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Development of a Decentralized Digital Product Passport for Enhanced Lifecycle Management of Electrical and Electronic Equipment

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Abstract

The Eco-design for Sustainable Products Regulation has introduced the Digital Product Passport (DPP) as a key tool for tracking and promoting the sustainable development of products. Despite the growing interest in DPPs, standardized models are yet to be established, with only experimental alternatives available from various organizations. Moreover, no existing model fully exploits the data, as conducting a life cycle assessment (LCA) still necessitates acquiring additional data from various life cycle stages. This study aims to bridge this gap by developing a fully decentralized DPP prototype specifically for the Electrical and Electronic Equipment (EEE) sector. The research begins by defining a tree-structured hierarchical model for data collection and management, aligning with regulatory standards. The prototype's implementation employs an eXtended Markup Language (XML) file for data digitalization and blockchain technology to ensure secure data sharing and storage. Tested on a household appliance, the DPP prototype demonstrates how digital passports can enhance product lifecycle management, driving sustainability in the EEE sector and supporting the implementation of circular economy scenarios.

*Keywords:*Eco-design; Digital Product Passport; Lifecycle Management; Electrical Electronic Equipment; Blockchain.

1. Introduction

Electrical and Electronic Equipment (EEE) play a crucial role in modern society but present substantial environmental, economic, and social challenges [1]. The issue of planned obsolescence, coupled with the complexities of material recycling, has led to a significant increase in Waste Electrical and Electronic Equipment (WEEE), contributing to biodiversity loss and posing risks to human health [2]. In 2022, approximately 62 million tons of WEEE were generated globally, with over 77% improperly treated [3]. This failure not only results in the loss of valuable materials but also leads to informal recycling processes and increased CO2 emissions, with an estimated 3.15 kg of CO2eq released for every kilogram of unrecycled waste [4]. Although material recovery from recycled waste in 2022 prevented 52 billion kg of CO2eq emissions [5], this positive impact remains insufficient to counterbalance the overall effect. These challenges underline the urgent need for strategies that go beyond the traditional linear model of take-make-dispose, focusing instead on reducing emissions and optimizing resource use. The core issue in inefficient resource management lies in product design, which often fails to prioritize recyclability and reusability [6]. The lack of traceability impedes data collection, making it difficult to optimize design and develop the necessary infrastructure for efficient resource recovery. This, in turn, drives the overconsumption of critical raw materials (CRMs), whose demand is rapidly increasing, further exacerbating concerns about resource scarcity and security [7]. To address these challenges, the European Union has launched several initiatives to drive the transition toward a circular economy, with the Digital Product Passport (DPP) that has a central role

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in the Eco-design for Sustainable Products Regulation (ESPR). The battery sector will serve as the first test for the DPP, mandated by the Battery Regulation from 2027 to address rising demand and environmental impact, while ensuring secure, regulated data access [9]. Recognizing the EEE sector as equally critical as the battery sector, similar measures will be necessary. However, the specific requirements for the DPP in EEE are still under development, with uncertainties surrounding the IT technologies that will support its implementation. Developing DPPs poses a significant challenge, requiring flexible data models to ensure interoperability across evolving regulations and sectors. In this problematic context, the present paper aims to propose a standardized, multi-stakeholder DPP prototype for EEE, based on blockchain technology to ensure transparency and immutability of information. The proposed model is designed to facilitate the adoption of DPPs with a scalable and interoperable approach, ensuring accessibility for all the lifecycle stakeholders involved.

2. Literature Review on DPPs

DPPs have the potential to overcome key barriers to circular product lifecycle information flows, such as those identified by Kurilova-Palisaitiene et al. [10]: lack of awareness, underdeveloped shared value systems, and limited data sharing due to competitive concerns. Various technologies can be employed to create functional DPPs, each serving different purposes across phases such as data collection, curation, sharing, and leveraging [11]. Research by Wiesner et al. [12] identified the static and dynamic information that DPPs must manage throughout a product's lifecycle, which can be categorized into three key data groups: material traceability, sustainability, and product-specific data. Currently, there are over 80 documented DPP initiatives [13], each exploring different architectural choices and sector-specific approaches [14]. However, many of these initiatives face challenges related to scalability, interoperability, and the adoption of decentralized technologies. These initiatives often adopt sector-specific or lifecycle-specific approaches, while others remain at a conceptual stage. Moreover, none of the models fully leverage data to make them Life Cycle Assessment (LCA)-ready, which is essential for ensuring a comprehensive evaluation of environmental impacts. Among the various initiatives, the Standardized Battery Passport Data Model (SBPDM) provides a modular structure adaptable to various battery types, covering the entire lifecycle from cradle to grave [15]. Inspired by this model, a framework is being developed for EEEs to meet the sector specific challenges [16].

Regarding IT architectures for DPPs, several approaches have been explored. Wiesner et al. [12] demonstrated how an architecture integrating the Asset Administration Shell (AAS) at the batch level can serve as a proof of concept for integrating legacy infrastructures. Similarly, Koppelaar et al. [17] proposed an IT architecture for the circular management of CRMs in EEE using DPPs. Expanding on this, Plociennik et al. [18] introduced a DPP model based on AAS for managing post-end-of-life electronic waste, supporting LCA through automated data acquisition. Further, Hulea et al. [19] tested a dual blockchain infrastructure for DPP management, utilizing cheqd.io for decentralized identification (DID) and implementing smart contracts on Hyperledger Fabric. Meanwhile, Nowacki et al. [20] proposed a multisectoral DPP framework incorporating IoT, Distributed Ledger Technologies (DLT) such as IOTA, and smart contracts. Despite progress, key challenges remain. Interoperability across different sectors and systems is limited, while blockchain's high costs and energy demands hinder large-scale adoption [21]. Scalability issues arise as data volumes grow, and integrating legacy systems with newer technologies can be complex. Finally, ensuring user-friendly access to DPP data for stakeholders remains a significant hurdle, as current models lack tools to simplify data use and interpretation.

To address these challenges, the focus of the present study is on optimizing the use of blockchain technology to reduce costs and energy consumption, ensuring scalability for large-scale applications. A fully decentralized IT infrastructure is developed to guarantee interoperability across sectors, while maintaining security and transparency. Additionally, the platform is designed to be accessible, with user-friendly tools that simplify data access and interpretation for all stakeholders, including manufacturers and recyclers. This approach aims to create a more inclusive and sustainable DPP system, supporting the entire lifecycle of EEE.

3. DPP for EEE

The DPP model presented comprises two main components: a data model, as outlined in section 3.1, and a fully decentralized IT infrastructure outlined in section 3.2. Section 3.3 demonstrates practical use scenarios, highlighting how stakeholders interact with the system across different lifecycle stages, from registration to updates and consultation.

3.1. Data Model

The data model is based on parameters identified through the methodology developed by Gianvincenzi et al. [16] which employs a multidisciplinary approach to populate a Foundational Data Model (FDM) — a neutral variant of the SBPDM — following an integrated analysis of technological, regulatory, and lifecycle aspects. From a technological perspective, the product is structured as a modular hierarchy, comprising a *PRODUCT* node and subordinate *PART* nodes. Each *PART* node represents a discrete component of the product, which can be further decomposed into sub-components, facilitating detailed representation and flexibility in the data structure. From a regulatory standpoint, unlike battery sector, the EEE sector lacks a specific regulatory framework providing predefined parameters for the DPP. Consequently, an unstructured approach is required, starting from the ESPR and supplemented by voluntary European standards, as CEN 45552-45559. These standards provide essential guidance for ensuring compliance with sustainability criteria in product design. In terms of lifecycle analysis, both the *PRODUCT* and *PART* nodes are structured with child nodes corresponding to distinct lifecycle phases, including MATERIAL, *MANUFACTURING*, *USE*, *END OF LIFE*

(*EOL*), and *TRANSPORT* nodes. Table 1 delineates the parameters extracted, as well as their allocation within the specific nodes of the FDM.

Table 1: Data model for EEE parameters

Parameter	CEN standard	Position NODE
Expected Useful Life	45552	PRODUCT//USE ATTRIBUTE
Optimum Operating and Environmental Conditions	45552	PRODUCT//USE ATTRIBUTE
Guide to Maintenance and Repairability	45552	PRODUCT//MANTEINANCE ATTRIBUTES
Expected Failure Rate	45552	PRODUCT//ATTRIBUTE
Common Failure Modes and Reliability	45552	PRODUCT// ATTRIBUTE
Part Dimensions X,Y,Z	45553	PART//EOL ATTRIBUTE
Range of Accessibility ΔX, ΔY, ΔZ	45553	PART//EOL ATTRIBUTE
Dismantling Information	45554	PRODUCT-PART//EOL ATTRIBUTE
List of Available Spare Parts	45554	PART//MANTEINANCE ATTRIBUTE
Design for Reuse Information	45554	PART//EOL ATTRIBUTE
Upgrade Options	45554	PRODUCT//MANTEINANCE ATTRIBUTE
Diagnostic Support and Interfaces	45554	PRODUCT//MANTEINANCE ATTRIBUTE
Recyclability rate	45555	PRODUCT-PART//EOL ATTRIBUTE
Number of parts or materials of the product	45555	PART//ATTRIBUTE
Material Mass	45555	PRODUCT-PART//MATERIAL ATTRIBUTE
Recovery Rate	45555	PRODUCT-PART//EOL ATTRIBUTE
Design for Reuse Information	45556	PRODUCT-PART//EOL ATTRIBUTE
Raw Material Name	45558	PRODUCT-PART//MATERIAL ATTRIBUTE
Raw Material Mass	45558	PRODUCT-PART// MATERIAL ATTRIBUTE
Raw Material Type	45558	PRODUCT-PART// MATERIAL ATTRIBUTE
Raw Material Location	45558	PRODUCT//USE ATTRIBUTE

Once the structure of the data model has been identified, it is encoded into an XML schema. This file will then be used as the base for every new DPP created through the IT infrastructure described in the following section and will be populated with product-specific information.

3.2. IT Infrastructure

The architecture consists of four main modules, which operate in synergy to ensure efficient and secure management of DPPs across their entire lifecycle, encompassing creation, consultation, and updates (Fig. 1). The present section outlines the core functionalities of each module and their interactions within the system.

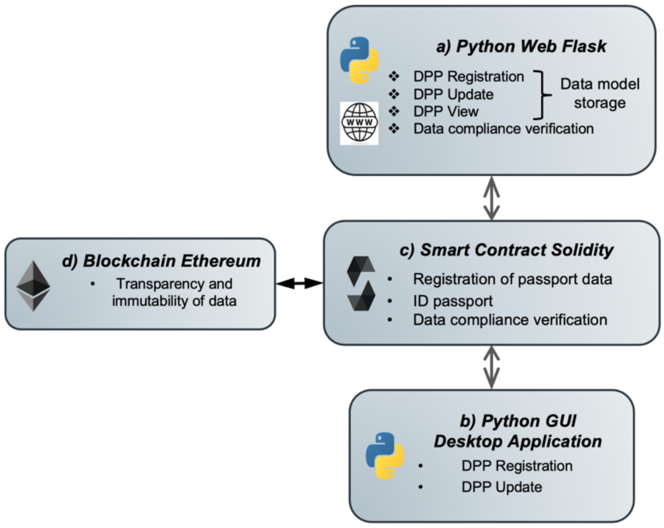

Fig. 1: DPP - IT infrastructure

The *Python Web Flask* platform acts as the interface through which stakeholders interact with DPPs system to consult, verify, and archive them. Additionally, it allows users to download a package containing specific instructions for the stakeholder, the XML schema (base version for creators, or the latest version with updated data for updaters), and the tool described in point b) for managing the DPP. The platform, developed using the Flask web framework in Python, is designed to verify the information before registering it in the system. Specifically, it compares the input data, such as the passport ID and hash, by querying the smart contract, thereby ensuring the integrity and authenticity of the data model.

The *Python GUI Desktop Application*, realized with Tkinter, provides a user-friendly tool for managing DPPs, enabling the creation, update, and verification of passports. It simplifies the process by automating the communication with the smart contract, ensuring that even non-experts can efficiently manage DPPs. The GUI handles the input of the XML-based data model, and once the file is uploaded, it automatically generates the document's hash and transmits it to the smart contract. If a new passport is being created, the smart contract emits the "*AddPassport*" event, while for existing passports being updated, the "*UpdatePassport*" function is triggered. This entire process is handled seamlessly by the system, limiting human errors and barriers to the use.

The *Smart Contract Solidity*, deployed on the blockchain, contains the rules for creating, updating, and verifying passports. Every time a passport is created, the smart contract emits an event and generates a unique identifier (ID) for the passport. This ID, along with the passport hash, the address of the passport creator or updater, and the hash function used, is recorded permanently and immutably on the Ethereum blockchain. To optimize the costs associated with blockchain transactions and ensure accountability among stakeholders, the system converts the XML data model into a hash function, minimizing the amount of data stored.

The *Blockchain Ethereum*: The blockchain operates as a decentralized ledger, recording all transactions related to digital passports, ensuring data integrity and preventing unauthorized changes.

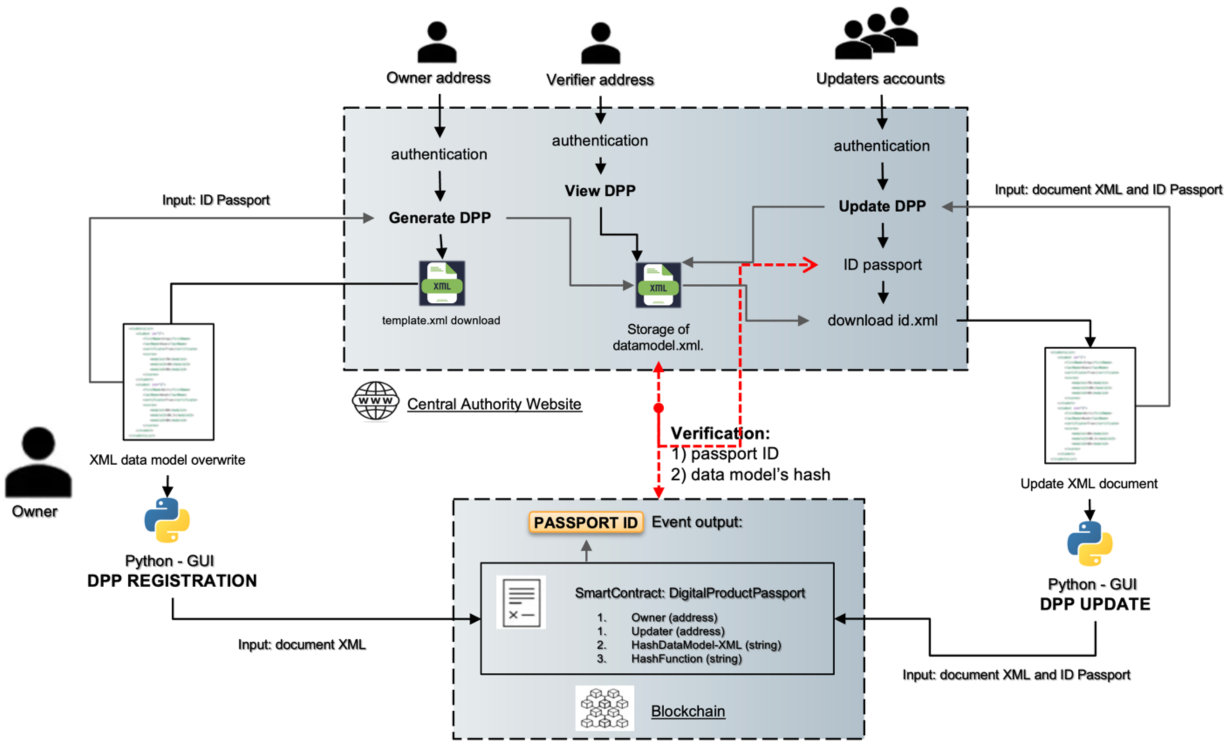

Fig. 2: DPP - Use Scenario Workflow

3.3. DPP Use Scenarios

The DPP management system is used by various stakeholders throughout the entire product lifecycle. Fig. 2 illustrates how each actor interacts with the IT infrastructure modules at different stages based on their specific operational needs, access profiles, and use scenarios:

- *Generate DPP*: In the process of registering a new passport, the manufacturer or designated user (defined as Owner) authenticates on the web platform to download the XML data model (*template.xml*) and the *.py* file to launch the GUI locally. The user updates the data model by entering product or part-specific information. Through the GUI, a blockchain transaction is executed, registering the data model's hash, the hash function used, and the owner's address on the contract. This occurs only after the user inputs the contract ID and selects the XML document for the hash calculation. In output, the GUI returns the newly generated passport ID via the "*AddPassport*" event. Finally, after authentication, the data model is archived in the web platform's database, but only after the passport ID and hash are automatically verified through interaction with the blockchain by the platform.
- *Update DPP*: This phase is intended for suppliers, maintenance technicians, recyclers, or any actor involved in modifying a passport (defined as Updater), and the process is consistent across all use cases. After authentication on the web platform, the system prompts the user to enter the passport ID to download the data model that requires updating. Once the necessary changes are made, the user launches the GUI, which requests the passport ID and the updated XML file to compute the new hash and register it on the smart contract. Finally, as in the registration phase, the updated data model is archived in the central database via the platform, replacing the previous version after automatically verifying its integrity through hash matching and recording the modification.
- *View DPP*: Authorized stakeholders (defined as Verifier), such as regulatory bodies, can access the web platform to consult DPPs. By entering the passport ID and authenticating with their credentials, they can view passport's information to verify its compliance and data integrity.

4. Case study

4.1. Washing Machine DPP

To evaluate the objectives related to multi-stakeholder collaboration within the supply chain using the distributed DPP system, a case study was conducted focusing on the creation and updating of a DPP for a washing machine. This case study follows the workflow outlined in section 3.3, from which the data model was derived. The system has been tested in a local Ganache network, simulating an operational environment under realistic conditions. A small excerpt of the model is presented in Fig. 3.


```xml
<!-- PRODUCT -->
<tns:Product>
  <!-- PRODUCT ATTRIBUTES -->
  <tns1:Product_Attributes>
    <tns1:ProductCategory>LARGE HOUSEHOLD APPLIANCES</tns1:ProductCategory>
    <tns1:ProductType>WASHING MACHINE</tns1:ProductType>
    <tns1:TotalMass Unit_of_Measurement="kg">70</tns1:TotalMass>
    ...
  </tns1:Product_Attributes>
  <!-- PRODUCT MANUFACTURING -->
  <tns:Product_manufacturing>
    <tns3:Process>
      <tns4:ProcessAttributes>
        <tns4:ProcessID>ASID100</tns4:ProcessID>
        <tns4:ProcessName>1. Assembly of the basket and drum</tns4:ProcessName>
        <tns4:ListOfAssemblyParameters>list</tns4:ListOfAssemblyParameters>
        <tns4:LCAProcessParameters>
          <tns4:Water>
            <tns4:Value>0.1</tns4:Value>
            <tns4:Unit_of_Measurement>m^3</tns4:Unit_of_Measurement>
          </tns4:Water>
        </tns4:LCAProcessParameters>
        <tns4:Manufacturing_Date>2024-05-04</tns4:Manufacturing_Date>
      </tns4:ProcessAttributes>
      <tns4:Material>
        <tns5:MaterialAttributes>
          <tns5:Raw_Material_Name>lubricating oil</tns5:Raw_Material_Name>
        </tns5:MaterialAttributes>
      </tns4:Material>
      <!-- ENVIRONMENT NODE -->
      <tns4:Environment>
        <tns6:RecipeMid_Point></tns6:RecipeMid_Point>
      </tns4:Environment>
    </tns3:Process>
    ...
  </tns:Product_manufacturing>
  <!-- PRODUCT EOL (END OF LIFE) -->
  <tns:Product_EOL>
    <tns9:RecyclingRate Unit_of_Measurement="%">85</tns9:RecyclingRate>
    <tns9:RecyclabilityIndex Unit_of_Measurement="%">80</tns9:RecyclabilityIndex>
    <tns9:DismantlingInstructions>Remove motor before disposal</tns9:DismantlingInstructions>
    ...
  </tns:Product_EOL>
  <tns4:Environment>
    <tns6:RecipeMid_Point></tns6:RecipeMid_Point>
  </tns4:Environment>
  <!-- PART INSERTED BY SUPPLIER (WASHING MACHINE MOTOR) -->
  <tns:Product_Part>
    <tns10:Part_Attributes>
      <tns10:Part_ID>00061A</tns10:Part_ID>
      <tns10:Part_Name>Washing Machine Motor</tns10:Part_Name>
      ...
    </tns10:Part_Attributes>
    <!-- PART TRANSPORT -->
    <tns10:Part_Transport>
      <tns7:TransportScenario>
        <tns7:Distance Unit_of_Measurement="km">900</tns7:Distance>
      </tns7:TransportScenario>
    </tns10:Part_Transport>
  </tns:Product_Part>
  <!-- PART INSERTED BY MAINTAINER -->
  <tns:Product_Part>
    <tns10:Part_Attributes>
      <tns10:Part_ID>00071A</tns10:Part_ID>
      <tns10:Part_Name>Replacement Motor</tns10:Part_Name>
      ...
    </tns10:Part_Attributes>
  </tns:Product_Part>
</tns:Product>
```


Fig. 3: XML Data model for a washing machine (Responsible: Orange - Owner; Green - Supplier; Blue - Maintenance technician; Red - Recycler)

During the simulation, the following use cases were followed:

1. *Owner* (orange box in Fig. 3). The appliance manufacturer, responsible for registering the digital passport, completes the data model with the information in its possession, including lifecycle data: Manufacturing, detailing the parts produced internally; Use, providing product performance data; End-of-Life (EoL), outlining disassembly processes; Transport. This process is carried out via the GUI, after which the updated model is transmitted to the web platform for verification and secure storage within the blockchain.

1. *First Updater* (green box in Fig. 3). The supplier, an external manufacturer of the electric motor, updates the digital passport by adding a new *PART* node to the data model's tree structure, representing the integration of the supplied component. As with the subsequent Updaters, this process is carried out using both the GUI and the web platform.
2. *Second Updater* (blue box in Fig. 3). The maintenance technician replaced the electric motor and subsequently updated the washing machine's passport by adding a new "part" node corresponding to the replacement. This update reflects the maintenance operations performed.
3. *Third Updater* (red box in Fig. 3). A recycler modifies the digital passport to include information regarding the end-of-life processes of the washing machine in PRODUCT node and of the specific components in the PART nodes.

Passport Visualization. An authorized regulatory body accesses the web platform to consult the information contained in the passport.

4.2. Discussion

The analysis and testing of the DPP prototype demonstrated its ability to address critical gaps identified in the literature, particularly in functionality, scalability, and interoperability. By leveraging blockchain technology, the system ensures decentralization and accountability through hashing algorithms, maintaining data integrity and immutability—key aspects often lacking in previous DPP initiatives [12, 18]. This work directly tackles barriers such as fragmented information flows and fear of competition, as highlighted by Kurilova-Palisaitiene [10]. The modular XML schema enables interoperability across sectors, while the combined use of the GUI and web platform decentralizes responsibilities, fostering transparency and collaboration among stakeholders. These advancements address the underdeveloped shared value systems and limited data-sharing mechanisms cited in previous research. Moreover, the workflow minimizes blockchain transactions and optimizes data storage by converting the data model into a hash, reducing costs while preserving integrity. Unlike earlier models that struggled with scalability and high transaction costs [21], this design ensures the system's adaptability to resource-intensive industries. The DPP also enhances traceability and transparency by recording every lifecycle modification, addressing information uncertainty and inflexibility. By providing a structured, lifecycle-ready framework, the prototype bridges the gap between conceptual models and practical implementation, creating a robust foundation for LCA. These improvements position the DPP as a scalable and interoperable solution that addresses the shortcomings of existing initiatives, while offering cross-sector applications and advancing the goals of circular economy practices. Beyond administrative benefits, the DPP enhances lifecycle management by fostering transparency and data-driven decision-making. It encourages manufacturers to address the environmental impacts of their products while enabling policymakers to promote sustainable practices through verifiable data. By countering greenwashing and driving accountability, the DPP has the potential to influence sustainable product design and supply chain practices in the long term. Although this research focuses on the EEE sector, the proposed approach is inherently flexible and adaptable to other industries adopting the FDM. The system provides a scalable framework for adoption in sectors like automotive, furniture, and even fast-moving consumer goods. Challenges specific to each industry, such as varying regulatory requirements or material complexity, can be addressed by customizing the data parameters within the FDM. Despite these achievements, several challenges emerged during testing. The management and operation of the system highlight the need for the establishment of a supervisory body tasked with overseeing the integrity and security of the entire infrastructure. This body would ensure compliance with international standards and regulations, a crucial requirement for widespread adoption across various sectors. Another limitation lies in the complexity of the processes required from stakeholders. Despite the significant reduction in knowledge barriers due to the high level of automation in the communication between the DPP system and the smart contract, challenges remain. The current reliance on manual XML document compilation is still a potential source of errors. Further automating or simplifying this process would be essential to alleviate the technical burden on users and minimize the risk of human error. Moreover, the management of sensitive information within the system remains a concern. Although blockchain ensures transparency, implementing mechanisms for granular access control is essential to restrict sensitive information access or modifications to authorized users.

5. Conclusions

The prototypal DPP presented in this paper represents a significant advancement in enhancing product traceability and promoting lifecycle management for EEEs. By leveraging a fully decentralized architecture based on blockchain technology, the system ensures transparency, accountability, and data integrity, addressing key challenges in circular lifecycle information management. The flexible FDM allows adaptation to diverse product characteristics, making the system applicable across sectors and capable maximizing the exploitation of input data supporting robust LCA. Additionally, the design minimizes transaction costs through efficient data hashing mechanisms, ensuring scalability and economic feasibility for industries with resource-intensive supply chains. While the prototype demonstrates promising results, further refinements are needed to facilitate large-scale adoption. Real-world testing is essential to validate its scalability, interoperability, and financial sustainability. Enhancements to data security, including more granular access controls, and the development of automated tools for XML data model compilation will be critical areas for future improvement.

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