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A digital platform for cross-sector collaborative value networks in the circular economy

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Abstract

In recent years there has been a growing interest in Circular Economy (CE), which promises to reduce waste and improve sustainability. The promise of CE is to change the conventional "take–make–dispose" that causes massive waste flows based on the integration of demanufacturing and remanufacturing processes within value chains. This integration requires breaking the "silos" of the circular chain to establish new collaborative and sustainable value networks. The paper introduces a novel digital platform for the CE, which is currently under development in the H2020 DigiPrime project. The platform is destined to facilitate seamless and trusted information exchange across circular actors, while offering a range of value-added services that enable manufacturers, remanufactures, recyclers and other actors to gain insights in the status of recycling and waste management processes. The latter facilitates the implementation of zero waste processes, along with the assessment of the performance of the circular chain. The paper introduces the architecture of the digital platform, along with its data modelling, exchange and data traceability mechanisms. It also presents a CE use case used to validate the platform.

Keywords: Circular Economy; Demanufacturing; Remanufacturing; Supply Chain Management; Lifecycle Assessment; Data Analytics; Blockchain

1. Introduction

The vision of CE is to change the current linear "take–make–dispose" economic approach, which causes massive waste flows. The CE paradigm brings restorative and regenerative approaches by intention and design [1]. Recent studies show that a transition to CE may represent a new sustainable growth path as well as a business opportunity for the worldwide industry [2]. A new industrial model that decouples revenues from material input, and production from resource consumption is needed for achieving a sustainable development path, both in early-industrialized countries and in emerging economies. Nevertheless, there is a proclaimed structural gap between the CE vision and current industrial practices. CE is implemented by collecting post-use products through reverse logistics systems. It performs demanufacturing and remanufacturing operations to recover reusable materials and components from the product and to sell them back to the manufacturing industry for re-use in new products or in spare parts for aftermarket services. This model is effective and economically sustainable only for simple products and for specific classes of materials such as steel. It cannot be effective in cases of smart products with embedded intelligence, which poses significant challenges to the implementation of sustainable CE practices in the future.

An interesting opportunity for establishing sustainable value networks for high value-added products is the creation of cross-sector circular value-chains, where the residual value of a product is maximized by establishing alliances between stakeholders in different sectors. This hinges on transferring the product components and materials from the original sectors into applications in different sectors. For example, glass fiber (GF) and

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carbon fiber (CF) reinforced polymer composites have revolutionized important manufacturing sectors, such as transport (e.g., automotive, aircraft, boats) and construction (e.g., building and infrastructures, plants, wind turbines), due to their lighter weight and better corrosion resistance with respect to metals. Also, materials coming from waste parts in wind energy industries have sufficient mechanical properties suggesting their re-use in other sectors, such as the automotive sector. Similarly, the automotive industry is undergoing a transformation pervaded by the transition from traditional fuel cars to Electric (EV) and Hybrid (HEV) vehicles. This revolution is accompanied by a transformation in the car design, featuring an evolution in the car components and materials. Lithium-ion Battery packs (LiB) constitute one the most important car components, making up 35-50 percent of the cost of the EVs. This change brings at the same time a challenge for post-use product treatment and a huge opportunity for new CE businesses, affecting the entire automotive value-chain.

1.1. Circular Economy Challenges

While the above-listed cross-sector scenarios are very promising, there is still no easy way for implementing them in practice. The implementation of promising cross-sector sustainable value-chain opportunities is strongly bounded by various limitations. First, product data and knowledge is not seamlessly exchanged among manufacturers and demanufacturers and remanufacturers, nor among different sectors. This is a serious setback to unlocking cross-sector material re-use. Second, there is no exchange of recovered component and material information among sectors. This is a barrier to novel CE models, that hinge on cross-material re-use. Third, there is a lack of certification protocols for secure re-used materials and components transfer among sectors. Finally, there is also poor acceptability of products embedding recycled materials by end-customers. This is partly due to the poor visibility of customers in the circular chain. The digital transformation on industrial enterprises could alleviate some of the above-listed limitations. For instance, a digital platform could enable the trusted and secure exchange of information about demanufacturing and remanufacturing materials between circular actors. Likewise, it could facilitate the traceability of different entities like materials, products, and waste indicators.

1.2. Related Work

The importance of IT-based platforms and digital technologies (e.g., BigData, Artificial Intelligence (AI)) have been validated in a variety of supply chain applications, including applications with CE aspects. E.g., in [3] the use of BigData technologies for linking aggregated real-time customers' application pattern to the product design and manufacturing phase in the automotive industry is discussed. As another example, in [4] a CE case in the construction industry is presented. The work leverages digital information and tools (e.g., Building Information Modelling (BIM)) for integrating CE concepts and data in the supply chain, with the goal of improving waste efficiency in building design. In this direction waste analytics and reporting for construction supply chains are also implemented. A broader range of sectorial cases studies are presented in [5]. Other work has introduced digital platforms for CE value chains and applications. In [6] requirements for a digital platform to support batteries recycling are outlined, along with general benefits in improving economics and sustainability. The work focuses on how IT-based platforms can support management, legislative and social perspectives of CE systems. The latter perspectives are particularly important for Small Medium Enterprises (SME) that engage in CE networks [7].

Recently, digital technologies such as blockchains, Cyber Physical Systems, and AI have been used to enhance the functionality, trustworthiness and reliability of CE platforms. E.g., Distributed Ledger Technologies (DLT) [8] provide means for secure and resilient information exchange across value chain networks. As another example, the EU-funded KYKLOS 4.0 project is currently developing a platform that combines Cyber Physical systems, AI and Augmented Reality to enable CE functionalities in production related pilot applications, including product life-cycle management and life-cycle assessment [9]. However, state of the art digital platforms do not address the need for cross-sector value networks and do not interconnect all the business actors of the circular chain. Hence, they are not sufficient to support the next generation of value-added cross sector CE networks.

1.3. Paper Structure and Contribution

In this paper, we introduce a novel platform that is destined to support cross-sector end-to-end interactions for CE applications, namely the platform developed in the H2020 DigiPrime project [10]. This project develops and showcases a CE digital platform that overcomes current information asymmetry among value-chain stakeholders, in order to unlock new circular business models. The platform supports the data-enhanced recovery and re-use of functions and materials from high value-added post-use products with a cross-sector approach. We present its logical architecture in terms of its main digital components and the structuring principles among them. We also present how the platform manages CE data. The paper is structured as follows: Section 2 presents the logical architecture of the platform, emphasizing on user authentication and authorization, data sharing aspects and the use of distributed ledger services for data traceability. Section 3 is devoted to the presentation of the main data management principles of the platform, including the modelling of CE information. Section 4 outlines indicative CE use cases where the platform will be validated and evaluated. Section 5 concludes the paper.

2. DigiPrime Digital Platform Architecture

Figure 1 illustrates the main components of the DigiPrime platform for cross-sectorial CE collaborative networks. The platform is an IT system that enables digital data collection and data acquisition from the business actors of the circular chain, including for example manufacturers, demanufacturers, remanufacturers, recyclers, certification authorities and more. These data are stored in the platform and used to provide a range of

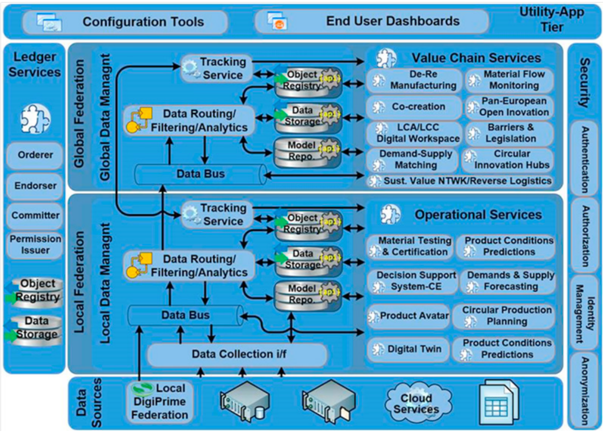

Fig. 1. **Logical Architecture of the DigiPrime Platform**

value-added services to the various stakeholders. These services can be classified into two broad categories: (i) Operational Services that are typically restricted to the across within a specific sector and (ii) Value Chain Services that are provided across the cross-sector value chain. The platform enables the different stakeholders to access the outputs of these value added services. The overall design of the platform is driven by a review of common requirements in the sector, which has also led to the specification of the main services that are supported by the platform. Furthermore, the platform design and implementation has taken into account guidelines and best practices from reference architecture models for industrial applications. Specifically, the data collection and processing functionalities of the platform are influenced by the reference architecture of the industrial internet consortium (IIRA) [16], while the cross-organizations, data exchange and value chain functionalities follow the design principles for the industrial data spaces published by the industrial data spaces association [15]. Finally, the operation of the platform is empowered by different types of services, which are described in following paragraphs.

2.1. *Security and Identity Management Services*

The DigiPrime platform comprises authentication and authorization services, which are applicable to both local and global federations of DigiPrime. They include:(i) **Authentication**: Authentication of the various users of the DigiPrime digital platform. (ii) **Authorization**: Provides stakeholders with access to the capabilities of the platform in-line with their roles in the circular chain; (iii) **Identity Management**: A set of framework services and policies that manage users' authorizations within the digital platform. It manages multiple authorizations and authentications in heterogeneous environments (e.g., credentials like certificates and single sign on functionalities).

2.2. *Data Sources - Data Collection*

The digital platform is a data-driven system, which facilitates the structured exchange of data across different CE stakeholders. Different data sources can be integrated in the platform to collect information about products, materials, recycling processes and more. Data sources are integrated within a local federation. It is assumed that individual data sources are not provided as direct inputs to a global federation. This is because global federations comprise data provided by two or more local federations rather than individual data sources.

2.3. *Local and Global Federations for Data Sharing*

A local federation enables the exchange of data and services interactions between stakeholders within a specific sector or business domain. In support of a local federation, the DigiPrime architecture specifies the following services: (i) **Data Storage**: Hold data about the circular economy processes and their support by DigiPrime. They provide the means for sharing, storing and managing data about all the key entities managed by the platform, including sharing products, components and materials information across stakeholders. (ii) **Models Repository**: Hold various models that will be specific to the DigiPrime services, such as Product Condition Prediction and Lifecycle assessment models and potentially models for specific services of the DigiPrime digital platform. (iii) **Operational Services**: Enables data sharing and service interactions across the Operational Services of the DigiPrime digital platform.

A global federation of the architecture enables cross-sector data sharing and service interactions. It provides similar services and functionalities as the local federation, but in a cross-sector context. It includes the following elements: (i) **Data Bus**, for seamless data transfer across the various components. (ii) **Data Routing and Processing** that enables pre-processing and routing of data streams to the various components. (iii) **Tracking Service** that tracks objects and processes. (iv) **Object Registry** that provides information about physical objects (components, materials, products). (v) **Data Storage** that enable the management and exchange of data. (vi) **Models Repository** that manages models used by services of the global federation. (vii) **Value Chain Services** that enables data sharing and service interactions across the Value Chain Services. The combination of the global and local federation concepts provides a two-level approach to support data exchange. The distinction between global and local federation is primarily logical. From an implementation perspective, local and global federations share data using similar technological infrastructures. However, local federations support intra-sector interactions, while global federations enable the cross-sector interactions.

2.4. *Operational Services and Value Chain Services*

On top of the Data repositories and the data management services, Operational services are implemented: (i) **Product Avatar tool**: Acquires and stores product lifecycle information to support end-of-life decision making. (ii) **Product conditions prediction service**: Calculates correlations between a remanufactured product and the current product condition, supporting users in predictions and estimations. (iii) **Decision Support System for CE**: Defines the best strategy for post use (re-use, recycle, substitute, remanufacture). (iv) **Demand and Supply forecasting tool**: Leverages information from product sales and availability forecasts in terms of the need of components, to support actors in planning and assessing their circular business cases. (v) **Circular production planning**: Integrates existing production planning with Decision Support System (DSS) for CE recommendations. (vi) **Material Testing and Certification repository**: Collects past-experiences and defines a procedure for material testing and certification.

The Value Chain Services include: (i) **De- and remanufacturing data management and share**: Allows users to have access to a large amount of information provided by the entire ecosystem. (ii)**Co-creation environment**: Collects and share ideas on new product/processes. (iii) **LCA (Lifecycle Assessment) tool with a digital collaboration workspace**: Enables the identification of new potential and sustainable circular routes for the products, across different value-chains, and starting from the design phase. (iv) **Demand-Supply matching tool**: Provides search criteria on products, and supports negotiation and traceability. (v) **Value-network configurator**: Supports actors to maximize the cross-sectorial performance guiding users in identifying partners in the ecosystem. (vi) **Material flow monitoring system**: Provides an aggregated view of components and materials that circulates across the nodes, based on an advanced visualization interface.

2.5. Ledger Services

The ledger services support decentralized and trusted sharing of data. Specifically, the platform exploits the security, decentralized trust and anti-tampering properties of DLT [13] to support data provenance and traceability through recording metadata about each CRUD (Create Update Delete) data operation. The traceability serves a two fold objective: (a) ensures the transparency of data operations, and (b) enables the extraction of platform usage information. The ledger services are provided by a permissioned blockchain based on Hyperledger Fabric [14]. It offers better performance when compared to public blockchains, as it does not need to implement computationally expensive Proof-of-Work (PoW) schemes. The ledger services provide means for peer nodes to read and write in the blockchain, and to execute smart contracts that alter the state of the data tracked and traced in the blockchain. While the circular data will be persisted in centralized repositories of local and global federations, their traceability metadata along with the applicable data policies are stored and tracked in the blockchain. The blockchain holds metadata and is used for data provenance and the extraction of usage statistics that empower the platform's business model, as illustrated in the following paragraph.

Figure 2 illustrates how the DigiPrime blockchain is integrated to form a data sharing network using popular technologies like the Java programming platform and MySQL database management system. The integration leverages the services of an identity and access management platform, namely Keycloak, that provides authentication services. This platform may exchange information with the blockchain to support different use cases, notably those entailing changes in data policies. Although the blockchain enables decentralized operations, a Certificate Authority (CA) is needed to manage permissions in the permissioned blockchain. The CA controls which organizations participate in blockchain. Data owners and recipients interact indirectly with the blockchain via RESTful APIs exposed by

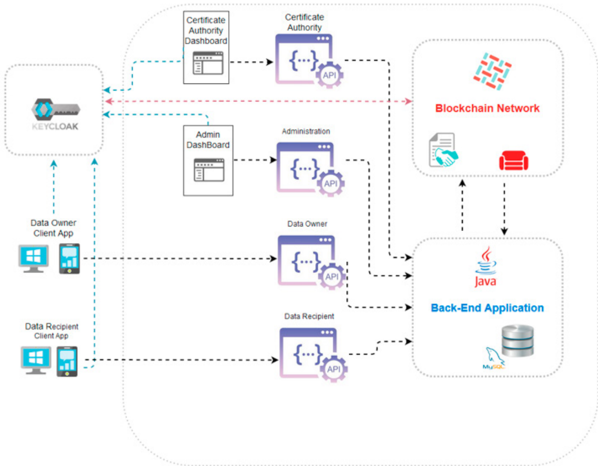

Fig. 2. **DigiPrime Blockchain Services Platform**

Back-End services. Administrative tasks are carried out through a dedicated dashboard.

2.6. Dashboards and Utility Applications (Utility-App)

A set of utility applications to facilitate the deployment, configuration, and operation of the platform. They reside at a separate tier of the platform (i.e. Utility-App tier) and include: (i) Configuration Tools to configure the different infrastructures and components as well as functionalities for the different repositories; and (ii) End-user dashboards for business information about data tracked in the platform (e.g., products, materials), their history, state changes etc., and the service outputs.

3. Modeling Circular Data Entities

CE use cases are diverse and involve different stakeholders from various sectors. Therefore, it is not realistic to design a single static data model for CE use cases. Rather there is a need for an extensible model that can be enhanced to support cross-sector CE interactions. The DigiPrime data architecture enables an extensive modelling and management of data entities used in CE use cases. The modelling starts with a baseline data model comprising the most prominent entities of CE applications, including models for a Company (i.e. the base entity of the model), a CircularEntity comprising internal and external resources such as materials, processes, and services as shown in Figure 3. The baseline data model defines the interrelationships between the various entities. A company is linked to a sector and one or more value chains. The model is abstract and can be instantiated to accommodate different needs and use cases in various sectors and CE value chains.

Figure 4 presents the high level data management architecture of the DigiPrime platform, which makes provision for data storage, data search, ontology management, and orchestration. These services are provided at local level and orchestrated at a global level (i.e. cross-sector).

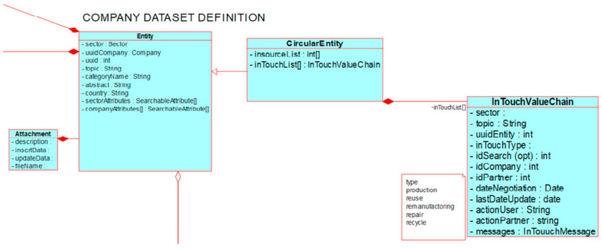

Fig. 3. **DigiPrime Circular Entity Data Model**

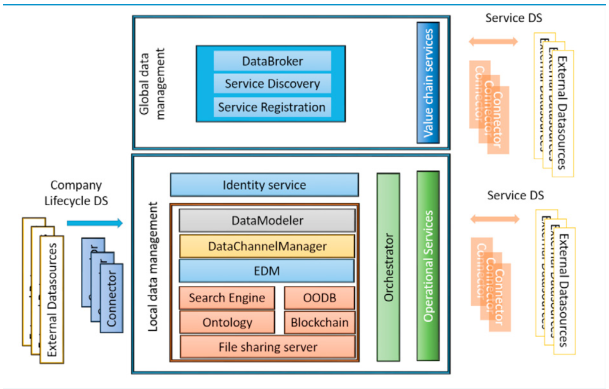

Fig. 4. **Data Management Architecture**

3.1. Extensible Data Management

The data storage services layer comprises an Extensible Data Manager (EDM) as front-end middleware (Figure 4). EDM allows platform services to interact with many different persistence layers without special data management skills, using a single API. Key to supporting multiple persistence layers (i.e. multiple systems that persist data) is the concept data polymorphism i.e., the management of a data entity based on different data structures and formats. This is important for supporting cross-sector interactions, through the management of data sources (DS) at the level of the internal repository, as well as external data sources. Overall, the EDM component reduces the complexity of persistence management for end-users and lowers the barriers for CE developers to use the platform.

3.2. Ontology Service

This is a local service providing an interface to a triplestore layer for use case specific semantics. It provides data checking and data control functionalities to help users understand whether expandable attributes sets and data enrichment prerequisites can be effectively combined. The service enables cross-sector services to match entities/attributes combinations in one sector to related pairs in other sectors. This is useful as different sectors may label related attributes differently. The Ontology service offers an inference rules mechanism, which enables the extraction and inference of new facts by reasoning on the data present in the data model.

3.3. Data Search

Data Search services are important for tracking and tracing the status of circular data entities, as well as their lifecycle through the platform. A common operation of the CE involves collecting and integrating all the data that concern a circular data entity. In this case, there is a need for navigating all the datasets of the involved parties in the circular chain to discover the lifecycle of an entity. E.g., when dismantling a car, the user could be interested in finding lifecycle data and shared datasheets of a battery, by searching topic and serial number on all federation sector nodes.

3.4. Orchestrator

Integrates all the data services and interconnects them with other platform parts, taking into account security, service discovery and registration. For example, the orchestrator service facilitates choosing the right EDM sectorial instance or finding the required value chain services. In essence, the orchestrator is the point of contact between end-users and data and between sectorial services and value chain services and the platform.

3.5. Data Driven Business Model

The platform supports a utility-based data driven business model based on a "data-as-a-service" paradigm. Circular actors get credits for using the platform based on contributed data points. Likewise, the utility that circular actors get from platform is measured based on the accessed data points. Such measurements are supported at the level of the data model and based on the traceability functionalities of the blockchain. The latter enables credible access to the statistics about the data points contribute to or accessed from each participant to the platform.

4. Circular Economy Use Case: Li-Ion Batteries

The use case focuses on remanufacturing and reuse of second life Li-Ion battery cells with a cross-sector approach linking the e-mobility and the renewable energy sectors. The goal is to re-use battery cells that feature suitable residual performance suitable for less-demanding stationary applications. Currently, Energy Storage Systems (ESS) cannot directly benefit from new Li-Ion batteries due to their cost although they could take advantage of recycled batteries as part of CE business cases. The value of the DigiPrime platform lies in: (i) **Proactively tracing the health and availability of batteries** to decide which batteries can be recycled for secondary use. (ii) **Offer visibility on the structure of the battery packs** to adjust the demanufacturing and remanufacturing strategy and enable the selection of the most proper cells for re-assembly second-life use. (iii) **Identify excessively degraded cells which cannot be re-used** and should be sent to high value recycling, based on their material compositions. To support these functionalities, the DigiPrime platform provides various services that facilitate stakeholders' collaboration in the CE chain, including the examples below.

4.1. Demand-Supply Matching

This service performs a match-making between the demand and supply of post use components and recyclable materials.

The match-making process entails: (i) Support for Negotiation and (ii) Traceability of transactions and contractual agreements. It implements auctions between the supply and the demand side targeting market equilibrium. The service is realized as follows: (i) the different stakeholders are authenticated and authorized via the user management services; (ii) demand side stakeholders provide via the data collection interfaces the information about the battery products they would like to purchase; (iii) demand side stakeholders visualize information via the dashboards; (iv) Authorized car dismantlers access information about requests for batteries and components by different remanufacturers and recyclers; (v) Remanufacturers and recyclers leverage the data collection interfaces of the platform to provide information about post-use batteries and components. They also visualize available offers from different providers. Finally, the platform is also used for coordinating and moderating the negotiation process. This goes beyond simple search and access functionalities, leveraging the orchestrator's functionalities.

4.2. Manufacturing data management

This involves management and sharing of demanufacturing and remanufacturing data. It is conceptually supported as a global federation of different stakeholders, which supports the establishment of a cross-sector value chains. Different stakeholders are authenticated and authorized to participate to the global federation. Accordingly, they contribute information to the value chain service via the data collection interfaces, including web forms, CSV, and JSON data interfaces. Data sharing is realized as follows: (i) OEM and car manufacturers provide the technical information about the battery, components and product chemistry information, along with the data structure of the battery management systems (BMS) and (ii) Remanufacturers provide requirements and information needed for disassembly and remanufacturing. The information is routed and persisted in the data repositories (i.e. data storage) of the platform, where is it accessed via data query interfaces provided by the various stakeholders: (i) OEMs access batteries EOL information provided by battery collection centers, remanufacturers and recyclers after the post use and post remanufacturing phases; (ii) Authorized car dismantlers access information about batteries' technical information for their inspection, diagnostics and dismantling processes; (iii) Remanufacturers access technical data about batteries of different models towards supporting their remanufacturing operations in a safe and efficient way; (iv) Recyclers access information about batteries' chemistry and the material compositions of different models. In accessing this information the object tracking service of the platform is used.

5. Conclusions

The presented platform unlocks the potential of cross-sector recycling scenarios. Its main highlights are: (i) A Support for cross-sector data sharing; (ii) Decentralized data traceability; (iii) Configurable and extensible approach to managing data; (iv) Support for complex CE workflows via search and orchestration. The platform provides support for a rich set of operational and value chain services, which support real-life CE systems. Several parts of the platform are currently under development and validation in the context of different CE applications. Our vision is to provide a platform that will be appealing to CE stakeholders due to its support for trusted sharing and data traceability. The success of the platform will be tracked against stakeholders' participation and data points availability. The value of the platform will be gauged against the useful data points that it will comprise. The latter data points will be the main incentive for CE actors to engage with the platform.

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