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Digital product passports as enablers of digital circular economy: a framework based on technological perspective

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Abstract

Taking into consideration the existing Industry 4.0 infrastructures and the rise of Industry 5.0 (I5.0), more and more solutions are being developed, aiming towards increased environmental consciousness through advanced technologies, and human centricity. However, there are ongoing requirements on data traceability, and access to the related actors, to ensure the establishment of sustainable solutions, within the context of a digital circular economy (DCE) environment. Digital product passports (DPPs) constitute such novel technological solution that can enable the transition toward DCE and sustainable I4.0 and I5.0, as digital identities that are assigned to physical products, capable of tracing their lifecycles through data such as their technical specifications, usage instructions, and repair and maintenance information. Although the respective research community has started providing a thorough analysis of DPPs potential to constitute a CE enabler, their technical requirements are still unclear. As part of our contribution to this issue, we propose a fundamental CE framework with integrated DPP characteristics, with the potential of being adapted in different sector stages for the generation and distribution of DPPs both for stakeholders and consumers. The corresponding solution is further supported through a systematic literature review that follows a technological approach to the DPPs implementation.

Keywords Digital circular economy · Digital circular economy framework · Digital product passports

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1 Introduction

Circular economy (CE) is a concept that gradually attracts the attention of both the research community and global initiatives, for the utilization of re-functionalities through a variety of application fields. The particular concept is further evolved through the implementation of digital technologies for additional enhancement of the corresponding functionalities.

Digitalization of CE emerged due to the ongoing need for real-time information and data, regarding the condition of products and services, tracking the reusability of components and materials, and overall management of utilized resources. Steadily progressing, initial research attempts focused on examining the potentiality of combining digital technologies and characteristics such as re-functionalities in industrial environments and businesses, aiming towards the evolution of traditional CE, as seen in [1, 2]. Similarly, the first steps towards practical implementation of the concept began by researching digitalized circularity principles in the supply chains of electronic devices, as seen in [3].

Considering the impact of I4.0 and the rise of Industry 5.0 (I5.0) in terms of efficiency and the promotion of sustainable manufacturing industries through the implementation of appropriate digital technologies, as also stated by the European Commission [4], a digitalized CE is capable of providing the required feedback on the circularity performance of such infrastructures [5]. Some of the main technologies structuring such Digital CE solutions are the Internet of Things (IoT) for proper functionality and overall efficiency of data collection and processing, Big Data due to the quantity of the collected data, artificial intelligence (AI), and machine learning (ML) for advanced accurate prediction and automation of tasks and results, Cyber-Physical Systems and Cloud Computing for smart interconnection between processes, as seen in [6–8].

At the same time, digital certifications or identities of products and services are approaches gradually being empowered by the European Commission, focusing on the registration of data and information by production companies [9]. Originally, a digital certificate is updated throughout the production process, with shipping details and status being updated through timestamps. As a result, the customer is capable of verifying the authenticity of the product or service with the data provided in the digital identity [10], while also enabling the concept of digital servitization, by focusing on service-based principles towards the related actors [11]. Such certification systems can be applied in key value chains, such as electronics, batteries and vehicles, packaging, plastics, textiles, constructions, and food [12], as well as the health sector, e.g., COVID-19 passports implemented during the global pandemic [13].

Digital product passports (DPP) are part of the "Circular Economy Action Plan" and promoted by the European Commission as a system of potential CE solutions [14]. A DPP can be considered a byproduct of the corresponding union between CE and digital technologies, signifying the importance of data for the overall efficiency of circular approaches [15]. As a fairly new strategy in the context of CE, its main objective is the initiation and maintenance of communication among stakeholders, in the form of logs, containing relative information on materials and components used in products and services. The indicative process is established as a collaboration between producers and recyclers, resulting in a thorough data sheet, assisting in the optimization of product design and its lifecycle, as well as proper tracking and management of the respective components and materials [16].

Our main contribution is the introduction of a digital CE framework, with integrated DPP principles and the potential for adaptability. It is structured into the essential components required for the generation of two DPP versions with indicative suggestions on suitable technologies for each component based on the available literature, and further supported through a theoretical use-case scenario. Moreover, we hypothesize and separate the structure of a DPP into three different data tiers, for the proper organization of the corresponding technologies according to their functional purpose, supported by a thorough analysis of prior academic work. However, although additional factors are involved within a conservative digital CE approach, such as the impact of end-user participation in the circular motion, our work is purely focused on the technological perspective of DPPs.

The structure of our study is as follows: In Sect. 2 we study related published academic papers on the topic of DPPs. Section 3 presents the process followed in regard to conducting the respective research. Section 4 is focused on the fundamental analysis of technologies for three different data tiers of a DPP: Data Collection, Data Curation and Sharing, and Data Leverage supported by previously proposed solutions and mechanisms that utilize the corresponding technologies. Meanwhile, it presents our proposed solution based on the initial technological research and associates the analyzed technologies with each component of the framework respectively. Section 5 utilizes the suggested framework through a representative use case scenario, by taking into consideration fundamental requirements and clarifying its impact. We close our work with the respective discussion on the results of our research and current limitations, and the conclusion on the technological perspective of DPPs in relation to CE applications.

2 Related work on digital product passports

In this section, we discuss previous research in the field of DPPs, that has some relevance to the current study while highlighting key contributions that support the in-depth analysis of the concept. Table 1 presents a comparison of our work with prior published papers mentioned in the corresponding section. Our comparison criteria are the research on data collection, curation, sharing, and leverage technologies, studying the indicative content of DPPs, their consideration of circularity principles, and potential adaptable frameworks. Content that exists in the published material is marked as "+", and the non-existent as "−".

Initial analysis on the concept of DPPs, as an enabler of CE, was conducted by the authors of [9]. The researchers study the impact and functionality of DPPs in relation to circular chain actors, focusing on the role of stakeholders, as well as the importance of generated data in the formulation of such passports. However, there is a clear understanding that the particular concept requires extensive research regarding information and policy requirements, as well as the need for implementing digital technologies for the realization of DPPs.

In 2021, research was conducted by Donetskaya and Gatchin [17] on the content requirements of Digital Passports. The corresponding article separates the respective requirements into two categories, the content of the Digital Passport and design solutions. According to the authors, the content should incorporate the life cycle stages of the product or service, the related manufacturing procedures during the life cycles, and the respective types of data related to the product. Simultaneously, the designed solutions are dedicated to the management of the production data, design, and production procedures.

A similar approach is presented in [18], with the authors investigating the content's indicative requirements that constitute a Digital Passport for the overall support of CE. The authors clarify that the majority of DPPs are designed according to specific sector requirements while specifying that their work is based on different perspectives. The researchers list the essential objectives of DPPs while clarifying their corresponding requirements, e.g., data related to manufacturing, usage, life cycle, end-of-life, collaboration and trust among stakeholders, product and service identification, and the implementation of mandatory regulations.

The authors of [19] focus on the analysis of the solution called Product Circularity Data Sheet (PCDS). The particular solution is part of the Circularity Dataset Standardization Initiative, launched by the Ministry of the Economy of Luxembourg, aiming to the development of a global open-source industry standard that acts as an enabler for the exchange of circularity data among stakeholders, improves the efficiency of data exchange, and supports circularity optimization of products. The main components of PCDS are a template of standardized circular data, a completion guide, and a generalized draft of the data sheet's IT infrastructure.

Table 1 Comparison of related work on DPPs

Related work	Data collection technologies	Data curation technologies	Data sharing technologies	Data leverage technologies	DPPs content	Circularity consideration	Proposed adaptable framework
Adirson et al. [9]	–	–	–	–	+	–	–
Donetskaya and Gatchin [17]	–	–	–	–	+	+	–
Plociennik et al. [18]	–	–	+	+	+	+	+
Mulhall et al. [19]	+	–	–	–	+	+	–
Our work	+	+	+	+	+	+	+

3 Research methodology

In this work, we adopt a Systematic Literature review, with the criteria and approach being guided and validated by respected publications such as [20–23], integrated with a Conceptual Framework Development, and validated through a theoretical use-case scenario, similar to the methodologies followed in [24, 25]. However, we further enhance our research methodology by implementing a Requirements Definition approach on the implemented use-case scenario, combined with a form of Comparative Analysis, to correlate the findings of the literature analysis with the components of the proposed framework and the operational flow of the theoretical use-case.

By utilizing the Scopus search engine, the terms "Digital Circular Economy" and "Digital Product Passports" were searched and filtered with our respective subject area of "Computer Science" and keywords such as "Circular Economy" and "Digital Technologies". According to the results, research interest in Digital CE started emerging in the years

2016–2017, with technological implementations being published in 2018. Similarly, the concept of DPPs started being an active point of research in the years 2021–2022. Due to the limited evidence on the technological requirements of DPPs, and to avoid potential technological conflicts, we proactively proceeded by processing and working with published material closer to the time period of DPPs publications, an action also validated in [23].

The Google Scholar platform was used for the collection of the literature due to the high quantity and quality of the available academic and research material. Also, considering the constant evolution of technological strategies and approaches, and the novelty of Digital CE and DPPs as two relatively new concepts, both conceptually and strategically, we provide a state-of-the-art and up-to-date systematic review, by focusing our search on the years between 2018 and 2023, as mentioned above, and utilizing databases such as ScienceDirect, IEEEXplore, and Elsevier. The main keywords used were “Digital Product Passports”, “Digital Product Passports Technologies”, “Digital Product Passports Circular Economy”, “Data Collection”, “Data Curation”, “Data Sharing”, and “Data Leverage”, which resulted in the collection of (144) research papers.

The initial evaluation of the collected material was based on the title and research scope mentioned in the abstract, by supporting a two-part process as part of the filtering and selection stage. First, we conducted a three-round filtering procedure searching for publications related to DPP solutions, moving to research material focused on Digital CE applications, and finishing with generic IoT implementations. Secondly, we proceeded with a correlation of the filtered material with the three data tiers of data collection, curation and sharing, and leverage, which resulted in the final collection of (70) research papers.

Once the respective material was collected, a detailed systematic analysis of the published literature was conducted in Sect. 4.1. Specifically, in relation to the papers assigned for each data tier, thorough research on the proposed solution was performed, in order to record novel and adaptable strategies and mechanisms, capable of being combined with other technologies. Due to the nature of DPPs and Digital CE, a greater emphasis was given to mechanisms that are capable of processing, utilizing, and securing data efficiently.

The next stage was focused on a Conceptual Framework Development methodology while taking into consideration essential requirements stated in the collected literature, and state-of-the-art components capable of being adapted in the context of DPPs, as presented in Sect. 4.2. The initial objective of the proposed framework is the presentation of a system, consisting of each data tier as the basis of each component, by fulfilling an efficient, effective, and circular data flow. This approach assisted in the designation and proper position of components related to DPPs and circularity. The particular stage concluded by correlating the collected technologies of Sect. 4.1, to each component of the framework's architecture, regarding their potentiality to enable the components' primary functionalities e.g., data collection, data curation and DPPs generation, DPP leveraging and sharing, and data reusability.

Finally, application trends related to Digital CE were investigated, in order to validate the functionality of the respective combination of technologies that comprise the proposed DPP framework, through a combination of Requirements Definition and Comparative Analysis, through a Theoretical Use-Case scenario. For that purpose, we proceeded by performing the realistic use-case scenario, as seen in Sect. 5, by identifying essential requirements of the selected application field, and examining the functionality of each technology studied and implemented within the framework's infrastructure, in relation to the use-case stages and the researched literature.

Excluding Sects. 1 and 2, the main research scope of our paper was supported as follows. A total of (17) references were researched for listing potential digital technologies, capable of supporting the development of DPPs, while focusing on the data tiers of data collection (5), curation and sharing (8), and leveraging (4). Next, a total of (15) research publications were utilized to support the architectural design of our solution, (2) citations for the respective design, (4) papers for correlating our framework's components with data collection functionalities, (7) papers for data curation and sharing, and (2) for data leverage. Last, a total of (18) papers were utilized to support the applicability of our use case scenario. Specifically, (5) papers were researched on the initial research trends to select the corresponding application field, (6) papers were examined for the investigation of essential supply chain requirements, and (7) papers were investigated for vital manufacturing processes.

4 Analysis results

4.1 Results of literature analysis

As a core part of our investigative approach and research methodology through the available literature, in this section, we discuss the variety and combination of technologies used in DPPs components. Taking into account the impact of data in DPPs, we hypothesize that their overall structure consists of three data tiers:

- Data Collection
- Data Curation and Sharing
- Data Leverage

The selection of suitable technologies for each tier is thoroughly analyzed through proposed research solutions for DPPs, which are considered part of CE, or other industrial and non-industrial IoT applications. Table 2 presents a summary of the corresponding technologies.

4.1.1 Data collection technologies

Digital technologies constitute an integral part of Digital CE applications, such as DPPs, especially in relation to data exploitation considering their collection and analysis for proper passport formation [26].

The authors of [27] analyze their proposed solution for implementing IoT mechanisms in the form of smart printed sensors created by functional ink, for proper data integration, focusing on the creation of DPPs, as enablers of CE. The particular tags react according to different environmental conditions, which produce two types of data: type of product and tag condition. The functional ink utilized consists of sensors with thermochromic and photochromic ink, related to temperatures and light exposure changes respectively, with the related information being encoded as part of the product's QR code data matrix. Data access is achieved through a traditional scanning process of the QR code, with each scanning accessing a different URL depending on the functional ink changes. However, two of the main limitations of the particular solution are the restricted number of available QR codes that can be generated, and the gradual reduction of ink readability.

Another research project presented in [28] focuses on the development of a digital CE framework, capable of being integrated into supply chains, and resulting in the creation of DPPs that can be shared among the related stakeholders. The authors clarify that the main components of the framework: Data Pipeline, Passport Generator, and Passport Pool are based on state-of-the-art technologies, such as IoT, AI, and Blockchain. Regarding the data collection process, IoT devices are utilized for the extraction of data during physical resource flows, such as data related to environmental conditions through smart container seals, and monitoring the origin of raw components according to mandatory legislation. All the collected data are then inserted directly into the generated passports.

A more specified solution researched in [29] was devoted to the generation of DPPs dedicated to electric vehicle batteries. The overall structure of the corresponding passport is separated into four main categories: battery, value chain actor, sustainability and circularity, and diagnostics, maintenance, and performance, with each category consisting of subcategories of specified data. Technologically, the authors clarify the importance of digital twins (DTs) as part of data generation and integration, by utilizing virtual replicas of their physical counterparts for real-time monitoring and observation of supply chains, life cycles, and functionality benchmarks, leading to data extraction for the related DPPs.

The researchers of [30] followed a different perspective related to the health sector, due to the recent COVID-19 pandemic. The proposed solution analyzes the development of digital and decentralized immunity passports and vaccination certificates, stored in a mobile device with the individual's biometric data and vaccination records, with the data being shared through QR code, Bluetooth, or NFC. It provides two different data collection mechanisms related to platform user registration and extraction of test results from the responsible health systems. During the registration process, the user registers through biometric data (e.g., PIN, fingerprint, face recognition) through the FIDO2 protocol used for cryptographic authentication, camera capture of the user's ID card, and a face selfie for liveness detection. Regarding the extraction of COVID-19 test results, once the user logs into the platform, he interconnects with the Fast Healthcare Interoperability Resources (FHIR) interface, which is connected to the Electronic Medical or Health Records (EMR/EHR) for the collection of health data. According to the authors, FHIR is considered a highly functional API supported by AI and ML mechanisms, guarantying data accuracy, and consistency for a variety of national health organizations datasets.

4.1.2 Data curation and sharing technologies

Proper data curation is essential for the creation, organization, and management of the overall collected dataset, while being accessed and utilized by the stakeholders of the circular chain.

A study in [31], emphasized the impact of Smart Manufacturing and its related technologies, e.g., Industry 4.0 (I4.0) applications and deep learning (DL) approaches, for the overall efficiency and optimization of state-of-the-art production mechanisms. However, the researchers clarify that current approaches may encounter challenges regarding the quality of data used as inputs for DL algorithms while suggesting key data curation techniques in order to tackle this issue. Starting with data denoising for the subtraction of background noise from valuable data, suggested techniques are increasing the signal-to-noise ratio (SNR), local geometric projection (LGP), and empirical model decomposition (EMD). Continuing with data cleansing by handling unneeded values, autoencoders and probabilistic neural networks (PNN) for outlier detection, as well as recurrent neural networks (RNN) and convolutional neural networks (CNN) for data imputation or annotation.

The authors of [32] provided an additional perspective on smart manufacturing while emphasizing the interconnection of data between actors and processes, and proposing a model for monitoring and interconnecting data by utilizing graphs for the creation of digital threads. The main goal of

Table 2 Summary of potential technologies for DPP frameworks

DPP tiers	Technologies	Description
Data collection	IoT	Smart devices implemented with sensors for data collection related to environmental conditions, production, and supply chains
	Digital twins	Utilization of digital copies for efficient monitoring and data collection, instead of their physical counterparts
	Cryptographic authentication	Capturing biometric data through personal devices
	AI–ML	Utilization of AI and ML models, during the interconnection of databases, for detection and collection of desired data
Data curation	Data denoising	Reducing background noise through increasing SNR, LGP, and EMD
	Data cleansing	Processing and filtering of unneeded values
	Data imputation—annotation	Taking advantage of autoencoders, PNNs, and CNNs
	Digital threads	Utilization of digital threads for the interconnection of databases, processes, and layers, throughout the life stages of a service or product for the curation of the collected data
	Big data analytics—M.L	Once mass amounts of data are collected, they are properly analyzed in a cloud while using M.L. algorithms for the desired prediction models
Data sharing	IOTA—L2Sec	Interconnection of devices and data exchange through the IOTA Tangle, while using the L2Sec protocol as a secure communication channel
	DDAXML	Data sharing framework, developed by BIM, for information exchange between devices in the semantic and application layers
Data leverage	Blockchain	Selection of proper Blockchain platform, processing, and maintenance mechanisms according to business requirements. Combination of Blockchain with other technologies for improved efficiency and instant transmission of product data once collected
	Piggybacking	Extension of data pipelines in production and supply chains, interconnecting the stakeholders while using business data for CE purposes

the framework is the implementation of digital threads to provide enhanced perception and data access in smart manufacturing applications. In this particular system, data curation is achieved through the concept of digital threads, supporting the interconnection of different data sources throughout the product lifecycle. Specifically, the proposed solution is based on lifecycle information framework and technology (LIFT), by utilizing agent-based adapters to manage the process of curation. A master handle system is used by the adapters to connect the data sources and organize related data into user-friendly datasets.

A more traditional IoT application was investigated in [33], related to the development of a technological framework used for the collection and curation of data that originate from land-side monitoring, with the data curation layer being supported by a combination of Big Data Analytics and ML algorithms. The overall back-end system is hosted on a cloud, with the collected data being transferred through an HTTP interface. The authors utilize the Node-RED development tool for the organization of data into segments and pre-processing, before they are used as inputs for ML training models in order to accomplish accurate predictive rates.

An additional solution considering data pre-processing and curation in smart manufacturing was presented in [34]. The authors researched an IoT mechanism as part of the production lines by adopting features of predictive maintenance. The suggested system utilizes IoT sensors that are distributed to the infrastructure, collect the generated data, and proceed with thorough pre-processing for appropriate ML models for the prediction and avoidance of potential production errors before they occur.

Studying the importance of security on data sharing technologies, the authors of [35] researched available methodologies of data transmission such as datagram transport layer security (DTLS), and distributed ledger technology (DLT). The proposed solution is based on a combination of the IOTA Tangle and the L2Sec protocol to enhance security during data sharing. The data collection devices are interconnected through the IOTA Tangle, with each device transferring or retrieving data through an IOTA node with gateway functionalities. The L2Sec protocol forms a data flow of linked data pieces with different indexes, that are anchored to the Tangle. The respective protocol provides authenticated encryption with associated data (AEAD), providing access to authorized subscribers for reconstructing or reading the data.

The authors of [36] further investigate the impact of the IOTA Tangle, through a proposal called PRISED Tangle. The particular framework focuses on the combination of Industrial IoT (IIoT) and the healthcare application field, by utilizing masked authenticated messaging (MAM) through the IOTA Tangle for the establishment of secure sharing of data that are collected through applications such as Google Fit. The system designates two roles for its functionality, the role of the publisher that shares his personal health data, and the role of the fetcher for healthcare experts that receive and access them.

A similar approach to the utilization of DLT can be found in [37]. The researchers propose a Blockchain-based framework, both for data collection and sharing, through features of Ethereum for secure sharing and Deep Reinforcement Learning for efficient data collection. Smart mobile terminals are a vital part of the proposed system, with each terminal being capable to encrypt the collected data with private keys and store them in Ethereum while being able to request other returned data through queries.

A solution for data utilization for the prediction and simulation of building performance throughout the different lifecycle stages, in the context of CE, was presented in [38]. The authors propose a thorough analytics system, by visualizing data related to building performance, element deconstruction, and deconstruction advice. Part of the system's architecture is the semantic layer, which is responsible for data exchange and data transmission to the application layer. The connected devices exchange data through the deconstruction and disassembly analytics XML (DDAXML), which is part of the green building XML, a data-sharing framework for building information among different BIM software components.

4.1.3 Data leverage

Leveraging circular data assists the overall process of forming a sustainable DPP, in order to provide value to the information flows generated by CE business models and enhance cooperation among the circular chain actors.

The researchers of [39] recognized the impact of CE on business models, as well as the enhanced features provided, when combined with digital technologies on data-driven circular chains. However, the study states the presence of significant challenges, e.g., predictability of return flow, lack of smart regulations, and sustainable footprint blocks, once digital CE systems are implemented, especially in relation to transparency and leveraging the information flow generated. As a result, the authors study the utilization of Blockchain technologies to overcome such challenges and guarantee traceability, trust, and privacy. Their proposed solution approaches Blockchain in three steps: choosing a platform according to business needs, selecting a consensus mechanism for proper leveraging, and maintaining leveraged data in a cryptographic cloud.

Utilization of blockchain for data leverage was further enhanced by the authors of [40]. The researchers investigate the impact of blockchain technology on CE, through the different levels of the ReSOLVE framework, developed by the Ellen McArthur Foundation, and further supported by a number of real-life use-case implementations. The majority of

Table 3 Selection of technologies for the proposed framework's components

Data tiers	Components	Technologies
Data collection	Re-data	IoT, RFID—QR sensors, AI—ML
	New data	Digital twins
Data curation	Cloud environment	AI—ML data preprocessing
	Business—user passport	Digital threads
	Automated user passport preparation	AI—ML data sorting
Data leverage	Business—user passport	Blockchain, extended data pipelines—piggybacking
Data sharing	Producers–partners, prosumers–consumes, stakeholders–consumers	IOTA, blockchain

blockchain solutions are related to smart contracts for automated secure transactions and leveraging the information flow throughout supply chains while providing traceability and transparency during data curation phases. However, the authors emphasize that blockchain effectiveness varies depending on the type of industry and application requirements, and suggest proper preparation for selecting suitable digital technologies.

Another perspective about blockchain as part of a sustainable transition in leveraging circular data was presented in [41]. The author states that sustainability should be adopted by all interconnected stakeholders in order to produce fully transparent and sustainable products and services. Moreover, assurance of common goals and leveraged data is essential and manageable through Blockchain technology. In the case of DPPs, a product's data can be stored with specified IDs in a blockchain, supporting the process of management and secure tracking of information of interest for the rest of the circular chain actors.

A different approach was suggested in [42], proposing a specified technique as part of data pipelines in digital CE frameworks and systems. The corresponding technique called piggybacking focuses on the separation of business data from the generated dataset, and their utilization for completely different purposes such as potential regulations, risk analysis, and compliance with government policies. The authors clarify that default data pipelines are structured and designed for interconnection and visibility between clients and producers, while pipelines supporting piggybacking require architectural extensions and blockchain characteristics for enhanced visibility of production chains, re-functionalities e.g, recycling, reshare, reuse, and DPPs that are attached to each product and services.

4.2 Correlation to proposed DPP framework

This study focuses on the investigation of technologies that have the potential of being integrated into the architecture of a DPP framework. Building on the initial work presented in [43], we present here a new and updated framework with infused DPP characteristics. The corresponding framework is designed by taking into consideration the concept of DPPs with their potential enabling technologies for their development, as researched in Sect. 4.1, while focusing on the core principles of I5.0, related to the harmonious coexistence of humans and automated systems, in the context of data interaction.

Also, accounting for the technologies used in the solutions, we attempt to correlate them with the key components of our proposed DPP framework, while supported by additional techniques and functionalities of the academic community. Table 3 presents an overview of the technologies used for each of the framework's components.

4.2.1 Framework overview

The updated version of the corresponding framework is depicted in Fig. 1 and consists of two main layers, Passport Generation and Digital Passport, the components of which are inspired and based on the technologies analyzed in Sect. 4.1.

To begin with, a production phase is connected to the Passport Generation layer and provides two types of data, newly manufactured and data collected by re-functionalities, which are returned by consumers. The particular components are directly correlated to the analysis conducted on data collection technologies, and specifically the work of [27–30], regarding the utilization of IoT and DT technologies for the extraction of data for Digital CE applications. Simultaneously, data provided by partners of the circular chain as external sources are infused into the Passport Generation layer specifically based on [29, 32, 35–37], due to the authors' statement on the significant importance of Data Pipelines for the direct interconnection of stakeholders, the implementation of digital threads for additional assistance in interconnecting different data sources, and the potentiality of decentralized technologies as effective mechanisms for secure and immutable data collection among stakeholders. Additionally, the basis of the particular layer is a cloud environment, where the production and partners' data are stored,

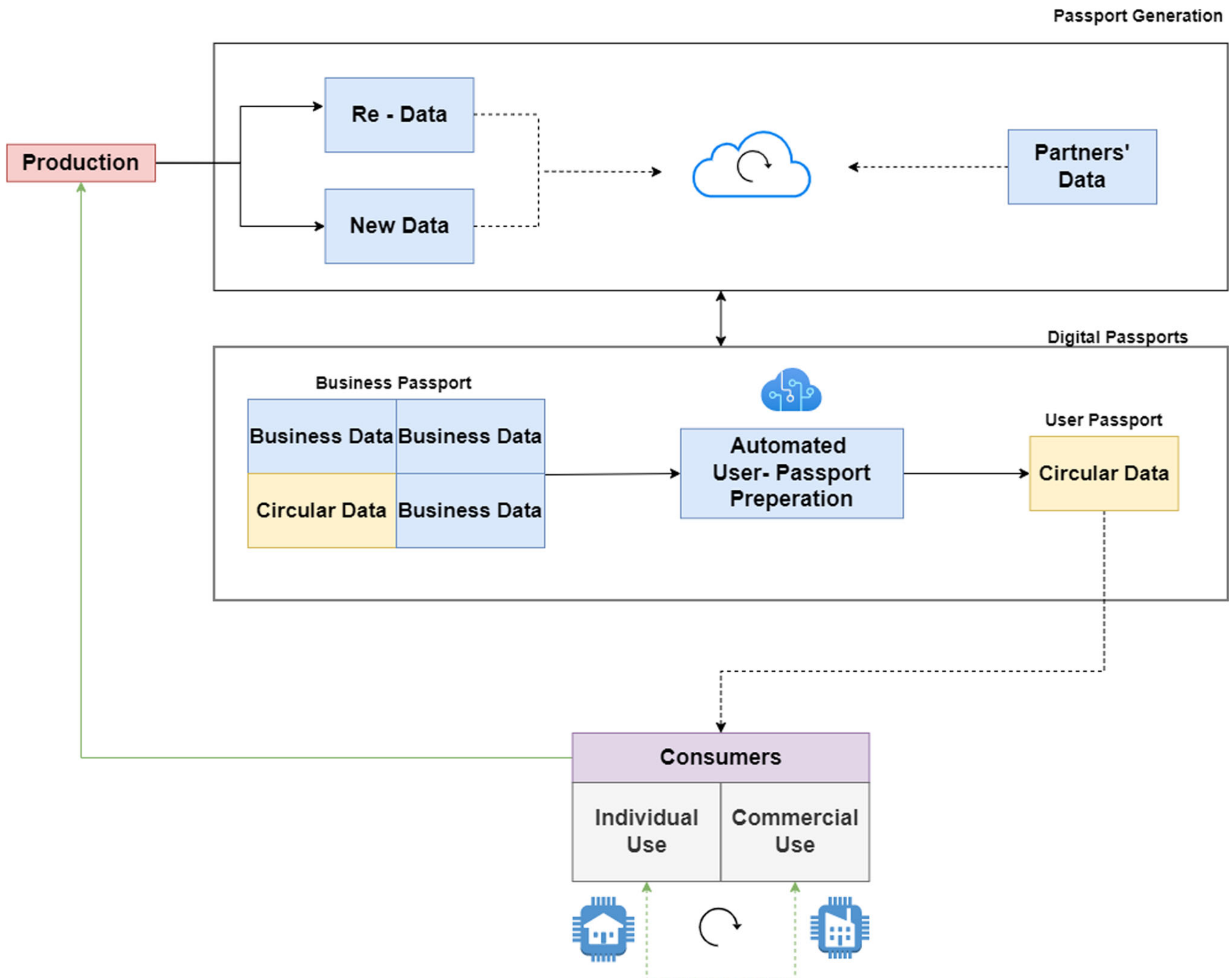

Fig. 1 Updated CE framework with implemented DPP characteristics

and interconnect with the Digital Passports layer for the DPP generation, which is also supported in [33] as a sufficient and efficient storage approach for curating mass amounts of collected data.

Next, the Digital Passport layer consists of a series of processes, directly connected to the Data Curation technologies, as researched in the works of [31–33, 38, 42]. The first step is the creation of a full DPP version, based on the data gathered in the Passport Generation layer, and consists of both sensitive, e.g., exclusive business, and consumer-friendly circular data. Then, the full DPP version is processed through automated mechanisms for the extraction of the circular data and the formulation of a User-friendly passport. For the particular phase, proper data curation signifies the resulted quality of the content that will be imprinted within the DPP e.g., the utilization of data denoising or cleansing in the case of false data, digital threads in the case of multiple sources of data, Big Data and ML for optimized curation of vast data amounts, separation of data into groups of different purposes, and data visualization for an efficient overview of the content.

Finally, the User-friendly passport is distributed to the consumers, while adopting the concept of Prosumers as seen in [44]. Once the passport is received by the consumers, they can decide whether to share their data with other consumers for commercial use, through smart contracts, or return them to the producer to assist in the collection process of re-data.

Overall, the totality of the framework takes into consideration the importance of leveraging data, especially in the case of Digital CE, for the effective distribution of DPPs. Such an approach is achieved through the interconnection of the different layers and components of the layers, as well as the approaches and technologies investigated for Data Leverage approaches, as seen in the works of [39–42]. Specifically, Blockchain technologies, such as IOTA, for the incorporated data types, stakeholders, and data transmission among the framework's layers, implementation of smart contracts to enable prosumer features and extension of data pipelines in case of potential additions of stakeholders or technical components.

4.2.2 Components related to data collection

Data related to the production process and the partner's data can be connected to the Data Collection tier, due to the essential data requirements for the Passport Generation layer. Moreover, we assume that the two types of Re-Data and New Data are also included in the Partner's Data component.

Re-Data are the outcome of re-functionalities that are utilized by consumers and returned to the producers. As mentioned in [45], a combination of IoT, AI, and ML is considered a significant enabler for CE functionalities. Specifically, with the implementation of IoT RFID and QR sensors at the end of a product's lifecycle, the manufacturers can monitor the product's condition, while installing AI to calculate and predict the possibilities of reusability and repairability before proceeding to the production process with recycled materials or data.

Regarding newly manufactured data, technologies related to DT is a considered a sustainable solution as supported by [46] and emphasize its impact on the stages of product design and manufacturing. In the case of product design, the utilization of modeling tools for the virtualization of physical parameters assists in the prediction of potential design errors, resulting in a low-cost and efficient production process. A similar approach can be seen in [47], with the researchers proposing a framework that processes historical and real-time data, for the generation of a fully virtual model for accurate and clean product design. DT in manufacturing is related to the overall simulation of the production chain, before the actual physical production, providing additional control, analysis, and precision. The authors of [48] presented a relative solution, dedicated to the enhanced support of the production chain by utilizing DTs for real-time monitoring and control, as well as cooperation between humans and machines for task allocation and accurate generation of data.

4.2.3 Components related to data curation

The process of Data Curation is essential once the required data are collected, for their proper preparation in order to provide an accurate and functional Digital Passport. Following the flow of our proposed framework, we assume that Data Curation technologies are implemented in the components of the cloud environment of the Passport Generation layer, and the components of Business and User Passports, as well as the automated preparation components of the Digital Passports layer.

Starting with the cloud environment of the Passport Generation layer, the goal of the specific component is to store, curate, and preprocess the data collected by producers and partners, before they are used as input to the Digital Passports layer. The researchers of [49] utilize a related concept through a framework called CloudTP. Raw GPS log data are used as input to the corresponding framework in order to undergo the required preprocessing, e.g., data denoising and cleaning. Once preprocessing is complete, the data are organized into ID indexes, resulting in curated trajectories provided to the users through selected cloud platforms.

To further elaborate on the preprocessing phase since the majority of the collected data are a byproduct of IoT sensing devices, proper denoising is required to effectively evaluate the amount of transmitted data and background noise, with the calculation of SNR being an effective solution. Specifically, the researchers of [50], in the context of examining a fully functional IoT network powered by LoRa technologies, proceeded by calculating the SNR generated by IoT devices in different testing locations, with varying spreading factors and bandwidths. As a result, the researcher concluded that increased bandwidth can reduce network noise, as well as packet loss percentage. Further data cleaning can be accomplished with the implementation of autoencoders, as also supported in [51]. The researchers experimented with data points being labeled as noise for outlier detection and cleaning, through the development and application of class-specific feature-based autoencoders. Finally, considering the potential requirements for data imputation, RNNs are an effective AI solution as also seen in [52], with gated recurrent unit (GRU) and long short term memory (LSTM) being the two most common variations of the particular approach, for predicting and replacing the missing sensed data, with GRU focusing on masking and time-interval representations, and LSTM on predicting values in spatiotemporal patterns.

As mentioned above, the data stored in the cloud environment are transmitted to the Digital Passports layer for the generation of the Business and User passports. A potential solution for the interconnection of data and the creation of an organized DPP is the utilization of Digital Threads. The authors of [53] study the impact of Digital Threads on smart manufacturing and its implementation as a vital technology supporting the functionality of a DPP, due to their capabilities of interconnecting verified data flows of a product or service throughout its lifecycle, and delivering them to the end user.

Once the Business Passport is generated, it is used as input to the automated User Passport preparation component, for the extraction of sensitive business data and sorting of circular data that can be shared safely with the end users, thus creating the User Passport. A related mechanism of extraction and sorting can be seen in [54], where the researchers propose a solution for utilizing decision-making techniques based on circularity principles, for COVID-related waste. The suggested solution extracts the features of the collected waste, utilizes AI and ML to train classification models for digitally sorting the waste according to common features, and physically extracting it depending on the outcome of the prediction models.

4.2.4 Components related to data leverage

Leveraging the content of DPPs is vital for the circular flow and ensuring the ongoing interconnection between actors, both business partners, and consumers. Regarding the proposed framework, we assume that data are leveraged both in the case of the Business Passport due to its sensitive data, and the User Passport considering the possibility a consumer adopts the role of "Prosumer".

The most common and effective solution is the utilization of Blockchain technology. As supported in [55], a combination of Blockchain and CE is efficient in clarifying and verifying the source of data, as well as guarantying secure data sharing among partners, especially through smart contract and tokenization features. An additional solution is an implementation of piggybacking through the extension of data pipelines of the circular chain. As stated in [56], extended pipelines offer additional visibility of the data origins due to the simultaneous connection of actors that are interested in the circular flow, data collection at the moment of their generation, and official regulations by the responsible authorities for secure supervision.

4.2.5 Components related to data sharing

The last operational characteristic is the capability of efficient data sharing throughout the flow of the suggested framework. Specifically, in the cases of data trading between producers–partners, and prosumers–consumers, as well as DPP sharing from the stakeholders towards the consumers, and from consumers back to the producers.

A significant example that can be considered a combination of leveraging and decentralized data sharing is the utilization of IOTA and Blockchain, as researched in [57]. The authors propose a blockchain-based framework called Directed Acyclic Graph-based Vehicle-to-Grid (V2G) network (DV2G) for lightweight data sharing through an IOTA-based P2P network. The system is capable of supporting multiple parallel data trading transactions between devices and actors with the use of tokens, and with each transaction being connected with previously traded data to ensure traceability. Each transaction is connected to a smart contract that is activated and stores information during data-sharing requests.

5 Framework applicability

5.1 Supply chain management for an industrial manufacturing use case

In order to further support the impact of our proposed framework, and further validate its applicability and functionality, within the concept of selecting the proper technologies for the generation of DPPs as an innovative and state-of-the-art solution, we attempt to describe its functionality through a realistic use case scenario.

Starting with selecting a suitable application field as a basis for our use case, we investigate the latest research trends available in the academic community. According to [24, 58–61], there is an emphasis on investigating, designing, and developing solutions related to the optimization and efficiency of supply chain management, in the context of implementing digital circularity principles, as an essential part of smart manufacturing.

Moreover, we recognize the following vital requirements for efficient and optimized supply chain management, as supported in [62–67]:

- Identifying available resources, considering environmental implications
- Identifying environmental-friendly materials, capable of supporting basic re-functionalities
- Proper scheduling of production chain processes
- Proper scheduling of delivering products, services, and maintenance materials to end users
- Enabling resharing capabilities in the cases of Business-to-Consumer and Business-to-Business
- Enabling the capability of returning materials to the producers
- Providing traceability of materials throughout the production and supply chains
- Minimizing unnecessary expenses and inventory

Therefore, we discuss our framework's application in supply chain management in a manufacturing company.

5.2 Indicative operation flow of the manufacturing company

As a production entity, the manufacturing company produces a number of products, resulting in the generation of required data, e.g., technical specifications, hazardous and environmental-friendly materials regarding hardware, tools used, firmware details and software diagnostics, comments about the production process, inventory status, as also supported in [68–70]. Upon production, the company proceeds with two simultaneous production processes: newly manufactured products, and existing product lines.

In the case of newly manufactured data, the company utilizes technologies based on DTs for designing, visualizing, and simulating the functionality of the product, before proceeding to its physical production. As a result, the company avoids unnecessary consumption of materials, minimizes production costs and product functionality errors due to thorough data analysis of its digital counterpart, while optimizing the product's software and the scheduling of the production chain according to the number of steps required for assembly. The whole process generates a thorough dataset that can be used by the company's employees for the possibility of future upgrades and re-processes.

Once a product is ready to undergo the production process, IoT technologies are implemented through the installation of smart sensors as part of the product's components, with RFID tags and QR codes that provide useful data to employees and consumers. Specifically, the smart components support the ongoing monitoring of the product's condition throughout its lifecycle, while utilizing AI for calculating the lifecycle of products that combine new and recycled materials, as well as predicting their possibility of being repaired or reused, resulting in the minimization of waste generation and requirements on new resources.

In both cases, the generated data are collected and stored in the company's private cloud environment, through the utilization of digital threads that are connected in the main areas related to the company's supply chain, such as suppliers, production chain, inventory, warehousing, delivery, and end-user, as seen in [71, 72].

The company's partners, e.g., investors, suppliers, sister companies, share their own data with the corresponding cloud. It is supported by blockchain and IOTA features for decentralized and secure trading, guaranteeing the source and ownership of data through smart contracts, as well as promoting trust by providing product traceability and software integrity, with each partner having access to the data of interest. The stored data undergo thorough preprocessing for their proper organization and removal of unnecessary noise, avoiding errors related to costs, profits, material requirements, and product conditions, by taking advantage of approaches, such as evaluation of SNR and autoencoders to ensure the establishment of clean datasets.

Once the data are preprocessed, the Business Passport is generated with exclusive availability to the manufacturing company and its partners. As the full version, it consists of user-friendly information, e.g., instruction manuals, performance statistics, the origin of materials, circularity indicators and content, environmental impact indicators and content, as seen in [73]. Also, taking into consideration business-sensitive information, as seen in [74], company-related data are included, e.g., the product's total price, costs and profits per partner, investor-related statistical data, available materials and resources on the inventory, and the available number of the specific product line in warehouses. Generally, the Business Passport is an optimization enabler for purchasing only the required resources and producing the number of products according to market demands. Then, the Business Passport undergoes data sorting through AI, for the extraction of sensitive data and the creation of a User passport that consists only the user-friendly information and is linked to the product's printed QR codes and RFID tags.

The last stage is the distribution of products to consumers. Starting with the delivery process, real-life tracking of the company's fleet vehicles, and monitoring of cargo conditions are transmitted through the company's network for the product's DPP updates. Once received, the end users are capable of accessing the passports by scanning the product's QR code through their personal devices, offering them the awareness of the product's condition, and calculated lifecycle according to the percentage of reused and new materials, and its environmental impact. Throughout the product's lifecycle, consumption data are returned to the manufacturing company for utilization in the existing product lines. Moreover, the consumers are presented with a series of options at the end of the product's lifecycle: disposal, resharing with other consumers, or resharing with the manufacturer, promoting actions on environmental awareness.

Depending on the product's software diagnostics and DPP data, if a product or parts of it are capable of being reused, it can be disassembled, with the appropriate parts and materials to be reused in production chains, assisting in minimization of production costs, and extraction of new resources.

Figure 2 represents the flow followed by the manufacturing company as described in our representative use case scenario. All the main supply chain functional areas and DPP characteristics are included, with their related utilized technologies being depicted in cloud shapes and their overall Digital Threads interconnection through blue lines.

6 Discussions

6.1 Discussion on the technological approach

The main objective of this work has been the investigation of enabling technologies for the development of DPPs, in the context of CE, in order to introduce an effective DPP framework. Starting with the actual concept of the topic, we realize that although there are a number of articles available on the concept of DPPs, their requirements, and content, academic papers regarding technological requirements are limited, as also supported in [75] Therefore, we attempted to build our work on the available DPP studies, proposed Digital CE solutions and applications, as well as relative IoT proposed mechanisms.

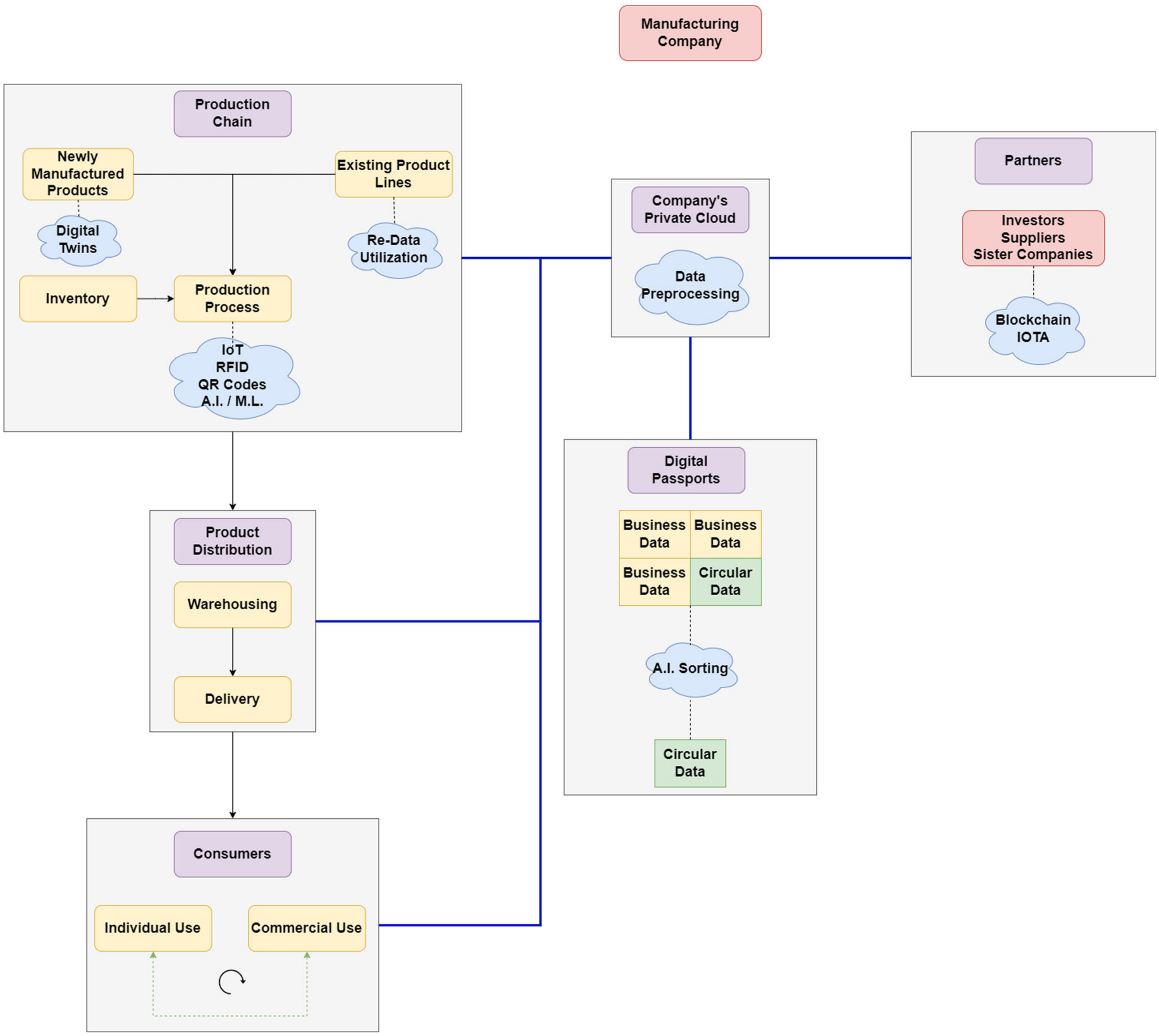

Fig. 2 The flow followed by the manufacturing company of the use case scenario

Regarding the assessment of digital technologies that could be utilized for the development of DPPs, we believe that the separation of its structure into data tiers is essential in order to research potential technologies in an organized manner, with a similar approach being supported in [76]. It is realized that there is a major preference for IoT technologies regarding data collection, whether the application field is related to circularity principles or not. Moreover, although most solutions follow the basic principles of data preprocessing, the majority of them are based on combinations with AI and Big Data, in order to fulfill CE requirements. Also, there is an exclusive selection of decentralized technologies to leverage and share such circular data, through different varieties of Blockchain applications.

Considering the results of our research, we propose the CE framework with DPP characteristics, with an explanation of its functionality through a manufacturing use case. Based on its current architectural state, the framework has the potential to be adapted within a production and supply chain while utilizing the proper combination of technologies that are used in different interconnected areas of a company. Such interconnection optimizes the content of the generated passport related to the circular data of interest that are collected throughout its lifecycle. Additionally, linking production entities, stakeholders, and consumers through automated means, e.g., the utilization of Digital Threads and the framework's main goal of data circularity and interactions, fulfill the I5.0 standards of human–machine synergy and sustainability principles via state-of-the-art technologies [32]. Moreover, the inclusion of business-sensitive data and the creation of two separate passport versions promote secure and trustworthy relationships between partners, environmental awareness for consumers, as well as reusability and efficiency for products, services, and their corresponding generated data.

6.2 Discussion on potential challenges

Although the current technological state of the Digital Circular Economy is promising in relation to the development and establishment of DPPs, there are a number of potential technological and managerial challenges and limitations that should be addressed, as stated in the works of [5, 77, 78]. However, in order to follow the scope and the main objectives of our paper, we dedicate the following discussion to the technological challenges of DPPs.

One of the most important challenges in the development of DPPs is researching the possibility and potentiality of a standardized DPP that is capable of supporting a unified format, rather than creating individual passports depending on the respective product or service. Such cases require additional resources and components that enhance the complexity of the procedure, by forcing the creation of separated DPPs that may vary in information, objectives, and data types.

Following the previous statement, the identification of the required data based on the product or service type is essential due to the specificity of certain materials, specifications, or production procedures. Although IoT technologies are vital enablers for the collection of numerous types of data, specificity issues will require additional investigation regarding technological mechanisms, strategies, and considering factors, such as sensory devices, geolocation of where the IoT devices need to be installed, accessibility issues to initial data of raw materials, etc. Additionally, there are identification challenges regarding the content manner of the DPP, such as the decision between product-based or stakeholder-based data, which will also impact the combination of required implemented technologies, due to the appropriate data type.

Similarly, ensuring the data collection during post-launch of products or services is a key aspect that should be further considered and investigated, as well as guaranteeing that data are up-to-date during the product's lifecycle. Current practices are heavily focused and dependent on data collection mechanisms based on production entities, both for newly manufactured and re-data, while relying on the user's motivation to complete the data-drive circular chain. However, the implementation of crowdsourcing practices is one of the most effective solutions to battle respective limitations.

Finally, there are a couple of limitations related to the digital infrastructure of the DPP's host that require further evaluation. Specifically, the efficiency of the infrastructure's preferred database should be guaranteed due to the vast amounts of data and variety of data types that will be stored and processed before their utilization in the formation of DPPs, while also implementing potential identifiers to avoid complexity in searching specific data of interest. Moreover, ensuring the digital integrity and security of the production entities responsible for the formation of DPPs, and relevant stakeholders, to avoid potential breaches, especially through the IP addresses that are implemented within the generated DPPs.

7 Conclusion

This paper investigated the selection of potential technologies for the development and support of DPPs, based on three different data tiers: Data Collection, Data Curation and Sharing, and Data Leveraging. Once the technological analysis was completed, we proceeded by proposing a digital CE framework with integrated DPP characteristics.

The results of our work showed that combining different types of technologies is necessary to satisfy the various data tier requirements for an efficient and successful DPP. More importantly, technologies such as IoT for data collection, AI for data curation, and Blockchain for leveraging and sharing are the most common, both as independent applications and as a unified combination.

However, there are certain technological challenges that need to be considered during the development of DPPs, such as the DPP format, including its content related to data requirements, ensuring post-launch data continuity, and approving the readiness of the production entities' digital infrastructure.

Last but not least, our proposed framework consists of two different layers as the basis of the DPP generation, resulting in the creation of two types of passports. Inline with our intention to contribute toward the development of I5.0 circular solutions, our framework's design is defined by the potential adaptivity, utilization of different technologies, and I5.0 core principles through the ongoing interconnection of all the necessary areas, for the collection and reusability of the required circular data, as seen in our indicative industrial use case, which illustrates the applicability of our framework in a manufacturing company.

Regarding our future work, further investigation is required for optimizing and evaluating the combination and functionality of the selected enabling technologies. Moreover, we must ensure that the proposed framework can be adaptive in a practical manner for different types of industries and application fields, while validating its capability of fulfilling both business-related and CE requirements.

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Declarations

Conflict of interest The authors confirm that there is no conflict of interest to declare.

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