Digital Product Passports: Use Cases Framework and Technical Architecture Using DLT and Smart Contracts

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***Abstract*—Digital Products Passports (DPPs) are digital documents accompanying individual product items and carrying data pertaining to product's life cycle; material and methods used in manufacturing, product distribution network, carbon footprint and environmental impact, context and time of use, and other. DPPs were first introduced in the EU Green Deal and are envisioned as a tool to facilitate the transition to a Circular Economy. Data stored and carried on DPPs will help inform policy making as well as consumer behavior. However, the wide scope of use cases and market sectors under consideration pose significant challenges in deriving a generic DPP system design. This makes difficult the development of corresponding standards, which in turn hinders market stakeholders from onboarding the use of DPPs. We address this problem by means of a DPP use case framework that captures the core underlying structure of DPP use cases that is common in its many application areas. We also present a technical architecture for DPP systems based on Distributed Ledger Technologies and Smart Contracts and provide the code for a working prototype. We conclude by discussing future extensions of this work, particularly with respect to evaluating the performance of our implementation.**

Keywords—Digital Product Passport, Circular Economy, Smart Contract, Blockchain

I. Introduction

Economic development and technological advancements of the past several decades have led the drastic improvement of quality of life in modern societies. However, the traditional paradigm of economic activity has been having a dramatic adversarial impact on the natural environment. This primarily human-driven change in planet earth ecosystem has been so dramatic that a new distinct geological era is proposed, the Anthropocene. Increase of climate awareness in recent years is leading to significantly more research and legislator development in that space. Intergovernmental Panel on Climate Change assessed that sustainability is a key challenge that will impact future outcomes where timing and decisions taken are crucial for a soft landing [1].

European Union (EU) is one of the few global actors with enough resources to drive the change for the better future for all, and that is why solutions implemented in EU should be designed in a way to scale across the world. EU has significant impact on the global discourse on regulations and markets due to its large number of wealthy consumers. Impact on data privacy, as well as materials used in various products and manufacturing processes are only some of the influences pressured by EU that have made many countries and businesses across the world adapt to the European green agenda [2].

The transition to a Circular Economy (CE) is one of the main pillars of the EU Green Deal Industrial Plan to mitigate the negative consequences of the current path of economic development. It supports the transition to climate neutrality while at the same time enhancing the competitiveness of Europe's net-zero industry. CE promotes a non-linear model envisioning to eliminate the notion of waste by introducing cascading loops across multiple stages of the production and consumption processes. While the notion of increasing the efficiency of the production and consumption cycles was first introduced in 1970's, the emergence and widespread adoption of digital technologies across the full life-cycle of products – from extracting raw material, to manufacturing, distributing, consuming, and eventually recycling or disposing of them – now enables a more fine-grained and scalable collection of data that can inform not only the production of products but also the consumers' behavior in making informed choices. Furthermore, such data can also inform the re-design or development of new processes and policies towards mitigating environmental impact.

Digital Product Passports (DPPs) are introduced by the European Commission as a means of facilitating the collection, sharing, and retrieval of product-related data. A DPP is a digital document accompanying an individual product item carrying information pertaining to its life-cycle; material and origin of materials used in its production, distribution information, history of use, carbon footprint, involved actors, and other. Compared to existing certification documents, DPPs leverage on modern ICT to collect and store highly granular data regarding specific individual items, rather than classes or types of products. The aim is for DPPs to greatly facilitate the discovery and collection of product data by key stakeholders, such as regulatory agencies and consumers. The concept has been recently introduced and details regarding the types of data

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involved, the implementation of DPP infrastructure, and DPP governance at the time of writing are yet to be defined and standardized.

Our contribution. Developing an understanding of how DPPs can be introduced and utilized in the life cycle of products, as well as how would a DPP system infrastructure be implemented are currently open questions that need to be answered for DPPs to be adopted. The wide scope of use cases and market sectors under consideration pose significant challenges in deriving a generic DPP system design. This makes difficult the development of corresponding standards, which in turn hinders market stakeholders from onboarding the use of DPPs.

In this work, we first discuss the existing policies landscape within which DPPs are introduced. We then introduce a DPP use case framework that captures the core underlying structure of DPP use cases that is common across many application areas. The framework aims to serve as a reference model for structuring and developing DPP use cases. The framework also provides insights on the requirements of DPP infrastructure. We present a technical architecture for DPP systems employing Distributed Ledger Technologies and Smart Contracts, and we provide the code for a working prototype. The architecture is use-case agnostic and provides the basis around which DPP systems can be developed independently of the application area. We conclude by discussing future extensions of this work, particularly with respect to evaluating the performance of DPP systems.

II. Related Work

A. Current Standards and Legislation

The European Union requires standardized product certification for products traded in the European Economic Area before they enter the market. It requires from manufacturers to prove that their products comply regarding health safety and environmental laws and compliance of management systems, services, and manufacturing processes is International Organization of Standardization, among many others. Before the product can be certified, the producer must undertake steps and tests to prove the product compliance. They must create documentation and make it available for request to relevant authorities. The authorized bodies check to see if all the safety requirements are met by a testing process called conformity assessment [6]. The most common test is a conformity inspection which means that an authorized person from an independent third party will take samples from your production line and inspect it to make sure it meets the European standards set out for this product. Goods can be checked by surveillance authority at any time and when conditions were not met, the actor responsible for product marketing is responsible for recall of products already sold to customers [6].

Through using standards, consumers can access with confidence goods and services on the market and understand the products better. Standards improve environmental protection and customer health and safety, as they provide the measures for product testing and control of hygiene, pollution,

Fig. 1. Cascading loops provisioned in product life cycle by Circular Economy.

material content, etc. Another advantage of widely recognized standards is removing trading barriers within the EU and providing lower prices as it is easier to trade products on a Single Market [7]. In the current linear economy and standardization, the process of enquiring information by customers is limited and the content of product description is not satisfying. Information is mostly lost at the stage of consumption and extremely limited knowledge reaches recycling and second life operators. Some information is still not required from manufacturers as the regulations cannot follow the emerging markets. Data quality and transparency varies across industries and businesses, which makes it hard for wider analysis of goods and services. Additionally human interference in the process makes it inefficient and diversified, which deepens the issue.

B. Grean Deal and Circular Economy

European Green Deal was introduced by European commission that sets the carbon neutrality by 2050 as the main priority. The decarbonization process is targeting the key sectors through carbon pricing, sustainable investments, policymaking, and overall transition. Sustainable investments and carbon pricing hopes to promote behavioral change among EU citizens which translates to shift from current thinking [8].

Industry is mobilizing for a clean and circular economy which currently is estimated to generate 50% of total greenhouse gas emissions and more than 90% biodiversity loss due to extraction of resources and material processing. Only 12% of materials used in EU now come from recycling, proving that current approach is not effective. Digitalization must be leveraged to close the gap of material waste and identification of main bottlenecks in manufacturing and consumption [9].

A Digital Product Passport is a product-unique dataset that registers, and processes information related to the product. Data is being shared between stakeholders, such as supply chain actors, governors, and consumers. The growing need is clearly visible in European Green Deal and the path to net zero future [12]. Digital Twin is believed to be an enabler for climate neutral sustainable Europe considering modern world

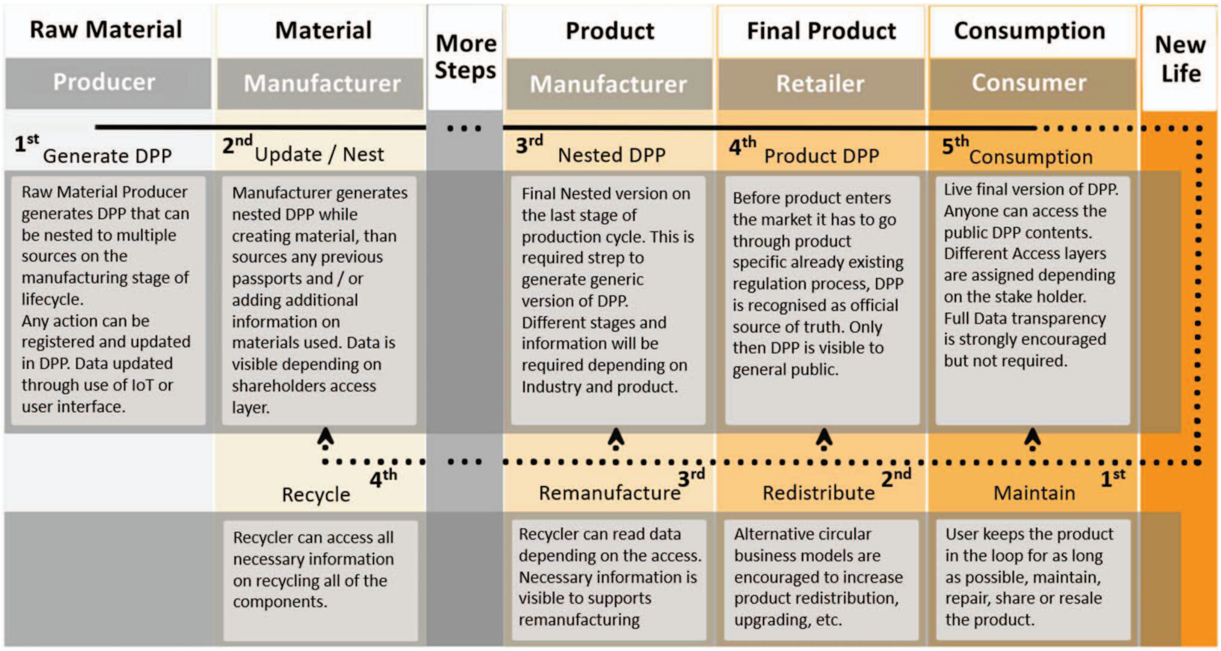

Fig. 2 Digital Product Passport Exchange Use Case Description.

digitalization. DPP would allow to not only get the information regarding product recycling but generally improve the time span of the product usage and transform them into another commodity and support implementation of alternative sustainable business models [13]. Easily accessible data would also inform consumers on their purchase decisions and how to repair and maintain product as well as expected lifespan to inform product reuse decisions [13]. In case of businesses, remanufacturing, material recovery and recycling information would be provided allowing manufacturers to make decisions based on reliable information sources [13].

Under the current model of linear economy most of product-related information is lost or unavailable to most stakeholders. This is due to the lack of standardization of digital product information, and lack of policies that would require or incentivize producers and manufacturers share this information.

The latest Circularity Gap report shows that only 7.2% of the economy is circular. Comparing results to previous years shows the downtrend of circularity from 9.1% in 2018, 8,6% in 2020. The report states that circularity cannot keep up with rapidly growing use of virgin materials therefore current efforts are proven not to be meeting the needs of meaningful change [15]. European SMEs engaging with circular economy activity perceive the administrative complexity, administrator compliance and the lack of human resources as the major blocker for circularity adoption [16]. Other major challenges that slow down the development include lack of definitions and standardization, unharmonized standards as well as major challenges with implementation considering international trade [17]. Another challenge described in 2018 report points out that low carbon energy alone cannot meet with available carbon budget and there are several more practices that must be practiced. Circularity implementation challenges lie with innovation regarding recycling capabilities among different industries and various materials. Although projections are promising, and growth is inevitable, legislative actions must be taken and awareness needs to be raised as there is a need for more research and investment in space to achieve desired goals [18].

III. Digital Product Passport Use Cases Framework

The use of DPPs and their embedding in the product life-cycle strongly depends on the corresponding economic sector and market verticals. As such, different use cases are expected to have different requirements and therefore to be structured in a different way. However, there exist requirements and design choices that lie in the core of any use case and can serve as the common basis when considering the application of DPPs. Identifying these core requirements will then help us derive nominal reference and technical architectures for DPP use cases and infrastructure.

A. DPPs and Digital Twins

A somehow related notion to DPPs is that of Digital Twins. This is because a DPP is a digital document meant to accompany a product item throughout its lifecycle, thus working as a digital counterpart of the physical product. In this context, considering the design goals for Digital Twins can inform the design of a DPP infrastructure. The following design goals for Digital Twins are proposed in [14]:

Controllable. Product owners have full control of what data is being added to the product digital twin.

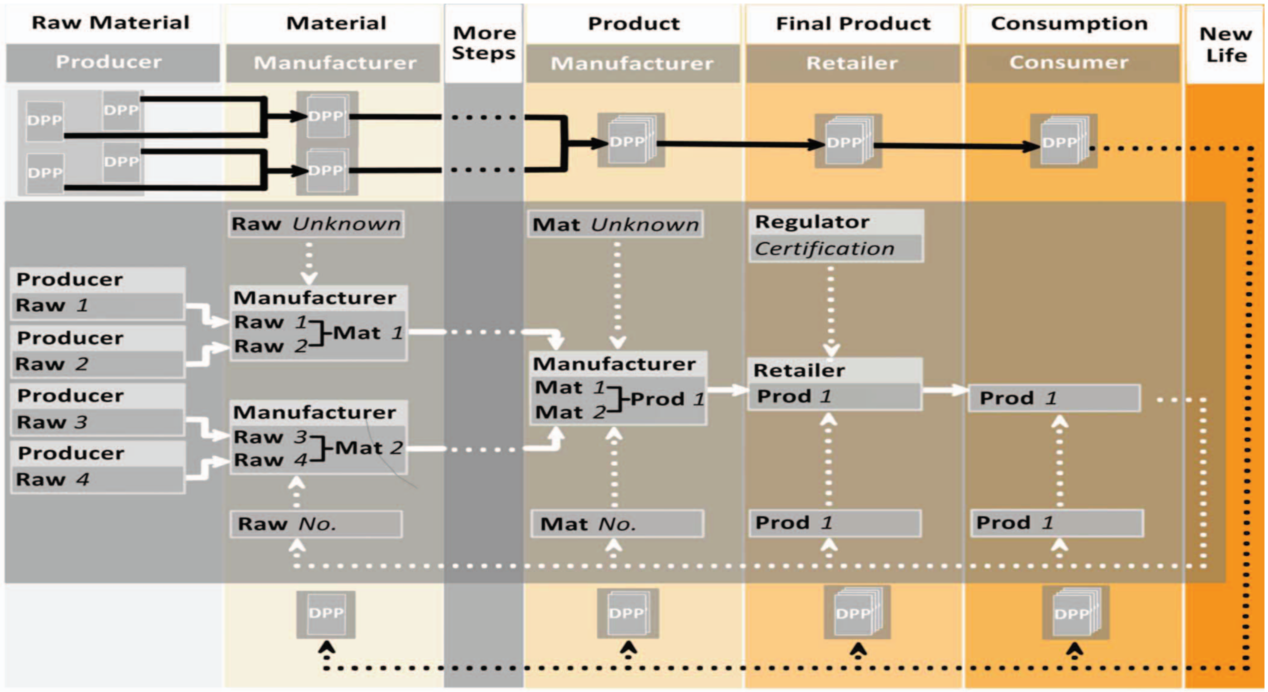

Fig. 3 Reference framework of Digital Product Passport use cases.

Decentral. The ideal system would be decentralized which would prevent the single point of failure and risk of central governance and give ownership to chain actors.

Private. Business will have to share only required information publicly and choose what else to share with who. This will allow us to protect business secrets and the privacy of users.

Secure. Data must be correct and secure as well as the origin of the data having to be verifiable by the governing body.

Discoverable. All required information must be easily accessible by all stakeholders that wish to access the data. Users need to have a different data view compared to Recycler, for example that will need much more specific information on recyclable components of the product.

Interoperable. Data structures need to be standardized and already existing information should be reused where possible.

Portable. Product identity must remain permanent and usable across all different networks and ecosystems.

Simple. All market players should be able to access and write the data easily.

Extensible. System structure should be able to adapt to future needs, new use cases and standardization. Additionally, the possibility of international use would be greatly beneficial.

B. *Reference Architecture for DPP Use Cases*

Figures 2 and 3 outline the reference framework for and description of DPP use cases. A use case scenario starts at the raw material stage. During the extraction of raw materials, each batch would get its own unique passport that would be generated by the producer. Information depending on the scenario would be captured by IoT devices or provided manually by the product owner. In the instance depicted in Fig. 3, four individual Producers are providing four unique raw materials that are passed on to next-tier manufacturers. Other services, like transportation and any change of state, can be recorded in the DPP at any stage before it reaches the consumer to give as much context to the lifecycle and production flow. During the tier 2 Manufacturing level, raw materials are combined into material that is given its unique passport that refers to two previously created raw material passports. Depending on the scenario, if the manufacturers are using raw materials that were not given a DPP, the manufacturer can add information on the material themselves following the required product-specific legislation and standards. If the raw material came from a product with an assigned DPP the required information can be extracted and nested to the newly created material passport. Production stages and DPP nesting continue for as long as needed until reaching the original equipment manufacturer which will be depending on the scenario. OEM (original equipment manufacturers) who in this scenario is an authorized representative of the product must make sure that the product complies with every standard and legislation that is required. Alternatively, if the product representative cannot provide any information on previous stages (if this is legally accepted), they can create a new DPP at this stage. This approach was taken as in practice not every manufacturer has access to infrastructure or the capabilities to provide all data or trace the information at the origin of materials used in the products. Based on research done on stakeholders' views on

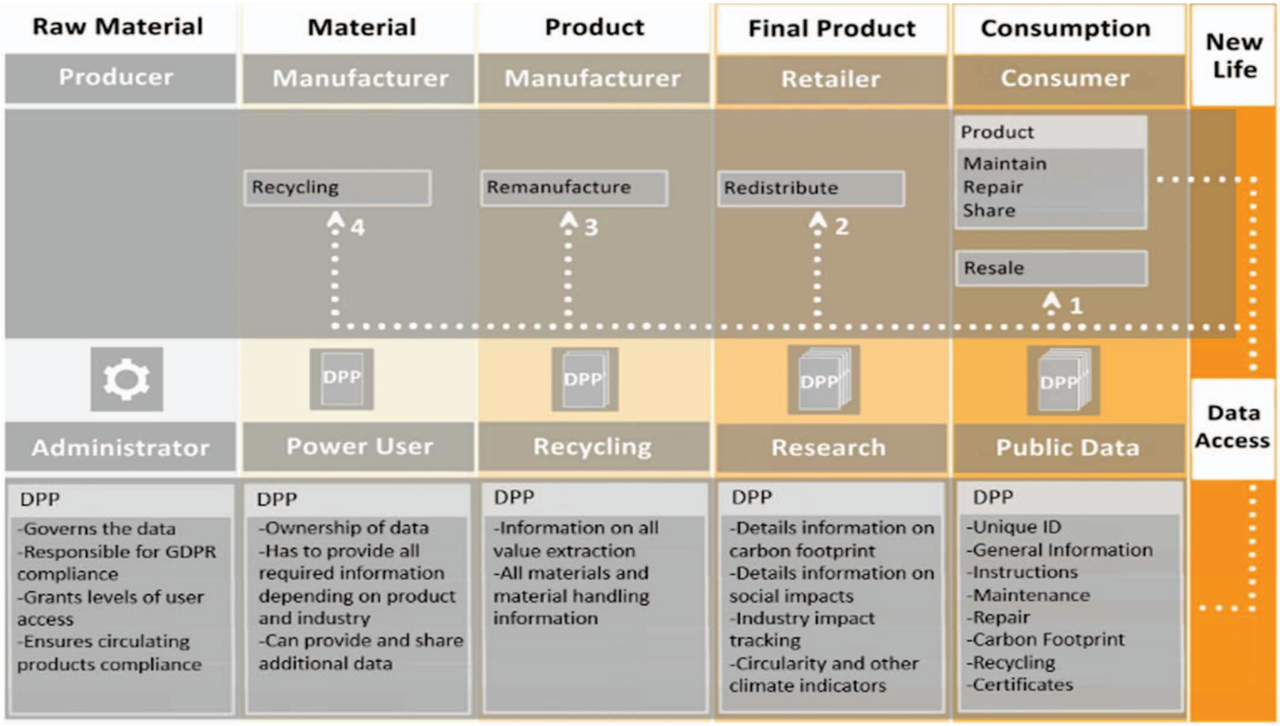

Fig. 4. Data exchange between stakeholders. Information from DPP is being used during consumption to support keeping products in loop for as long as possible. After consumption DPP informs distributors, manufacturers, and recyclers on how to retrieve value back from the product. Data stored in DPP is available based on levels of user permissions. Different users depending on access, can access different information for analytics, support circular actions, prove of regulation compliance, certification etc.

business secrets [10], DPP contents should include the following information to fully support the Circular Economy intentions [12]:

a) Unique Identifier

b) Product Information and Instructions

c) Maintenance and Disassembly

d) Carbon Footprint

e) Product Recycling

f) Product-specific certificates and standards

g) Legislation compliance

The distributor placing the product on the market, after it went through every needed legal step provides the product with a QR code that will allow consumers to access DPP data. The product consumption/use step is not registered for the protection of consumer privacy. Depending on the context of the use case, during the product recycling phase it can get a new life (i.e. be upcycled) at any previously described phase. Consumers can resell the product and inform potential buyers by providing a corresponding QR code validating the authenticity of purchased goods by accessing product data. Alternatively, the product can come back to any stakeholder that will extract necessary information about the material that is being repurposed and nest it to a newly created DPP.

Data requirements are subject to change depending on European Union decisions regarding DPPs and their use in different departments. It could be required to provide end-to-end information covering the entire product lifecycle end-to-end; from raw materials to end-product. In other cases, when decided by a regulatory body, only last-stage information could be required. This proposal was influenced by concern of difficulties with adoption regarding smaller businesses and producers from developing countries trying to participate in EU market.

Legislators are faced with the challenge of data governance, user access assessment and deciding what information will be available publicly, including reparability. It is necessary to identify all possible use cases and scopes and relate to them during development of the infrastructure. Also, it would be feasible to create a road map for transition from simple minimum capabilities to much more complex structures.

International standards should be put in place to define data verification and enhancements of circularity of business operations. Digital Product Passports must be a very versatile system which will be useful across all supply chains, not only used for reporting but also provide the data pipeline and exchange between stakeholders. All aspects like objectives, and barriers must be identified and data requirements and how this will be used need to be defined. Unique Identifiers should be introduced across multiple sectors due to many cross-sectoral operations where each sector would adopt current legislations and standards that it must comply with.

DPP's are crucial in the case of key value chains such as batteries, electronics, construction, textiles, chemicals, etc. Depending on Industry and type of product DPP should be unique to each item but in case of case of smaller, less valuable, mass production products DPP could be assigned to a batch, or a series of products.

Our design approach of DPP can be implemented in various industries and hopefully implemented for the whole economy. The High value chains, and various business to business models should be prioritized during the prototyping period, but our suggestion is to let anyone participate to support gradual implementation across every industry. This would support future policy, design, and permission decisions as well as evaluate the design across multiple product types.

Legislators and policy makers should be conscious of complications coming with developing necessary infrastructure by smaller manufacturers. Substantial changes should be ruled out gradually to avoid deepening the gap between large corporations and local businesses who should have an equal chance to adapt to the new market environment.

IV. Technical Architecture for DPP Systems

As discussed in Sec. II, DPPs have started gaining research attention due to Circular Economy being regarded as a strategic priority of the EU. Similar to identifying the core structure of DPP use cases (by means of a reference use case architecture), developing a reference technical architecture for DPP infrastructure will help with identifying the underlying challenges, standardizing the process of developing DPP systems, and eventually facilitating DPP uptake by use case stakeholders. In the following, we present and discuss our proposed technical reference architecture for DPP systems.

A. Technological Enablers for DPP Systems

The following technologies are identified as key enablers for DPP infrastructure.

Internet of Things (IoT). The Internet of Things is a system paradigm supporting Machine-to-Machine communication and allowing sensors and embedded electronic devices to communicate through the Internet. IoT is regarded as the nexus point between the physical and digital worlds, enabling the collection and processing of sensory data in the context of broader complex systems.

Distributed Ledger Technologies (DLT). Distributed Ledger Technology (DLT) is a rapidly developing data storage technology enabling synchronized copies of data to be stored on computers (referred to as nodes) over a decentralized network of peers [20].

Blockchain Technology. The blockchain technology, which is a sub-category of DLT, was first popularized in 'Bitcoin: A Peer-to-Peer Electronic Cash System' by Satoshi Nakamoto [21]. It is a peer-to-peer, decentralized append-only database, which means it cannot be changed or altered and is distributed across all of its nodes [22]. This architecture of the blockchain has helped develop transparent and secure systems. Depending on the architecture's needs, blockchain systems can be centralized or decentralized.

When the blockchain idea was first introduced, it brought a new perspective to technology. However, it was not yet mature enough to support many use cases and goals. With the growing popularity of blockchain, new distributed ledger technology (DLT) projects have been developed over the years. In 2014, the Ethereum project was announced by Vitalik Buterin [23]. Ethereum was a project developed over Bitcoin, like many other blockchains, but it was heavily leveraging the concept of smart contracts. Even though the smart contract idea was first published by Nick Szabo [24], the Ethereum blockchain stood out as the leading platform for smart contracts [25]. The combination of Ethereum and smart contracts introduced the ability to process data in blockchains without the coordination of a central authority; a key aspect for DPP systems.

Consensus Mechanism. Consensus mechanisms are an important part of DLT as they address key problems in it [26]. These mechanisms define the characteristics of the DLT, including its security level and performance, but one consensus algorithm cannot meet the needs of every application [27]. Since Bitcoin's Proof-of-Work consensus mechanism [21], various consensus algorithms have been created over time to address the unique demands and specifications of different DLT applications, each one with their own characteristics [33].

IOTA and IOTA Smart Contracts (ISCP). IOTA is a distributed ledger technology optimized for Internet of Things (IoT) architectures that was first released in 2015 [28]. IoT architectures involve the use of many devices, and the usage of many devices makes scalability a critical challenge that needs to be addressed. IOTA was developed as a solution to this scalability challenge with its Tangle technology. Unlike other distributed ledger technologies such as Ethereum and Bitcoin, IOTA provides features such as feeless and lightweight messaging, and it communicates asynchronously through its Tangle technology [29].

Tangle Technology. Tangle is described as a 'probabilistic leaderless consensus protocol based on a directed acyclic graph (DAG)' in its publication paper [30]. The structure of Tangle allows for parallel validation of transactions and eliminates intermediaries, such as miners and validators, from the transaction validation process. These features make IOTA's Tangle consensus an ideal high TPS solution for IoT applications.

B. Architecture

We propose a reliable, transparent, system architecture for Digital Product Passports that utilizes IoT, Distributed Ledger Technologies, and Smart Contracts.

The design of the proposed system architecture begins with the collection of data for DPPs from IoT devices, which is illustrated in Fig 5. Once the data is collected from the IoT devices, it is transferred to a gateway device for data processing. The gateway device processes the incoming data from IoT sensors, creates a smart contract transaction for the IOTA network, and sends the transaction to IOTA nodes after the signing process. When an IOTA node receives the transaction, it broadcasts it to the entire network. Oracle nodes, which are specialized nodes for processing smart contracts, execute the smart contract transaction and save the execution result on the IOTA network.

As shown in Fig. 6 and Fig. 7, there are different methods used in smart contracts for DPPs. When a new DPP is needed,

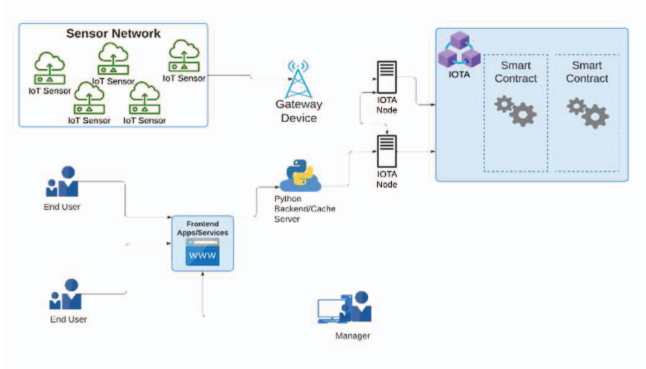

Fig. 5. Reference technical architecture of DPP infrastructure.

a new unique identifier is generated and assigned to the new DPP. After the unique identifier is generated, the data from IoT devices associated with the identifier is saved to the IOTA network. To maintain a log of transactions, DPP versions are saved on append-only arrays. When the DPP is updated, a new version of the DPP is appended to that DPP's array. Another important function is the merging of different DPPs. To achieve this, a new DPP is generated as explained before, and unique identifiers of the merging DPPs are added to the new DPP as a reference to their details.

After the data is processed and saved in the IOTA network, users will be able to access the DPPs through frontend applications or services. To provide these applications or services, Python backend and cache servers will be utilized. The backend services will provide further authorization and data processing, and will serve as a gateway to update or generate functionality to DPPs for authorized personnel. Cache services will be used to reduce calls to IOTA nodes and provide faster data to frontend applications or services. The code of a working prototype of this architecture can be accessed on GitHub in [34].

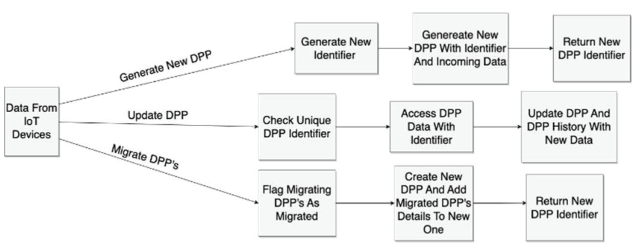

Fig. 6. DPP Smart Contract Transaction Methods [34].

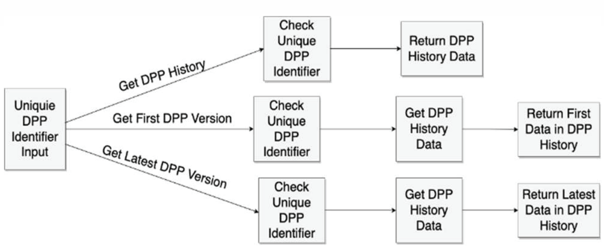

Fig. 7. DPP Smart Contract Call Methods [34].

V. Discussion & Future Work

Given the emphasis on speed in IoT architectures, distributed ledger technology (DLT) implementations within IoT require high transaction processing speeds (TPS) due to the high volume of data generated by IoT devices. Accordingly, we will evaluate the efficacy of our proposed IoT architecture based on the IOTA solution by considering both TPS and confirmation failure rates.

According to research, directed acyclic graph (DAG)-based distributed ledger technology (DLT), such as IOTA, demonstrates superior speed and scalability when compared to traditional blockchain technologies [31]. Unlike consensus protocols used in classic blockchains, such as proof-of-work (PoW) and proof-of-stake (PoS), DAG-based DLTs like IOTA do not have a technical upper bound on transaction processing speed (TPS), so long as new transactions are validated rapidly [32]. Also, distributed ledger technologies (DLTs) based on directed acyclic graphs (DAGs) exhibit higher transaction processing speeds (TPS) and greater capacity for data processing. Notwithstanding data processing capacity, [32] indicates that DAG-based DLTs can effectively mitigate confirmation failure probabilities, thereby reducing data loss. In conclusion, directed acyclic graph (DAG)-based distributed ledger technology (DLT), specifically IOTA which is developed for IoT architectures, has been found to be a suitable solution for the creation of automated digital product passport (DPP) system architecture in the context of the Internet of Things (IoT). The proposed system architecture provides benefits such as scalability, speed, and data assurance. However, it is important to note that the architecture of the DLT solution does have potential weaknesses regarding privacy and authentication.

The proposed system architecture utilizes smart contracts for authentication purposes, as current distributed ledger technology (DLT) architectures do not inherently support authentication without the use of smart contracts. This presents a potential security risk, as participants may be able to join the network and interact with smart contracts without proper authorization. As such, it is essential to explore DLT-based authentication methods to establish a secure environment. Furthermore, privacy is an additional challenge that requires attention, as the current solution relies on client-side encryption. However, this approach may not be sufficient for government audits, emphasizing the need for more robust privacy mechanisms to be developed.

In future work, we will address privacy and security concerns pertaining to sensor networks and gateway devices. Moreover, experiments will be conducted using smart contract-supported Directed Acyclic Graph (DAG) based Distributed Ledger Technologies (DLTs) to effectively address privacy issues. These experiments will also help determine the most performant DAG technology to be utilized.

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