; Jensen et al., 2023).

Following most recent theoretical concepts of DPPs, an effective response to handle the challenge of storing, attaching, and forwarding verifiable product-related data to end consumers may lie in developing an infrastructure that builds on cryptographic components to ensure an unambiguous assignment of information to a product and that facilitates their transfer along a supply chain (Babel et al., 2022; Gelhaar & Otto, 2020; Heeß et al., 2024). Against this background, this paper aims to develop a prototype of a human-centric infrastructure for DPP that facilitates the sharing and processing of verifiable data among the stakeholders of a product-value chain to improve the information basis on the end-consumer level. More specifically, we strive to demonstrate how technological concepts can be utilized to ensure that data, once reliably gathered, can be processed throughout a value chain in a digitally verifiable manner while lowering the tension between data availability and protection. The delicate information asymmetry between individuals and organizations along a value chain and the impulse for human-centric technological solutions for increasing sustainability form the core of our discussion. While we acknowledge the valuable contributions of prior research, this study reaches out to answer the following research question (RQ):

RQ: *How to design a technical infrastructure for DPPs that empowers end-consumers to make profound sustainable consumption decisions?*

In doing so, we seek to offer practical insights on designing a human-centric DPP infrastructure based on decentralized digital Web3 technologies by implementing essential parts of the DPP for a textile product. We focus on technological solutions such as wallet-based identity management systems, non-fungible tokens (NFTs) (i.e., unique assets residing on a Distributed ledger), and zero-knowledge-proofs (ZKPs) (i.e., a cryptographic method that allows to prove knowledge of a fact without revealing the fact itself) that enable data verifiability and privacy. Our research objective is to bridge the identified gap in IS literature, following the call of Heeß et al. (2023), and answering our RQ by developing, implementing, and evaluating a prototype for a human-centric DPP infrastructure. This paper builds upon existing knowledge on the design and implementation of DPPs (Heeß et al., 2024; Scheider et al., 2023) and solutions for end-to-end verifiable data processing (e.g., Babel et al., 2022) but to the best of our knowledge, is the first to propose a concept for a human-centric DPP infrastructure.

Against the previously described background, we intend to make the following primary contributions: (1) Implement a human-centric technological concept for a DPP infrastructure that leverages the transfer of verifiable product-related data to end consumers. (2) Provide insights into the applicability of the proposed infrastructure through a sound evaluation. The remainder of this article is organized as follows: In the next section, we give an overview of the "Background and related literature.” Further, we describe our research methodology in the section “Method” and present our results – the prototype of a DPP infrastructure – in the section “Results”. Afterward, in the “Discussion and Contribution” section, we examine the results and elaborate on the contribution, limitations, and potential for future research. Last, we complete our research with the section “Conclusion”.

2. Background and related literature

DPPs as enabler of a digital sustainable economy

DPPs are intended to convey detailed product-related data throughout a product's value chain. The objective therein is to unveil a product’s lifecycle transparently, make the information accessible to participating stakeholders, and empower end-consumers to make well-informed purchasing decisions considering the materials used in a product and the embodied environmental impact (Götz et al., 2022; Heeß et al., 2024). DPPs are increasingly posited as the primary source of data and information by functioning as mechanisms for documenting elements of sustainability (Adisorn et al., 2021; Götz et al., 2022), thereby facilitating the development of sustainable supply chains and a circular economy (Berger et al., 2022; Götz et al., 2022). Current research projects such as CIRPASS already explore the practical applicability of DPP within different industries such as electronics, batteries and textiles (CIRPASS, 2024).

However, when defining design criteria for DPPs (e.g., Heeß et al. (2024); Jansen et al. (2023)), current research is not yet expanding beyond theoretical frameworks and delving into the development of an applicable solution for a DPP. Thus, in this work, we intend to build a DPP based on wallet-based identity systems and advanced cryptographic approaches to keep data sharing between the actors at a minimum. Wallet-based identity systems, and digital identities in general, are fundamental pillars of data ecosystems. They play a crucial role in the development and industry-wide implementation of DPPs. These identity systems ensure secure and verifiable digital identities, which are essential for establishing trust and verifiability in data exchanges across supply chains. By leveraging concepts such as NFTs, wallet-based identity systems can enhance the reliability of DPPs. Therefore, understanding the significance of wallet-based identities and their integration with decentralized technologies is critical for appreciating their impact on the success of DPPs.

Decentralized Technologies as the foundation of DPPs

DPPs often comprise verifiable, attested attributes about products. Consequently, DPPs necessitate a digital and verifiable carrier to maintain these attributes throughout the product's value chain, ensuring that the initial issuer retains control until the product advances to the next production stage. Our current non-wholistic market perspective unveils that approaches for DPPs are mostly designed for B2B markets, neglecting the end-consumer perspective. Moreover, initial solutions already make use of Web3 technologies, such as Distributed Ledger Technologies (DLT), to build the infrastructure for DPPs. Therein, we see the potential to leverage these technologies further to improve the B2C relation of DPP infrastructures. Wallet-based identity management systems appear to be a suitable medium for facilitating the verifiable representation of this information. In such systems, trusted parties issue verifiable credentials (VCs) – signed digital certificates attesting to specific attributes – to holders. These holders then present the VCs to verifiers in a self-sovereign manner (Jørgensen & Beck, 2022; Wang & Filippi, 2020). This method grants holders control over their data while enabling verifiers to efficiently receive machine-verifiable data.

However, VCs are typically designed to remain with a single dedicated holder, with cryptographic mechanisms binding these credentials to their holders to prevent fraud and unauthorized sharing (Wang & Filippi, 2020). As products change ownership, the associated DPPs must also be transferred, presenting challenges to the identity management systems' ownership control mechanisms. Traditionally, a central intermediary or trusted issuer would manage these ownership changes throughout the product's lifecycle. However, revoking and reissuing certificates with each ownership change is impractical and centralizes knowledge of ownership transfers with the initial issuer. This is undesirable in a system that aims to facilitate the transfer of information to the final entity in the supply chain (Sunyaev et al., 2021), DLTs apply consensus mechanisms in a decentralized network to prevent double spending of token. Therefore, NFTs can manage ownership relationships for things such as digital art and verifiable credentials – or explicit DPPs – by linking a unique identifier of the DPP to the NFT. Consequently, when facilitating VCs for DPPs, ownership transfer could be directly manageable by their current owners while preventing double spending of DPPs. This approach not only links DPPs to their associated physical goods – despite the challenge of unique identification – but also helps prevent fraud by connecting DPPs to their owners.

Moreover, NFTs enable ownership management without disclosing extensive information about the asset (Ethereum, 2021). In addition to product lifecycle information, ownership transfer information must also be protected from fraudulent actions when transferring a DPP. The concept of integrating Zero-Knowledge Proofs (ZKPs) on blockchains to receive shielded tokens has already emerged for fungible tokens (e.g., ZCash) (Ben-Sasson et al., 2014) and is also applicable to shielded NFTs (EY, 2024), and their extension to shielded fractional NFTs (SFNFTs), which allow fractional ownership of shielded NFTs (Babel et al., 2022;). Thus, applying ZKPs to NFTs allows ownership transfers to be hidden from the public ledger, enhancing the privacy of the involved stakeholders (i.e., supply chain actors).

SFNFTs achieve this level of privacy protection by using Merkle trees, created through recursive pairwise hashing of objects into a tree structure (Merkle, 1988). The leaves of the tree represent the SFNFT ownership relationships. When ownership changes, a new ownership relation is added as a new leaf, and the old one is invalidated by adding a deterministically derived ID to a "nullifier" list. To propose a new ownership relationship, the owner submits a ZKP proving the existence of a valid, non-nullified ownership relationship in the tree by providing the deterministic ID for the old relationship, verifiable against the nullifier list. The owner also proposes a new leaf for the tree containing the new ownership relation (Ben-Sasson et al., 2014). Thus, ZKPs ensure the validity of all information involved, proving a statement's truth without revealing additional information (Babel et al., 2022). This aspect is particularly relevant when aiming for the transfer of information with a DPP along multiple independent stakeholders in a product chain.

The Merkle root or the entire tree (excluding the pre-images of the leaves) can be publicly available on a distributed ledger. Since ZKPs ensure full disclosure of ownership transfer information and DPPs are bilaterally transferred, no further privacy protection for the transactions is necessary (Babel et al., 2022). Given the foremost conceptual development of DPPs based on decentralized technologies, selecting an operator without a DLT for implementing shielded SFNFTs as DPPs may be a practical initial approach. In this scenario, a trusted party (TP) would be required to ensure the verifiability and correctness of the processed information. Considering the current nascent state of DPP infrastructures and the low adoption of DLTs as market infrastructure, installing a TP and ensuring the verifiability of the transferred data through a VC infrastructure seems to be the most suitable option for our endeavor. The SFNFTs facilitate the transfer of the holder's ownership relation of VCs while protecting the privacy of individual stakeholders, protecting their information from being accessible to third parties outside the value chain. Thus, this approach facilitates the development of a human-centric DPP infrastructure.

3. Method

Initially, we identify the need in current research for practical implementations of DPPs (Heeß et al., 2024; Jansen et al., 2023) that facilitate verifiable data sharing as a fundamental pillar to provide a comprehensive information base on a product's footprint on end-consumer level (Step I). Hence, in the underlying work, we develop a DPP infrastructure utilizing the concept of SFNFTs (Babel et al., 2022) to ensure the verifiable transfer of data. We thereby follow a problem-centered multi-step approach aligned with the design science paradigm (March & Smith, 1995) and the sequential iterative design approach of Hevner et al. (2004) (cf. figure 1). In Step II, we screen current IS literature on DPPs to ensure our approach acknowledges the design requirements of current research on DPPs. For our research, we use the following databases: Web of Science, AIS eLibrary, IEEE Xplore, and Science Direct. We limit the results of our screening to papers published from 2014 to the present to reflect the fast development of this research area. In Step III, we analyze the current literature on DPP and recognize the lack of information sharing between organizations and consumers and the resulting information asymmetry between end-consumers and organizations as the primary driver for DPP development. This aligns with current research on creating a digital sustainable economy (Human et al., 2022; Kotlarsky et al., 2023), highlighting the need for verifiable data sharing as DPP design specification (Heeß et al., 2024; Jansen et al., 2023). Given the pressing need to facilitate data sharing and enhance information availability at the end-consumer level, we established the following design objective (DO): *Develop an IS artifact for a DPP that enables the verifiable transfer of data to reduce information asymmetry for end-consumers with the aim to enable sustainable and informed purchasing decisions*. In Step IV, we develop the prototype of our DPP based on the concept of SFNFTs (Babel et al., 2022) and wallet-based identities, allowing end-to-end verifiability of processed data and ensuring data protection through a privacy-by-design approach (see section 4). Although the technological concept is industry-agnostic, we implement a DPP for the textile industry to demonstrate its applicability.

The textile industry's growth has led to overproduction and fast fashion, worsening environmental and social issues, while affordable means to increase the sustainability of their products remain limited for individual stakeholders (World Economic Forum, 2023). The EU is already addressing this issue with proceedings within sustainable and circular textiles and a draft of a DPP for the textile sector (European Commission, 2022). Therefore, the textile industry and the need on the producer and consumer side for more transparency is a valid starting point to implement our concept of a DPP.

We evaluate the prototype in Step V. Therefore, we follow the FEDS framework by Venable et al. (2016) for design research, opting for a quick and simple strategy. We conduct benchmarking tests on the basic NFT operations to demonstrate the real-world applicability and efficiency of the developed DPP. The results from these tests are used to refine the technological concept further and discuss the implications of the results, laying a foundation for future research.

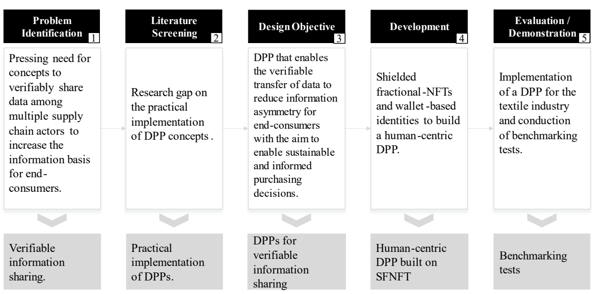

Figure 1. Design science research-oriented approach (based on Hevner et al. 2004)

4. Results

In the following section, we present the prototype of our human-centric DPP infrastructure. To demonstrate the applicability of our developed artifact, we implement the DPP for a shirt. Against this background, figure 2 depicts one of our findings, namely the value chain of the shirt aligned with the VC and SFNFT flow to transmit the product-related data to the end consumer in a verifiable way.

Our results illustrate how product-related information adds up by chaining multiple VCs initially issued by trusted parties (TPs) and transferred at each production stage change through SFNFTs managing ownership and preventing double spending of the DPPs. We propose to connect the DPP with the owner of the finished good instead of the parts of the good itself, as this might not be feasible since the unique identification of the components of the physical good is challenging. Within the scope of our proposed solution, we consider product-related information, as we assume organizational information to be kept private under data protection regulations. We find that due to the complexity of accessing external data in a reliable manner (i.e., oracle problem) (Caldarelli 2020) that, a TP can ensure the integrity and verifiability of the product-related data by issuing VCs at each production stage. Simultaneously, our results illustrate an IS architecture that empowers end customers to participate equally with companies in the supply chain.

The first production stage (**stage I**), *the extraction of raw materials*, involves obtaining the materials needed to produce the shirt. Since cotton is commonly used, this phase includes growing cotton plants and harvesting their fibers (see figure 2). At this stage, our prototype installs a TP that creates a new DPP by issuing a new VC that stores additional information on the country of origin and the environmental impact of the cotton on the cotton-producing company (C1). Simultaneously, the TP mints a SFNFT on the ledger linked to the issued VC claiming the quantity of produced cotton to the ownership of C1. C1 stores the cotton-VC and the cotton-SFNFT in its private wallet. We highlight that a cotton-SFNFT and its fractions can only map ownership for a dedicated cotton-VC. Figure 3 depicts the detailed flow of NFTs and VCs throughout the exemplary supply chain (cf. figure 3).

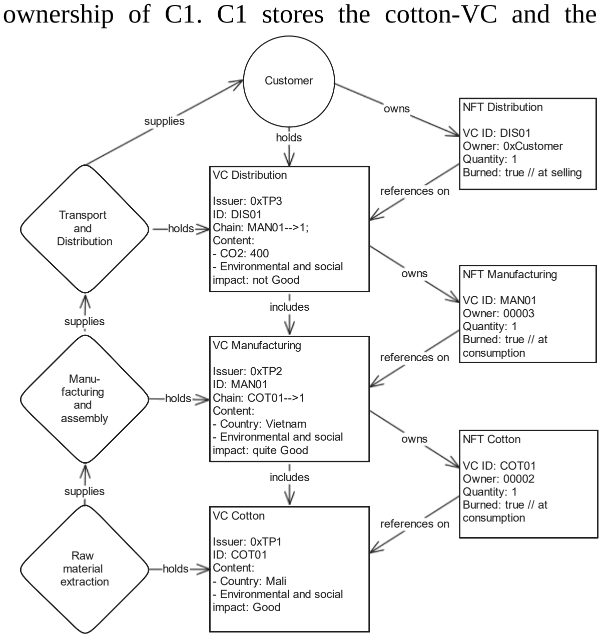

Figure 2. Flow of product-related data through NFTs and VCs (own illustration)

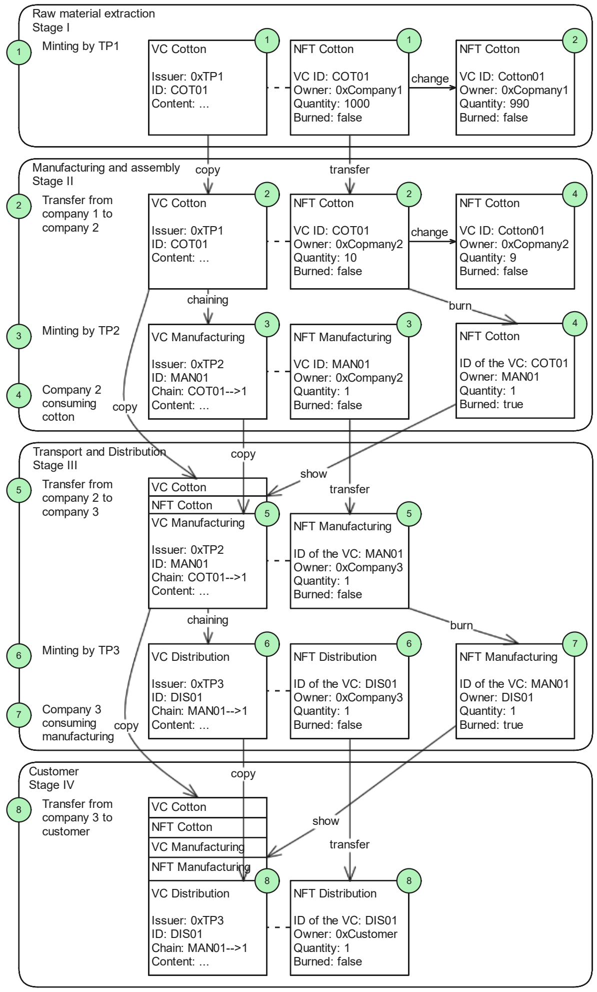

Figure 3. Detailed flow of NFTs and VCs (own illustration)

In **stage II**, the shirt's *manufacturing and assembly*, the extracted materials are processed and converted into fabric. The cotton fibers are spun into yarn, which is subsequently woven or knitted to produce the fabric for the shirt. This fabric is then cut and sewn together to form the shirt shape. The company manufacturing the shirt (C2) receives cotton for production from C1. Accordingly, C1 transfers the DPP for the cotton by sending the cotton-VC and transferring the corresponding amount as fractionalized cotton- SFNFT to C2. At this stage, TP2 issues the manufacturing-VC and mints the corresponding manufacturing-SFNFT for the produced shirt to C2. This DPP contains information about the production site and its environmental and social impact. To avoid double spending and ensure the verifiability of the shirt's DPP, TP2 ensures that C2 chains the shirt's corresponding fraction of the cotton-DPP to its manufacturing DPP by transferring the ownership of the fractional cotton-SFNFT to the manufacturing-VC using a unique identifier. Analogously to the physical share of cotton used for the shirt production that cannot be used again, our results propose that the digital representation (i.e., the SFNFT) gets burned, thus becoming unusable for a second time use.

Once the shirt is manufactured, it reaches **stage III** the *transport and distribution* stage. This phase involves shipping the shirt from the factory to the distribution center, retail stores, or customers. Transportation methods such as trucks, ships, or airplanes are commonly used to move the shirts and must be considered within their environmental and social impact. Our solution proposes that C2 transfers the DPP containing: the cotton-VC, the burned cotton-SFNFT, the manufacturing-VC, and the manufacturing-SFNFT to the distribution company (C3). When distributing the shirt, a TP3 chains the DPP from C2 to the newly created one.

The fourth and final stage (**stage IV**) of the supply chain commences when the consumer purchases and begins wearing the shirt. The end-consumer receives the shirt, and the DPP is represented through three VCs chained by three SFNFT of the value chain from C3 to the final end-consumer, see figure 2. The consumers not only hold the physical good but also have verifiable information on the production circumstances and environmental and social impact of the shirt in their ownership (SFNFT) and possession (VC) on their private wallet. In the same way, the data was managed by the previous supply chain actors.

We find that through the implementation of a sample DPP transfer our solution is applicable in terms of performance, evaluated through benchmarking tests. Our implementation is written in Rust, leveraging the Arkworks framework[1] to prove circuits programmed in Circom (Muñoz-Tapia et al., 2022). To enhance the performance of witness generation, we use the witnesscalc C++ library[2]. We utilize the Poseidon hash function for signature and Merkle tree hash functions, which perform exceptionally well in ZKPs (Lorenzo Grassi et al., 2021). The source code is publicly available on GitHub[3]. The client, acting as the NFT owner, is using an Intel(R) Core (TM) i5-6600 4 Core with 16GB of RAM, and the server, that is the ledger authority, is using an AMD EPYC 7742 16 of 64-Core

[1] https://arkworks.rs/
[2] https://github.com/0xPolygonID/witnesscalc/tree/main
[3] https://github.com/matthiasbabel/Human-Centric-Digital-Product-Passports

Processor with 16GB of RAM. The evaluations were performed with a Merkle Tree depth of 20 and a trust list size of 1,024, resulting in 1,048,576 ownership entries per tree, ensuring sufficient herd privacy (Babel et al., 2022). The benchmarking of our prototype reveals several key performance metrics and optimization opportunities. The client runtime for all NFT actions is primarily influenced by ZKP generation, with constraints increasing linearly with the depth of the tree. Still, the workload is small enough to be computed on mobile devices, maintaining a runtime of under 500ms for witness and proof generation. The ZKPs remained efficient even for a depth of 27 (supporting 100 million elements), staying under 20,000 constraints.

For the ledger, we observe that registering, minting, transferring, and burning operations are dominated by ZKP verification, which maintains a constant time of about 3ms. Verifying the nullifier, ZKP outputs, and saving the updates combined takes less than 10µs. Figure 4 depicts the time required for an update relative to the size of the batches. By updating entire batches instead of single units, we significantly enhance the efficiency of our system, with an approximate time of 53ms plus 6ms per additional hundred units (cf. figure 4). The primary bottleneck in our tests was the server-side setup, particularly, the generation of the initial Merkle tree was limited by the RAM size.

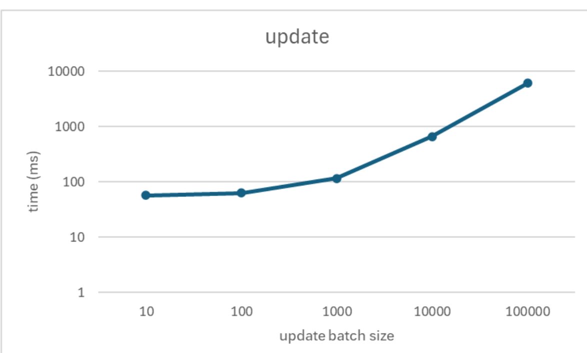

Figure 4. Performance of batched updates.

In sum, our benchmarks highlight that the DPP system is highly efficient and suitable for being utilized as a data storage and transmission system of data from an extensive supply chain to the end-consumer. While we were limited by the server's RAM, all other metrics indicate that scaling the tree depth well beyond 27 is only constrained by the initial setup’s memory requirements. Nevertheless, further optimization is necessary to scale the DPP system for more complex supply chains. Thus, engaging with practitioners will be crucial for identifying performance improvements.

Our findings suggest that our prototype builds on a ledger, which can be a DLT updated through each data owner at the time of transfer (i.e., ZK-Rollups), an operator on a DLT (i.e., optimistic rollup), or an operator ultimately without DLT (Ethereum, 2024). In the case of optimistic rollups, the operator must ensure the correctness of all transactions, e.g., by validating the corresponding ZKPs. Further, this party must not discriminate against any parties by excluding their ownership transfers, ensuring equality within the supply chain. We benchmark the operator without DLT, assuming a trustworthy intermediary, such as an NGO, to maintain the ledger and prevent fraud, resulting in significant performance gains. Optimistic rollups improve the data availability with minimal transaction costs and slight performance reduction. On the other hand, ZK roll-ups are the most expensive as we need ZKP verification on DLT and have no batching of transactions. Still, they come with the advantage of removing the reliability of an operator. Our approach ensures bilateral data transfer without involving a central data broker, relying on trusted parties throughout the supply chain. Our results illustrate that trust remains subjective, requiring all verifiers to trust the issuer, emphasizing the importance of perceived reliability over an objective TP. This aspect is of particular importance for international supply chains with differing jurisdictions.

In summary, we outline a novel concept for a human-centric DPP infrastructure that integrates VCs, SFNFT, and TPs to ensure data integrity and verifiability across the supply chain. We demonstrate the applicability of decentralized technologies for secure data transfer through benchmarking tests, highlighting the scalability of the DPP system and pointing toward its significance for sustainable supply chains and consumption decisions.

5. Discussion and Contribution

In this work, we demonstrate the applicability of a human-centric DPP infrastructure through a prototypical implementation for a fabric product from the textile industry. Our concept enables supply chain actors to transmit verifiable process data – cryptographically provided by a TP - bilaterally to other actors (Heeß et al., 2024; Jansen et al., 2023). Especially at levels prior to the end consumer, to initiate and facilitate the transfer of data to the end consumer, achieving human-centricity in the design of a DPP infrastructure.

As this approach does not apply centralized platforms for data sharing and aggregation, only non-correlatable meta data of the transaction is stored on the public ledger (Babel et al. 2022; Ben-Sasson et al. 2014), while the DPP-related data is stored with the stakeholders and only transferred bilaterally. Thus, the approach ensures the equality of individual stakeholders while ensuring the availability of DPP-relevant data. Nevertheless, this approach may still pose data protection risks, as the information from lower-tier suppliers is transmitted through higher-tier suppliers, as illustrated in figure 3. To mitigate this circumstance, an architecture could be designed where end-customers establish direct, peer-to-peer connections with all suppliers across the value chain.

The infrastructure for DPP stands as the key **technological contribution** of our work. The proposed solution combines insights from the design of DPPs with technological approaches that ensure the verifiability of data while avoiding the double spending of DPPs. We embed approaches (e.g., NFTs and wallet-based identities) to provide end-consumers with a verifiable and chained proof of the production cycle to increase their level of information (Babel et al., 2022; EY, 2024). To the best of our knowledge, we are the first to suggest the utilization of chaining VCs through SFNFTs (Babel et al., 2022) for constructing a multi-layered DPP that focuses on transferring verifiable data to improve end-consumers positioning regarding their consumption decisions. Thus, we adhere to the requirement for more human-centric IS solutions (Human et al., 2022) – especially with a view to the needed development of a sustainable economy – within the context of design-oriented Green IS research (Melville, 2010).

As a primary **theoretical contribution**, stands the impact of our work on recent discussions within IS literature regarding the design of DPPs and their implications on sustainable supply chains and economies (Heeß et al., 2024; Jansen et al., 2023; Plociennik et al., 2022) and the importance of privacy concerns of supply chain actors in light of data sharing and data ecosystems (Abraham et al. 2023; Fassnacht et al., 2023).

Moreover, the **theoretical implications** of our study are twofold. First, our findings highlight the applicability of technological and cryptographical solutions for designing a DPP. The existing body of IS literature offers valuable insights into the necessity of data privacy when designing DPPs (Heeß et al., 2024; Jansen et al., 2023). In this context, our research also links to ongoing discussions on data sovereignty (Scherenberg et al., 2024). Combining theoretical design knowledge with applicable technological solutions allows us to reinforce the finding of Heeß et al. (2024) on the concerns of supply chain stakeholders regarding data control and information disclosure. We propose utilizing SFNFTs with wallet-based identities to ensure verifiable bilateral data sharing among supply chain actors while avoiding the sharing of information with third parties. Further, our findings may lead to the development of practical and theoretical knowledge on designing applicable DPP solutions and systems.

Second, our findings emphasize the necessity of developing human-centric IS solutions to foster the sustainable digital transformation of industries and economies (Scheider et al., 2023). By demonstrating the applicability of our prototype through a use case from the textile industry, we demonstrate how our concept could be utilized to transfer siloed information toward the end-consumer, strengthening their decision-making process and, their impact on a sustainable digital economy. While the developed DPP could serve any industry, consumers' requirements might have to be investigated further to determine the utilization of the proposed solution. Going forward, we propose that scholars build upon our DPP concept, develop it further, and investigate the design of a DPP's surrounding infrastructure and ecosystem, including a respective IS-enabled (data) governance.

Our research also provides **practical implications**. First, it outlines the relevance of human-centricity in designing and developing an infrastructure for DPPs. Siloed solutions only dealing with data processing between entities might lack the adoption of value chain actors, thus not providing efficient solutions toward implementing an industry-agnostic DPP concept. Developing a DPP that facilitates the transfer of product-related data to collaborating supply chain actors without revealing sensitive information to untrusted third parties benefits supply chains and their endeavors to foster a sustainable transformation. Second, regulators should acknowledge the importance of industry and technology-agnostic solutions as enablers for holistic DPP developments. More specifically, regulators should seek to leverage existing concepts (e.g., NFTs and wallet-based identities) to implement a future-oriented and scalable solution for DPP that adheres to current data protection requirements while highlighting the role of human-centric solutions.

6. Conclusion

In this paper, we propose a human-centric architecture for a DPP that digitally represents product-related information in a verifiable manner using VCs and SFNFTs. By chaining VCs and SFNFTs throughout the supply chain and linking the DPP to the finished good, our solution for a DPP infrastructure enables the seamless transfer of ownership to the current actor at each production stage. Our infrastructure allows organizations and consumers to interact on a common level, ensuring that consumers can base their decisions on detailed and verified product lifecycle information. Against this background, our design-oriented research enables informed consumer decisions and supports sustainability by a human-centric approach. Our work contributes to ongoing research in IS literature on DPP design by providing a technologically advanced and evaluated concept of a human-centric DPP infrastructure. By acknowledging the importance of technologies such as DLT and ZKPs, we also enhance current research on data sharing, facilitating verifiable data transfer in supply chains.

Like any research, our work has limitations. First, our solution can be seen as the first iteration of an extensive design cycle. Thus, additional qualitative (e.g., integrity and trustworthiness of the system; usability) and quantitative (e.g., accessibility and scalability of the transactions) evaluations are required to further develop the DPP. Second, we focus on the textile industry as an exemplary use case. Therein, we particularly link the DPP to the finished product rather than its individual components. To gain a broader understanding of the design requirements, our solution should be applied to various industries to develop an industry-agnostic DPP infrastructure and gain additional insights on the complexities of linking DPP to individual product components.

A possible starting point for future research lies in conducting consecutive evaluations to integrate additional design criteria besides data protection and verifiability, refining the artifact further. Moreover, our concept also requires additional attention considering information asymmetry and its impact on the adoption of DPPs in supply chains – also considering the ongoing discussions about the governance and decentralization of data sharing ecosystems and the environmental and social implications of DPPs in light of the circular economy. Our prototypical implementation in the textile industry demonstrates the practical applicability and benefits of DPPs, paving the way for industry-agnostic solutions.

Our study highlights the importance of reducing information asymmetry between end-consumers and organizations through verifiable data sharing, addressing human-centricity in the development of infrastructures for DPP. We believe that our findings provide valuable insights for researchers, organizations, and regulators and serve as an impetus for further developments, supporting the creation of a digital sustainable economy.

References

Abraham, R., Schneider, J., & Brocke, J.V. (2023). A taxonomy of data governance decision domains in data marketplaces. *Electronic Markets, 33*, 1-13. http://dx.doi.org/10.1007/s12525-023-00631-w

Adisorn, T., Tholen, L., & Götz, T. (2021). Towards a Digital Product Passport Fit for Contributing to a Circular Economy. *Energies*, *14*(8), 2289. https://doi.org/10.3390/en14082289

Babel, M., Gramlich, V., Körner, M.-F., Sedlmeir, J., Strüker, J., & Zwede, T. (2022). Enabling end-to-end digital carbon emission tracing with shielded NFTs. *Energy Informatics*, *5*(S1). https://doi.org/10.1186/s42162-022-00199-3

Ben-Sasson, E., Chiesa, A., Garman, C., Green, M., Miers, I., Tromer, E., & Virza, M. (2014). Zerocash: Decentralized Anonymous Payments from Bitcoin. In *2014 IEEE Symposium on Security and Privacy* (459–474). https://doi.org/10.1109/SP.2014.36

Berger, K., Schöggl, J.-P., & Baumgartner, R. J. (2022). Digital battery passports to enable circular and sustainable value chains: Conceptualization and use cases. *Journal of Cleaner Production*, *353*, 131492. https://doi.org/10.1016/j.jclepro.2022.131492

Caldarelli, G. (2020). Real-world blockchain applications under the lens of the oracle problem. A systematic literature review. 2020 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD), 1-6.

CIRPASS. (2024). CIRPASS Digital Product Passport. https://cirpassproject.eu/.

Ethereum. (2021). *ERC-721 Non-Fungible Token-Standard*. https://ethereum.org/en/developers/docs/standards/tokens/erc-721/

Ethereum. (2024). *Scaling*. https://ethereum.org/en/developers/docs/scaling/

European Commission. (2022). *New proposals to make sustainable products the norm*. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2013

EY. (2024). *EYBlockchain/nightfall_3: a mono-repo containing an optimistic version of nightfall*. https://github.com/EYBlockchain/nightfall_3

Fassnacht, M., Benz, C., Heinz, D., Leimstoll, J., & Satzger, G. (2023). Barriers to Data Sharing among Private Sector Organizations. *Proceedings of the 56th Hawaii International Conference on System Sciences (HICSS).*

Gelhaar, J., & Otto, B. (2020). Challenges in the Emergence of Data Ecosystems. *Twenty-Third Pacific Asia Conference on Information Systems, Dubai, UAE, 2020*.

Götz, T., Berg, H., Jansen, M., Adisorn, T., Cembrero, D., Markkanen, S., & Chowdhury, T. (2022). *Digital Product Passport: the ticket to achieving a climate neutral and circular European economy?* https://epub.wupperinst.org/frontdoor/deliver/index/docId/8049/file/8049_Digital_Product_Passport.pdf

Guillen, G., Hamari, J., & Quist, J. (2021). Gamification of Sustainable Consumption: a systematic literature review. *Proceedings of the 54th Hawaii International Conference on System Sciences (HICSS)*.

Heeß, P., Rockstuhl, J., Körner, M.-F., & Strüker, J. (2024). Enhancing trust in global supply chains: Conceptualizing Digital Product Passports for a low-carbon hydrogen market. *Electronic Markets*, *34*(1). https://doi.org/10.1007/s12525-024-00690-7

Hevner, A. R., March, S., Park, J., and Ram, S. (2004). “Design Science in Information Systems Research,” MIS Quarterly (28), pp. 75-105 (doi: 10.2307/25148625).

Human, S., Alt, R., Habibnia, H., & Neumann, G. (2022). Human-centric Personal Data Protection and Consenting Assistant Systems: Towards a Sustainable Digital Economy. *Proceedings of the 55th Hawaii International Conference on System Sciences (HICSS)*.

Jansen, M., Meisen, T., Plociennik, C., Berg, H., Pomp, A., & Windholz, W. (2023). Stop Guessing in the Dark: Identified Requirements for Digital Product Passport Systems. *Systems*, *11*(3), 123. https://doi.org/10.3390/systems11030123

Jensen, S. F., Kristensen, J. H., Adamsen, S., Christensen, A., & Waehrens, B. V. (2023). Digital product passports for a circular economy: Data needs for product life cycle decision-making. *Sustainable Production and Consumption*, *37*, 242–255. https://doi.org/10.1016/j.spc.2023.02.021

Jørgensen, K. P., & Beck, R. (2022). Universal Wallets. *Business & Information Systems Engineering*, *64*(1), 115–125. https://doi.org/10.1007/s12599-021-00736-6

Kotlarsky, J., Oshri, I., & Sekulic, N. (2023). Digital Sustainability in Information Systems Research: Conceptual Foundations and Future Directions. *Journal of the Association for Information Systems*, *24*(4), 936–952. https://doi.org/10.17705/1jais.00825

March, S. T., & Smith, G. F. (1995). Design and natural science research on information technology. *Decision Support Systems*, *15*(4), 251–266. https://doi.org/10.1016/0167-9236(94)00041-2

Melville, N. (2010). Information Systems Innovation for Environmental Sustainability. *MIS Quarterly*, *34*, 1–21. https://doi.org/10.2307/20721412

Munaro, M. R., & Tavares, S. F. (2021). Materials passport’s review: challenges and opportunities toward a circular economy building sector. *Built Environment Project and Asset Management*, *11*(4), 767–782. https://doi.org/10.1108/BEPAM-02-2020-0027

Plank, A., & Teichmann, K. (2018). A facts panel on corporate social and environmental behavior: Decreasing information asymmetries between producers and consumers through product labeling. *Journal of Cleaner Production*, *177*, 868–877. https://doi.org/10.1016/j.jclepro.2017.12.195

Plociennik, C., Pourjafarian, M., Saleh, S., Hagedorn, T., Carmo Precci Lopes, Alice do, Vogelgesang, M., Baehr, J., Kellerer, B., Jansen, M., Berg, H., Ruskowski, M., Schebek, L., & Ciroth, A. (2022). *Requirements for a Digital Product Passport to Boost the Circular Economy. INFORMATIK 2022. Hamburg.*

Scheider, S., Lauf, F., Möller, F., & Otto, B. (2023). A Reference System Architecture with Data Sovereignty for Human-Centric Data Ecosystems. *Business & Information Systems Engineering*, *65*(5), 577–595. https://doi.org/10.1007/s12599-023-00816-9

Scherenberg, F. von, Hellmeier, M., & Otto, B. (2024). Data Sovereignty in Information Systems. *Electronic Markets*, *34*(1). https://doi.org/10.1007/s12525-024-00693-4

Sunyaev, A., Kannengießer, N., Beck, R., Treiblmaier, H., Lacity, M., Kranz, J., Fridgen, G., Spankowski, U., & Luckow, A. (2021). Token Economy. *Business & Information Systems Engineering*, *63*(4), 457–478. https://doi.org/10.1007/s12599-021-00684-1

UN. (2021). *Climate Change ‘Biggest Threat Modern Humans Have Ever Faced’, World-Renowned Naturalist Tells Security Council, Calls for Greater Global Cooperation | Meetings Coverage and Press Releases*. https://press.un.org/en/2021/sc14445.doc.htm

Venable, J., Pries-Heje, J., & Baskerville, R. (2016). FEDS: a Framework for Evaluation in Design Science Research. *European Journal of Information Systems*, *25*(1), 77–89. https://doi.org/10.1057/ejis.2014.36

Wang, F., & Filippi, P. de (2020). Self-Sovereign Identity in a Globalized World: Credentials-Based Identity Systems as a Driver for Economic Inclusion. *Frontiers in Blockchain*, *2*, Article 28. https://doi.org/10.3389/fbloc.2019.00028