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Orchestrating a smart circular economy: Guiding principles for digital product passports

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ABSTRACT

In order for firms to implement the Circular Economy, and close all material and energy cycles, connections are needed not only within but also between multiple Industrial Ecosystems. To enable such complex interconnections, the European Union is preparing legislation to enforce the use of digital product passports (DPPs). These are verifiable collections of data about products' composition, environmental footprint and opportunities for preventing waste. The notion of the DPP relies heavily on a suitable digital infrastructure, and it opens the possibility of using the power of artificial intelligence (AI), to optimize circular production within and between Industrial Ecosystems. The benefits of DPPs will only be attained if their design, knowledge engineering, and implementation is well-orchestrated. The purpose of this paper is to develop a set of guiding principles for the orchestration of DPPs, based upon a *trans*-disciplinary analysis, that form a theoretical basis upon which future research can build.

1. Introduction

As part of its Green Deal, the European Commission proposes the introduction of digital product passports (DPPs) in the European Single Market as an enabler of circular business practices leading to efficient use of materials and CO_2 emission reduction (European Commission, 2022). The proposed regulation will mean that products can only be sold or put into service in the European Union if a DPP is available, providing an accurate and verifiable set of information about the products' environmental sustainability, intended to help consumers and businesses make informed purchasing choices. Additionally, DPPs are intended to facilitate repairs and recycling and improve transparency about products' environmental impact during production and throughout their entire lifecycle. DPPs will also enable public authorities to assess products' compliance with sustainable production and usage regulations, as they will include data to enable the tracking of any substances of concern throughout the products' lifecycle (Berger, Schöggl, & Baumgartner, 2022).

Implementing DPPs in practice presents a complex challenge to firms in industrial ecosystems to maintain high-value and high-quality material and energy cycles (Korhonen, Honkasalo, & Seppälä, 2018) as their supply chains extend around the globe, covering multiple administrative areas (Hopkinson, Zils, Hawkins, & Roper, 2018). Additionally, in order to close all necessary energy and material cycles, connections are required not only within such ecosystems but also between ecosystems, as waste from one industrial process may become input for a previously unrelated industry (Liu, Ma, & Zhang, 2012).

Scholars argue that through the digital transformation of industrial ecosystems, knowledge engineering will leverage data to generate sustainability impact by analyzing supply chain bottlenecks, taking autonomous decisions for production planning to shorten lead times, and improving supply chain flexibility and robustness (Feldt, Kontny, & Wagenitz, 2019). In this vision, knowledge engineering makes use of the data provided by DPPs, to enable a strategic transition to a Smart Circular Economy, a new socio-economic paradigm (Kristoffersen, Blomsma, Mikalef, & Li, 2020).

Despite the promise of DPPs, research has paid limited attention to the challenges of their implementation in practice (Adisorn, Tholen, &

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Götz, 2021). Due to the complexity of production processes and the new interconnections that need to be created across and between resource-intensive industries, no single industrial ecosystem can organize this alone (Walden, Steinbrecher, & Marinkovic, 2021). For the effective transition towards a CE, it is vital to understand how to orchestrate DPPs such that all relevant parties gather and provide access to the necessary data. The concept of orchestration in this context refers to the arrangement and direction of deliberate, purposeful actions by manufacturers in order to implement and exploit DPPs (King, Timms, & Mountney, 2022). For example, this can include extending industrial partnerships (Gualandris et al., 2015), managing the digital technology infrastructure (Berger, Schöggl, & Baumgartner, 2022; Chauhan, Parida, & Dhir, 2022), developing and maintaining DPP governance (Janssen et al., 2020), and promoting value-creation and value-capture activities across and between the industrial ecosystems (Lüdeke-Freund, Gold, & Bocken, 2019). Without clarity about the key issues relating to the orchestration and implementation of DPPs, negative unintended consequences for the transition to the CE may ensue.

As such, the purpose of this paper is to address the orchestration of DPPs within and between industrial ecosystems to enable effective knowledge engineering in the transition to the CE. In this context, the orchestration may be coordinated by large manufacturers themselves (Parida, Burström, Visnjic, & Wincent, 2019) or by independent intermediaries with the resources to bring the relevant parties together (Blackburn, Ritala, & Keränen, 2022). Our research question is:

What are the critical factors in the orchestration of DPPs that can enable knowledge engineering to boost circular practices within and across industrial ecosystems?

In order to answer this research question, a transdisciplinary, innovative approach is adopted as a methodological foundation. Given that CE and DPP have not yet been implemented at a large scale and both are multifaceted concepts, research in this area requires forward-looking and holistic approaches (Hofstetter et al., 2021). Therefore, transdisciplinary analysis is suitable because it goes beyond discipline-based approaches, is typically participatory, future-oriented, holistic, and transcends individual domains and practices (Bliemel & van der Bijl-Brouwer, 2018, p. 3). In this paper, the integration of perspectives from multiple disciplines leads to the development of a set of guiding principles and a framework to explain the orchestration needed to successfully implement DPPs in practice.

This applied and conceptual paper aims to be a step toward structuring the effective orchestration of DPPs. The guiding principles that we develop will help to nurture dialogue toward the understanding of key concepts, such as the use of DPP data for knowledge engineering for the improvement of circular business practices. These principles will help other scholars develop focused research into DPPs in the formation of models, analysis of case studies, data collection efforts, and more. In their own right, the framework and guiding principles provide a clear foundation for theorizing on the orchestration of DPPs, to enable knowledge engineering in order to improve circular practices within and across industrial ecosystems.

2. Research approach

To provide a conceptual and critical view on the implementation of DPP as a mechanism to facilitate the transition to CE, we adopt a transdisciplinary innovation approach where insights and perspectives from different disciplines are integrated to develop visionary guiding principles. Transdisciplinary innovation approaches go beyond discipline-based approaches; they are typically participatory, future-oriented, holistic, and systemic and transcend individual domains and practices (Bliemel and van der Bijl-Brouwer, 2018, p. 3). Such approaches are recommended to better frame and understand real-world problems, provide actionable insights for the pursuit of sustainable development, and integrate a wide range of stakeholders for addressing complex problems (Brennan et al., 2021). As the development and implementation of DPPs are in their infancy, there is a need for critical, transdisciplinary views to provide a roadmap for a future where a fully operational circular economy is underpinned by digital product passports.

The transdisciplinary research approach is illustrated in Fig. 1. Transdisciplinary analysis distinguishes itself from interdisciplinary research through its focus on three aspects: 1) the existence of investigators from different disciplines; 2) the joint work of the experts to create new concepts beyond individual disciplines; and 3) addressing a common problem and developing approaches that integrate insights from different disciplines (Harvard School of Public Health, 2022). These three steps were followed during the execution of this research, as shown in Fig. 1. First, a selection of experts from relevant disciplines was made by the initiator of the project. The fields of sustainable supply chain management and spatial sciences mainly add to the discussion on the wider context in which DPPs will be implemented. The field of information management is involved in providing in-depth knowledge on enabling Digital Technologies for the DPP landscape, presented in three distinct tiers according to the specific functionality they enable: i) data collection; ii) data curation, processing, and sharing; and iii) data use and exploitation. A senior practitioner from a Dutch applied research and technology organization is involved to engage with developments in practice and with ongoing policy discussions. All authors have experience with CE through the lens of their particular discipline. Following Jaakola (2020), we aim to link previously unconnected or incompatible constructs in a novel way.

Second, to actively engage the experts in a joint exchange, all authors have participated in a conference on knowledge engineering where the goal was to integrate insights from different domains and create new knowledge to better understand digital knowledge engineering. During the three-day conference, the author team actively engaged on different topics and developed a proposal for this study. On the third day, the proposal was presented to the audience, which consisted of academics and practitioners from different domains. Moreover, the preliminary insights have been discussed with an industry expert and government advisor on CE and material flows. The goal was to enable joint reflection and stimulate the exchange of ideas.

Third, the current insights from the literature and from the expert discussions are structured into first-order emerging codes on the socio-technical transition to CE which are grouped into second-order themes. These emerging themes form the basis of the guiding principles which integrate discipline-specific insights through joint exchange and interactive discussions as well as review of existing literature. The guiding principles presented in Fig. 2 are organized into a framework which provides a theoretical basis for scholars and practical direction for managers, because this allows us to frame the implementation of DPP toward a CE such that multiple scientific and societal views are recognized (Brennan et al., 2021). After presenting the emerging framework, a critical reflection on the function, relevance and boundary conditions of the guiding principles is again conducted jointly by the team of experts.

3. Transdisciplinary analysis of digital product passport implementation and adoption in CE

3.1. Enabling a circular Economy through digital product passports

3.1.1. Motivation for digital product passports in circular Economy

The Circular Economy (CE) is based on fundamental underlying concepts, such as introducing cascading loops in the flows of materials, that stem from the 1970s era when major schools of thought were established that sought to provide a systemic vision for transitioning to a sustainable economy. Cradle to Cradle, Biomimicry, Industrial Ecology, Natural Capitalism, and the Blue Economy represent major schools of thought, each assuming a different approach to achieving the transition. Indicatively, while Cradle to Cradle focuses on changing design

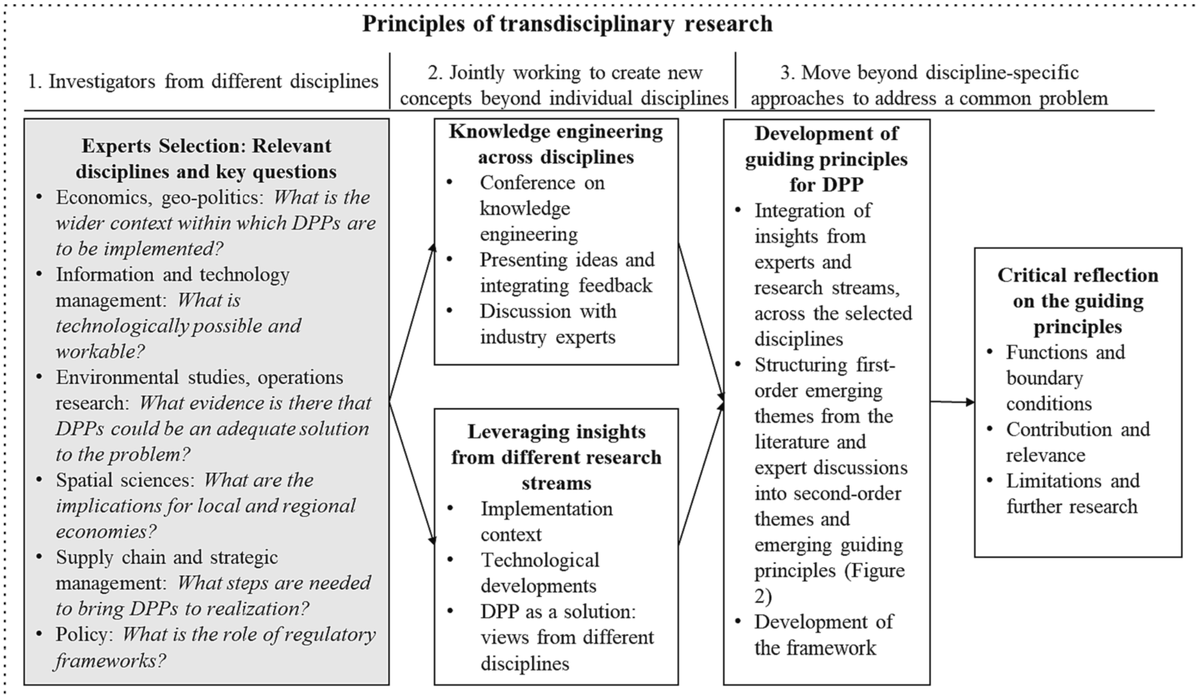

Fig. 1. Developing guiding principles for DPPs: A transdisciplinary approach.

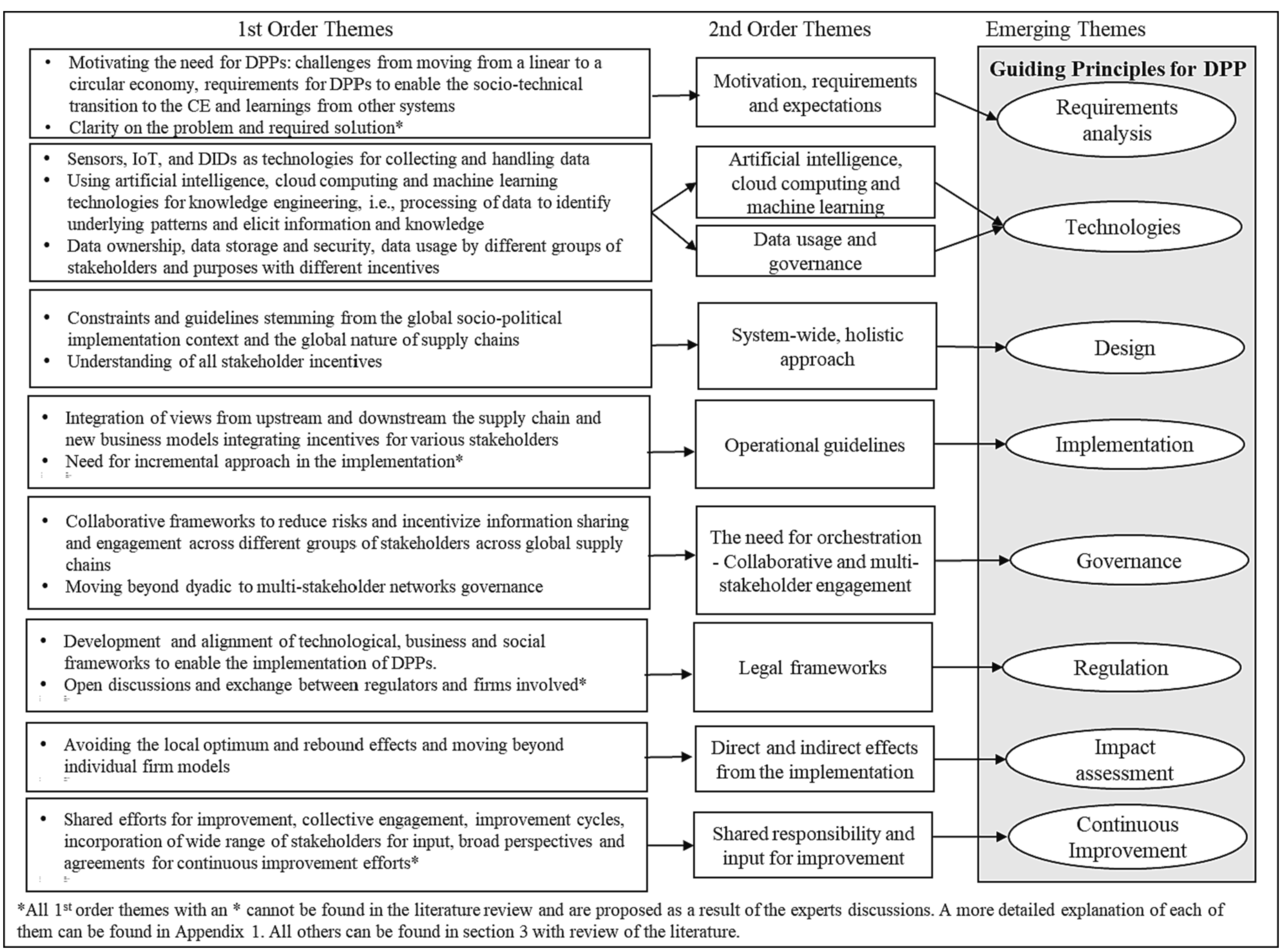

Fig. 2. Development of guiding principles: integrating discipline-specific insights through joint exchange and interactive discussions.

practices for endless product lifecycles, Biomimicry looks to nature for successful models of processes and systems, and the Blue Economy considers open-source collaboration and innovation.

CE can be defined as *"a regenerative system in which resource input and waste, emissions, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops"* (Geissdoerfer et al., 2017, p. 759). The main vision of the CE emphasizes the minimization of waste generation by enabling the circular use of materials and other resources in order to reduce the environmental footprint from resource extraction and break current destructive patterns of consumption and production (MacArthur, 2013; Geissdoerfer et al., 2017). Currently, fully circular product systems do not exist at scale, with the exception of small-scale pilots for regional industrial symbiosis or partial products internal to a single firm (Hofstetter et al., 2021).

CE often requires a socio-technical transition as it involves interactions between individual and collective agents mediated by technology and requires significant behavioral changes from individual consumers, businesses, and governments. This transition requires a strong focus on material flows, reverse supply chains, and material recovery strategies. The strong focus of CE on material flows rather than energy is justified because many materials have a practical limitation on supply, while non-fossil energy does not. The main focus within the CE is to *"close the loops"* by redesigning products to extend their lifecycles, as well as recycling, reusing, and remanufacturing products and their components and minimizing the amount of waste produced within production systems. Many small material loops throughout supply chains are seen as a way to reduce environmental impact because they require less processing of materials (Stahel, 2010). However, redesigning the reverse supply chain toward accelerated recycling and increased material recovery requires digital technologies that can collect, sort, and analyze information on the location and conditions of products and their constituent parts (Liu et al., 2022). Moreover, making effective end-of-lifecycle decisions about reusing components and materials involves the availability of real-time data on their status, maintenance, damage, and material compositions (Laskurain-Iturbe et al., 2021). Current literature focuses largely on using digital technologies to inform decisions regarding the repurposing, remanufacturing, refurbishing, reuse, and repair of products by collecting and sharing information between multiple stakeholders (Awan, Sroufe, & Shahbaz, 2021). Furthermore, as supply chains have become increasingly global and complex (Kim & Davis, 2016), the adoption of CE practices also needs to cross regulatory boundaries, as input is needed from upstream supply chain partners and outputs can be distributed to users all around the world.

One additional challenge relates to moving from transparency and availability of data toward transforming that information into sustainability outputs. Transparency in itself does not lead to CE practices, but using the knowledge resulting from such transparency may lead to different trajectories and tactics to achieve them (Ki, Chong, & Ha-Brookshire, 2020).

DPPs are envisioned as digital information tools holding product information pertaining to their entire lifecycle, from the extraction of raw materials and the manufacturing phases to shipping, distribution, and use until their end of life. Currently, several information tools exist that are used to certify certain properties and qualities of products, services, or processes. Table 1 compares indicative, widely used certification documents in the diverse areas of commercial products, services, food, and person identification. Similarly, Adisorn, Tholen, and Götz (2021) detail the characteristics of other existing information tools used in the areas of materials and energy efficiency and also compare them to DPPs. From these comparisons, a straightforward deduction is made that DPPs will be applicable to a highly diverse set of application areas and will address corresponding value chains end-to-end.

3.1.2. *Implementation challenges of digital product passports*

Recent advancements in digital technologies provide tools and methods for collecting and processing data from physical systems,

Table 1
Comparison of indicative contemporary certification and identification tools with the envisioned Digital Product Passports. Information on DPPs refers to their provisioned structure and use, which are currently under research.

	Application area	Topics addressed	Policy-making	Issuance or Certification	Data Governance
CE marking	Commercial products in the European Economic Area.	Compliance with health, safety, and environmental protection EU legislation.	Legislation developed by the European Union.	Depending on the product, certification may involve independent third parties, national notified bodies, or be self-certified.	Generated by the product manufacturer or distributor. Risk of not being harmonized with the latest legislation.
ISO certificate	A wide range of technical and non-technical fields, including electrical and electronic engineering (jointly with IEC)	Broad spectrum of products, services, and procedures.	The International Organization of Standardization comprised of national standards bodies.	Independent third-party certification bodies.	Product manufacturer or service provider. Intermittent data updates.
Regular passports	International travelers.	Identification of individuals.	National and regional (e.g., EU) legislation and the International Civil Aviation Organization.	National authorities.	Centralized data control by national authorities.
Organic certification	Primarily food but also textiles.	Production standards for growing, storage, processing, packaging, and shipping.	National and regional legislation.	Independent third-party certification and participatory guarantee systems.	Farmer or distributor.
Digital Product Passports	Individual product items.	Product sustainability, usage, and lifecycle data.	Potentially by regional legislation. Standards development by international SDOs (e.g., ISO/IEC).	Multiple actors across the value chain.	Fully decentralized, automated, and continuous data updates by multiple actors. Use of enhanced security and trustworthy technologies (e.g., self-sovereign credentials).

production processes, and product usage. This data can be collected and processed continually, in near-real time, and at scale, resulting in data sets with enormous potential for identifying inefficiencies (Kristoffersen, Blomsma, Mikalef, & Li, 2020). Consequently, novel data-driven design methods and tools for circular systems and processes that enable continual and fine-grained evaluation of their circular efficiency throughout the lifecycle management of a product or service can be developed.

Furthermore, the use of DPPs will be agile and dynamic, allowing multiple actors to continually update and augment the set of information carried by a DPP. The carried information will be granular enough to describe individual items (rather than product types), while also being structured and interoperable so that knowledge can be extracted regarding different scales, from the lifecycle of individual items to the cross-sectoral interdependencies between different value chains. This power of DPPs stems from the use of emerging ICT (AI, the Internet of Things, and others) that enables the continual collection and processing of highly voluminous and multi-modal data.

Çetin et al. (2022) propose a framework for a digital circular built environment that is based on the preceding (to DPP) concept of material passports. By using the construction sector as an example, they identify that data sharing and monitoring of CE progress are the main challenges to implementing CE. In particular, implementing looping actions (i.e., closing the loop between waste and resources) and measuring progress toward circularity necessitate the collection, storage, and sharing of relevant data among actors throughout the product lifecycle using digital technologies that facilitate collaboration and trust. In this context, the Internet of Things (IoT), Big Data Analytics, Blockchain, and Digital Twins are regarded as key enabling technologies.

Similarly, in Gligoric et al. (2019), authors consider product passports and data exchange as key facilitators for reaching the next stage of a Circular Economy. They also identify the Internet of Things and SmartTags based on printed sensors (i.e., using functional ink) as key technologies for collecting, sensing, and reading parameters from the environment, as well as tracking the lifecycle of a product. Their approach moves beyond currently established practices where QR codes and data matrices are used at the Stock Keeping Unit (SKU) level. Instead, authors envision using IoT and SmartTags to identify specific components, not just the integrated product, and to continually collect data throughout the lifecycle of the product. Such practices will not only facilitate the tracking of products, materials, and resources. However, it will also enable novel business models in line with the principles outlined by the major CE schools of thought (e.g., the Blue Economy).

While emerging digital technologies are key enablers for collecting and processing product-related data and information, their use extends beyond and covers equally important aspects of data transparency and trustworthiness. Berg et al. (2022) consider the plastics value chain and address the challenge of information asymmetry and intransparency in the market for recycled plastics (recyclates). In particular, they highlight the role of the knowledge gap between plastic recyclers and producers of plastic products (manufacturers) in underperforming markets and lower amounts of high-value recycling. Toward bridging this gap, the authors consider using product passports implemented as decentralized identifiers and verifiable credentials to overcome information deficits and information asymmetry in the circular plastics economy. They propose using a decentralized public key infrastructure (DPKI), which allows the creation of digital identities for companies and products and the exchange of trustworthy and digital product passport data among all players in the plastics industry. Key enabling technologies include Self-Sovereign Identities (SSI), Decentralized Identifiers (DIDs), and Verifiable Credentials (VCs).

Equally important to the technologies enabling the implementation of DPPs is the information that will be stored in and carried by the DPPs. Berger et al. (2022) claim that DPPs can help value chain stakeholders identify sustainable loop-closing pathways, thus facilitating the transition to a CE. In particular, DPPs can function as unique identifiers of the corresponding physical products by containing specific product- or material-related data and gathering real-time data over the entire life cycle of a product. Berger et al. (2022) consider the use case of electric vehicle batteries (EVB) and present a preliminary conceptual DPP information model based on a systematic literature review that also considered regional initiatives from the European Commission. The model provisions storing EVB-related information on the DPP pertain not only to the chemical and physical characteristics of the product but also to its sustainability and circular characteristics, such as the length and locality of the product value chain and the involved actors throughout its lifecycle.

3.2. *Digital technologies enabling digital product passports*

The implementation of DPPs and their leverage to facilitate the transition to more sustainable, and eventually circular, value chains is made possible by recently introduced and emerging digital technologies. Pagoropoulos et al. (2017) provide a systematic literature review in an effort to evaluate the application of key digital technologies in a CE. Moving beyond this scope, in the following, we provide an outline of enabling Digital Technologies for the DPP landscape, presented in three distinct tiers according to the specific functionality they enable: i) *data collection*; ii) *data curation, processing, and sharing*; iii) *data use and exploitation*.

3.2.1. *Data collection and handling for digital product passports*

The primary aim of DPPs is to hold data regarding the physical, chemical, structural, or other characteristic properties of a product. Such data is to be provided during the production phase by the manufacturer of the product but also needs to be collected throughout its lifecycle. This is because, depending on the use case, the characteristic properties of a product may be affected differently according to how it is being used, its operational environment, etc. This product data collection can occur either asynchronously at specified product lifecycle milestones or, ideally, in an automated and continual way.

Printed sensors and tags are devices manufactured using printing methods that can monitor a physical process and/or emit data, typically a few bits. Benefits of using printing technologies include the possibility to use flexible substrates, resulting in thin and light-weight devices at a very low cost, and using simpler infrastructure than, for example, the semiconductor industry (Gligoric et al., 2019), which can also be more sustainable; the authors in Maddipatla et al. (2020) provide a comprehensive review of state-of-the-art manufacturing techniques. The small and flexible form factor, along with the low production cost, allows the integration of printed sensors in several types of products in large numbers, thus enabling automated and continuous data collection from individual products en masse. The most intensively evolving types of printed sensors include biosensors, capacitive sensors, piezoresistive sensors, piezoelectric sensors, photodetectors, temperature sensors, humidity sensors, and gas sensors (IDTechEx, 2017).

Distributed and decentralized identifiers (DIDs) enable the unique identification of products at the item level. Contrary to currently established methods (such as printed QR codes) that enable the identification of the type of product and brand, DIDs enable the identification of the specific item, thus allowing the collection of data and tracking the item throughout its lifecycle, a key requirement of DPPs. On the other hand, self-sovereign identities (SSIs) enable individual actors to claim and prove their own identities without the need for a centralized trusted party. Verifiable Credentials (VCs) are a form of machine-readable credentials that are cryptographically secure and privacy-preserving. The combined use of SSIs and VCs enables different actors across the product value chain to access or add data to the DPP of a product throughout its lifecycle. The distributed and decentralized nature of the aforementioned technologies greatly facilitates the adoption and use of DPPs by highly diverse and large groups of product stakeholders that would otherwise be very challenging to manage with centralized approaches.

However, a currently existing disadvantage is the lack of universally adopted standards, which hinders the onboarding of the technologies. Nevertheless, steps are being taken in this direction, such as the approval by the W3C of the W3C Decentralized Identifiers 1.0 (W3C, 2021) as a new web standard in July 2022 (the first identifier approved as a W3C standard since the URL).

The Internet of Things (IoT) is a technological paradigm that enables the massive and seamless integration and interconnection of machines and devices with the Internet and the use of Internet services. To this end, the IoT encompasses a wide range of technologies, forming a rich and diverse technological system that enables the continual collection of dense data in the space and time domains. From recent advances in low-power and batteryless electronics, energy management (including wireless power transfer), efficient low-power wireless communications for local area networks (IEEE 802.15.4, XBee, Bluetooth Low Energy), and wide area networks (LoRaWAN in the unlicensed spectrum and 5G/NB-IoT in the licensed spectrum), to IoT service provisioning and composition, and innovative IoT-enabled business models. This rich technological system underpins broader socio-economic paradigms, one of which is data-driven or digital CE (Angelopoulos et al., 2019); i.e., a Circular Economy that can track and optimize the production and consumption of services and products throughout their lifecycles at great scale by leveraging digital technologies.

3.2.2. Data curation, processing, and sharing with digital product passports

DPPs are aimed at collecting and holding data pertaining to the entire lifecycle of individual items and products. Holding, processing, and sharing this vast volume of fine-grained and high-fidelity data necessitates the use of innovative digital technologies that, in several cases, go far beyond conventional approaches.

The first technology is Cloud Computing (CC), which enables the elastic and on-demand availability of computing resources (e.g., computing power and storage space) in a way that relevant technical challenges are hidden from the user. Its proliferation in the early 2000s underpinned the rise of new market sectors (such as e-commerce) by greatly reducing costs and dis-associating the physical and cyber spaces (e.g., in terms of accessing data and e-services). However, the continuously growing demand for computer resources and reduced latency in accessing them provide motivation for more agile and decentralized approaches. Multi-access Edge Computing (MEC) and the closely related Fog Computing paradigms enable the provision of computing resources at the edge of a network, close to the end users. This approach assumes distributed network architectures that contradict the highly centralized approaches in CC. Making computing resources available at the network edge significantly reduces the distance between running services and their consumers, leading to significantly reduced transfer and processing times. At the same time, data can be processed close to where and when they are generated, ensuring that they are timely and relevant for the end user (consider data referring to current environmental conditions). In addition to enhancing security and privacy, these decentralized and distributed architectures allow for the sharing of processed data rather than actual raw data with remote systems. In the context of DPPs, modern Cloud Computing (e.g., using microservices or serverless approaches) and MEC architectures enable the development of digital infrastructures that can support the great volume of transactions and data pertaining to (potentially) myriads of items and actors. As an example, consider a DPP infrastructure using Distributed Ledger Technologies to register data. A MEC architecture would allow transactions to occur on the edge of the network, in physical proximity to the actual item or actor, supporting high throughput rates and low latency.

Secondly, Data Analytics (DA), Machine Learning (ML), and Artificial Intelligence (AI) enable the efficient curation and processing of data to identify underlying patterns and elicit information and knowledge from it. Corresponding methods have been developed for various types of data, from large-volume data sets to continuous streams of data and from highly structured data to ad-hoc, unstructured data. Underpinned by advancements in the aforementioned IoT and MEC technologies, AI models can now be natively deployed on machines and embedded devices and operated without the need for continuous connection to the Internet. This way, new pathways for product data collection are revealed that are not dependent on the presence of other ICT infrastructure.

Finally, Distributed Ledger Technologies (DLT), including Blockchain, provide the means for maintaining distributed and structured collections of data (data ledgers). With the use of cryptographic methods, modern DLTs and Blockchains can provide guarantees regarding the timeliness and veracity of data, the attribution of actions on the ledger to actors, as well as technical means for maintaining the ledger synchronized across multiple sites, actors, and institutions. This is achieved using consensus mechanisms that operate over peer-to-peer networks without the need for a centralized managing authority (although, in specific cases, some level of control can exist, e.g., in permissioned Blockchains). These characteristics make DLTs and Blockchain promising technologies for enabling DPPs, as they provide the means both for maintaining and sharing structured data while preserving trust and privacy. In this regard, these technologies also promote circularity in broader contexts, such as Smart Cities (Damianou et al., 2019).

3.2.3. Data exploitation and use with digital product passports

Data collected and shared using the aforementioned technologies can be leveraged to support a broader set of functionalities such as designing and improving product design processes, informing decision-making for increasing the efficiency of value chains, and interconnecting disjointed value chains with the aim of closing loops. DPPs can be instrumental in facilitating such data exploitation at scale.

Digital Twins (DT) can be used to monitor, reflect, and potentially influence the current state of their physical counterparts. DT refers to virtual representations of physical objects, products, or systems built using Digital Technologies. A DT can vary in terms of complexity as well as its intended use. In its simplest form, a DT serves as a virtual model of an object, product, or system to represent its characteristic properties. The model can then be used in order to evaluate modifications and improvements through simulations before those are applied to the physical counterpart. At the next level of complexity, a DT serves as the digital shadow of its physical counterpart. In this case, the properties and the environment of the modeled subject are dynamically monitored (e.g., through smart tags and sensors) and reflected on the virtual model. At the highest level of complexity, the DT serves as a complementary digital component of a cyber-physical object, product, or service. It has the ability not only to monitor and reflect the current state of the physical counterpart but also to process this data and act upon it, thus forming an integral part of its operation and behavior.

Finally, marketplaces and trading platforms for physical and digital assets are virtual spaces and online services that enable the discovery and exchange of assets by leveraging corresponding digital data. With the ongoing digitization of products and their value chains, marketplaces exploit relevant data and facilitate the transition to the Circular Economy by helping close production and consumption loops. Indicative examples are the AssetHUB (https://www.asset-hub.co.uk/) in the UK, where providers of digital infrastructure make their assets available on the marketplace to be discovered by potential users, and the SyncOnSet Asset Hub (https://www.synconset.com/home/asset-hub/), where production companies can track and manage entertainment equipment. Marketplaces and trading platforms can address the need to discover and identify available assets at scale (e.g., in a Smart City), provided that the available data are structured and open. DPPs will be well-suited to address these needs at the level of individual products.

3.3. Broader operational environment of digital product passports

In the previous section, we provided an outline of enabling Digital

Technologies for DPPs. In this section, we move beyond the technical context of DPP implementation and provide a transdisciplinary analysis of their possible implications. In particular, we take a broader look at the operational environment of DPPs considering the perspectives of economic competitiveness, geopolitical relationships, and globalization processes, including implications for global supply chains.

3.3.1. Economic perspective of market competition

Economic principles suggest that without clear, reliable incentives, firms will not adopt circular behavior (Domenech & Bahn-Walkowiak, 2019). A major legislative failure globally has been the lack of true pricing, often termed "polluter pays" regulation (Green, 2021). This means that damage to public property through pollution or resource depletion is not factored into financial decision-making, and firms have little incentive to change. In fact, we can go further and say that this failure prohibits firms from adopting circular business practices, as they would be unable to match the cost structure of their unsustainable competitors. For industries and whole economies to truly embrace the CE, there needs to be a positive business case for it (Sarja, Onkila, & Mäkelä, 2021), including initiatives that support it, such as DPPs.

Socially, in some contexts, there is a growing consensus on sustainability as a legitimate basis for business practice. For example, many investment brokers are challenging firms seeking capital to improve their sustainability credentials (Weston & Nnadi, 2021). However, much of the world's population strives to attain a modern Western lifestyle with its high material use and emissions. Accordingly, for DPPs to contribute in any significant way to meeting climate goals, there needs to be a broad, unified implementation. This includes the viewpoints of both the firm and the consumer, so that all stakeholders understand how they can benefit from DPPs and use the data to minimize their environmental impact while remaining economically viable.

3.3.2. Geopolitical relationships and globalization

At the political level, control of raw materials is increasingly becoming a global issue as many developed countries outsource material extraction, mostly to developing countries, which suffer the environmental and social damage it usually brings. Outsourcing is done because developed countries usually want to avoid the environmental and social damage that resource extraction brings or because they do not have access to these resources themselves. Poorer countries that suffer the worst effects of climate change have been pressing for financial help from richer countries at each United Nations Climate Change Conference, with limited success. The implementation of regulations on DPPs is likely to add pressure on firms from developing countries, for example, by requiring them to invest in costly digital infrastructure to provide the high-quality data needed for the DPPs to work. Access to digital platforms cannot be evaluated uniformly across different countries and regions (Tiwari & Srivastava, 2020). For example, based on household surveys and additional modeling tools, the International Telecommunication Union (ITU) estimates that, globally, 76% of individuals in urban areas use the internet, compared to 39% in rural areas (ITU, 2021). In the Indian context, for example, there is a disparity between urban and rural areas in terms of physical infrastructure for digital operations, such as data centers, telecom infrastructure, and computer access. Therefore, a smart transition to CE will prove to be challenging in regions where digitalization is lagging, and policymakers need to be aware that DPPs have the potential to exacerbate economic inequality.

Uneven access to digital platforms and physical digital infrastructure is a result of ongoing globalization processes. Despite globalization, fuelled by digitalization, making the world appear flat (Friedman, 2005), economic activity has never been more geographically concentrated, meaning that economic activity, including innovation as a result of digitization, is still highly location-dependent (Florida, 2005). The development of digital technologies like DPPs is imperative to CE as they support and enable collaboration between partners (Chauhan et al., 2021). Digital platforms potentially solve information asymmetries, enhance effective information sharing, and reduce transaction costs (Wilts & Berg, 2018). However, a smart transition in CE through digitalization has inherent geographical limitations, and there is a distinct possibility that DPPs will intensify the geographic concentration of economic activity and innovation in CE.

The geographical and inter-regional implications of DPP are significant. In a worst-case yet not wholly unlikely scenario, these EU-centric DPPs will serve as a barrier for suppliers in developing countries where the EU sets production standards globally, insisting on a level of digitalization that is, for many countries, unattainable.

3.3.3. Challenges and opportunities for global supply chains

From a supply chain perspective, DPPs seemingly present significant opportunities for industrial ecosystems to become more transparent and resilient and increase the accountability of global producers. Industrial ecosystems are multi-tiered production systems involving heterogeneous agents operating in sectoral value chains and contributing to the capability domains of the ecosystem (and its participants) with closely complementary but dissimilar sets of resources and capabilities. The geographical boundaries of the industrial ecosystem are shaped by the evolving interdependencies linking organizations within the ecosystem and by the new linkages consolidating beyond that. Thus, the industrial ecosystem is a structured production space centered mainly on its productive organizations, as well as other institutions, intermediaries and demand-side actors, purposefully involved in co-value creation processes along various types of diversification and innovative industrial renewal trajectories (Andreoni, 2018, 10). As such, an industrial ecosystem consists of multiple value chains, or value networks, and in addition, value chains may stretch across various industrial ecosystems.

Yet, implementing DPPs presents a challenge to industrial ecosystems because of their highly complex, dynamic, and geographically dispersed supply chains. In this context, most firms do not have full visibility and transparency over their supply chains, including the supplier networks and origins of products (Kim & Davis, 2016). Even when there is full visibility of the supply chain nodes and linkages, the quality, reliability, and accuracy of the information coming from the different nodes of the supply chain is limited because of diversity in monitoring practices, suppliers' approaches to deceive the systems in place, and the difficulty with measuring sustainability impacts beyond the individual supply chain node level (Gualandris et al., 2015).

Traditional supply chains are largely linear, with limited attention to reverse flows where materials and products are brought back into the system. Moreover, these global supply chains are highly unbalanced compared to the natural ecosystems of plants and animals, where scavengers and decomposers play as important a role as producers and consumers (Tate et al., 2019). The Extended Producer Responsibility (EPR) models show that new types of ecosystem actors may be needed to manage recycling and waste collection on behalf of multiple producers. Yet, this can increase industrial ecosystem complexity because multiple such intermediaries might be needed for different types of products and countries (Kunz et al., 2018). The implementation of DPP presents major opportunities to address these challenges and strengthen the focus on reverse flows and a more balanced distribution of roles and functions across the supply chains, enabling the production and reuse, recycling, and remanufacturing of products.

3.4. Digital product passports in CE orchestration

The key value of CE revolves around the reduction of extractive practices, which account for a large environmental footprint while maintaining economic competitiveness. However, scholars are increasingly pointing out the unintended consequences of some seemingly beneficial steps. In this part of the transdisciplinary analysis, we explore these unintended consequences and describe the need for holistic orchestration of industrial ecosystems as they transition toward the CE through the use of DPPs.

3.4.1. Orchestrating circular industrial ecosystems

While many firms communicate a strong emphasis on sustainable practices, most solutions adopted in practice do not fully address the major shortcomings of the current industrial system and still largely focus on the use of virgin materials, fossil fuels, polluting technologies, short lifecycles, a lack of repair and upgrade solutions, complex and wasteful supply and distribution networks, and extensive marketing-driven overconsumption (Bocken & Short, 2021). Nevertheless, some regulatory solutions, such as Extended Producer Responsibility (EPR), are beginning to have some positive effects by forcing producers to take responsibility and bear the costs of waste resulting from the sale of their products. Key learnings from the implementation of EPR models emphasize the need for a collective approach to waste collection and recycling, harmonized legislation between different legislative areas, the development of a coordinating framework that can enable the proper enforcement of recycling standards, and the role of orchestrators such as Producer Responsibility Organizations (Kunz et al., 2018). The role of such orchestrators is also outlined by CE studies that advocate for independent intermediaries who can orchestrate and coordinate the collective efforts needed to implement CE practices across supply chains, as the emergence of circularity brokers in the food supply chain illustrates (Ciulli et al., 2020). The existence of such orchestrators requires new business models to provide economically viable ways to recover materials and reduce the consumption of virgin materials while being competitively viable (Lüdeke-Freund et al., 2019). Beyond this, consumers also have a large responsibility and should be included in the orchestration process. There is a need for clear regulatory incentives (e.g. producer responsibility) and a shift in social norms regarding pro-environmental behavior (e.g. moving away from single use plastics, flight shame) for CE adoption by both consumers and businesses. Research in this area suggests that pro-environmental norms can emerge and evolve as a result of individuals aligning their behavior with societal expectations (Young, 2015), whereby pro-environmental norms can be effective in shaping behavior by fostering a collective sense of responsibility and encouraging individuals to conform to environmentally friendly practices (Nyborg & Rege, 2003).

To advance the transition to the CE, there is a need for collaborative, cross-industry, multi-level efforts centered around joint planning and coordination of reverse material flows (Boldrini & Antheaume, 2021). Many successful CE initiatives are characterized by their relational nature; they are based on partnerships and collaborations between manufacturers, service providers, and non-economic actors, such as NGOs or governmental authorities, who are critical in raising awareness among relevant firms, consumers, and society at large (Lüdeke-Freund et al., 2019). Moreover, some recent studies suggest that while data collection within organizations is frequently used to increase energy and resource consumption efficiencies, it is the data collection from multiple external partners that can enable CE activities such as end-of-life activities, collaborative cradle-to-cradle design, and industrial symbiosis (Liu et al., 2022). Particularly, the orchestration of access to this type of cross-firm data is difficult, as many firms fear data security breaches or the loss of commercially sensitive information. These information vulnerabilities and hesitations from firms to share their data can be addressed by policies and regulations from the government (Chauhan et al., 2022). In this context, there is a need for system-wide orchestration of data access and usage, and therefore actors suited to this role are needed.

One particular form of collaborative efforts toward CE involves industrial symbiosis practices, in which traditionally separate industries are engaged in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products (Chertow, 2000): thus, a network in which waste from one industry is used as a resource for another industry. . Key components to industrial symbiosis are collaboration between industries and the synergistic possibilities that are offered by geographic proximity (Chertow, 2000). Industrial symbiosis at a large scale can enable material recovery with significant reductions in the system's environmental footprint. Enabling cross-industry material flows can significantly reduce waste by increasing the reuse of components and materials. While industrial symbiosis is a promising strategy, there is still enormous untapped potential in connecting disparate supply chains in new forms of industrial ecosystems (Neves et al., 2019). One of the main reasons for the unfulfilled potential of industrial symbiosis is the lack of integration and information sharing between different industries and the lack of data on supply and demand between different industries and companies, which is amplified by uncertainty surrounding quality and coordination issues (Ashton, 2021).

The orchestration of business strategy across networks, such as supply chains, is a process in which different stakeholder incentives are made explicit and aligned in such a way that a governance structure emerges for the benefit of the network as a whole, not just one dominant firm (Nambisan & Sawhney, 2011; Parida, Burström, Visnjic, & Wincent, 2019). This is brought about by knowledge mobility, innovation appropriability, and network stability (Dhanaraj & Parkhe, 2006).

3.4.2. Unintended consequences of digital product passports adoption

The implementation of DPP may give rise to unintended negative consequences, some of which could potentially be mitigated through careful orchestration of industrial ecosystems. Nonetheless, despite effective orchestration, some unintended effects may still persist, and an increasing number of studies have shown that linking the supply and demand of secondary materials does not directly reduce environmental impact, and there is a need for a more holistic view of secondary production and its interlinkages with demand and other economic factors (Zink & Geyer, 2017). The term Circular Economy Rebounds (CER) has been proposed to account for these secondary, unintended effects of CE (Zink & Geyer, 2017). CER incorporates indicators beyond energy use and emissions to add a wider range of other environmental implications, with possibilities to broaden the concept to include economic and behavioral feedback loops (Font Vivanco et al., 2016). CER can present itself in three main formats: increased demand for goods and services created by net savings; the ability to substitute primary production; and improved efficiency leading to increased usage of the same product, service, or energy (Warmington-Lundström & Laurenti, 2020). While there are many challenges with conceptualizing and operationalizing CER related to the boundaries of the concept, measurement issues, and domain-specific interpretations, there is agreement that a holistic approach is needed to assess the multifaceted impact of CE practices.

The last mentioned CER format can arguably be extended to the energy used for materials and products to cover the distance between industries. One of the aims of implementing DPPs is to enable cross-industry material flows in which waste from one industry is made available as a resource for any other industry. However, in connecting material flows, geographical distance and transport emissions play a significant role, which is often neglected in policy discussions. In order to close material loops within and between industrial ecosystems in an efficient and sustainable manner, physical distance should not be neglected. Ultimately, the CE is proposed as a means to realize efficient use of materials and CO_2 emission reduction. However, creating a global network of material flows is not necessarily logical for specific products and materials. For instance, the global transportation of large quantities of heavy materials, like recycled iron, might result in vast quantities of emissions, which goes against one of the main goals of the transition to the CE. Despite the environmental impact being smaller for lighter products and materials, it can be argued that DPPs should integrate transportation emissions in order to optimize material flows within geographical contexts, and orchestration efforts can design relevant regional clusters of mutually beneficial production processes.

One unintended consequence of the EU-imposed data sharing for enabling DPP is the heightened openness and distribution of data required. Compared to the situation without a DPP, where data sharing may be more limited, the open nature of data in DPP poses a potential risk for firms. The increased accessibility and availability of data through DPP could lead to concerns over intellectual property protection and potential competition risks, as firms might worry that their proprietary information and trade secrets could be more easily accessed and utilized by competitors or unauthorized parties, compromising their market advantage and potentially undermining their business interests. This perceived risk of data openness within the DPP framework may create apprehension among firms and impact their willingness to participate fully in the data space.

An additional difficulty is that different geopolitical regions adhere to different approaches to sustainability in the production and use of products. The EU, through its Green Deal, is developing far-reaching policy to force firms to comply with regulations that could help the region meet its emission reduction goals, including the Carbon Border Adjustment Mechanism due to come into effect in 2026 and the proposal for DPPs themselves, which are not a part of other regions' policy measures. The USA's patchwork of local and state legislation and its market-led approach to sustainability and the circular economy have resulted in a less regulated environment where consumer choice, typically motivated by price considerations, will largely determine the extent to which national climate goals are met. The increasing polarization of opinion relating to climate policy between the Democratic and Republican parties means that opportunities for bipartisan policy innovation are increasingly unlikely. China, the world's largest emitter of greenhouse gasses, has a mixed approach to climate policy, as it has invested heavily to become a global frontrunner in solar and wind power, as well as in electric vehicles, but, at the same time, it also invests heavily in highly polluting coal-fired energy production and continues to finance a significant expansion of coal-based energy capacity in both domestic and foreign markets (Sandalow, 2020). For DPPs to truly impact the global sustainability crisis, they must be acceptable and interoperable with all major global regions. This will require a long process of negotiation, and the EU's step toward a regional DPP regulation may thus be seen as one step in this direction.

Summarizing the previous section, Fig. 2 shows how the transdisciplinary analysis synthesizes current insights from the literature on CE and DPP to provide a state-of-the-art summary (1st order themes) on the socio-technical transition to the CE, leading to structured insights (2nd order and emerging themes). Fig. 2 also contains several insights specifically emerging from the experts discussion - a brief explanation of those can be found in Appendix 1. In the following section, these 2nd order themes form the basis of eight guiding principles for a framework for orchestrating of the implementation of DPP aimed to achieve a CE.

4. A framework for the orchestration of the implementation of digital product Passports: Eight guiding principles

Emerging from the transdisciplinary analysis described in the previous section, we distinguish between eight key steps or guiding principles in the DPP orchestration process throughout industrial ecosystems, as depicted in Fig. 3, whereby certain firms, such as hub firms, platform firms, or innovation intermediaries, lead collaborative network activities to ensure value creation and appropriation across industrial ecosystems without the benefit of hierarchical authority (Dhanaraj & Parkhe, 2006). The orchestration process guiding principles? begin with (1) the requirements analysis of regulations, such as the upcoming EU regulation on DPP, industry regulation, or firms' self-regulation. Using these requirements, the next step is (2) the design of DPPs and their governance, where good orchestration prevents the concentration of power that would lead to a "winner takes all" scenario and, instead, adheres to best practices in open infrastructures and decentralized data spaces that are modular, interoperable, transparent, and ensure data sovereignty (Braud, Fromentoux, Radier, & Le Grand, 2021; Beverungen, Hess, Köster, & Lehrer, 2022). Orchestration of (3) data technologies requires that beneficial choices are made with respect to the standardization policies to adhere to, the types of data to be included in the DPP, mechanisms for their verification and validation, knowledge engineering through AI, and more. A crucial part of the orchestration process is to align stakeholder requirements in (4) a governance mechanism that includes an analysis of participant incentives, a trust framework setting out which parties provide access to their data for which purposes and under what conditions, as well as contractual agreements. (5) Implementation in practice requires more than putting the technologies and governance mechanisms into operation, as it impacts the business models of firms throughout the industrial ecosystem, including their value propositions, cost structures, and revenue models, and may even change the customers that firms supply to. As the DPPs lead to efficiencies and reduce the limiting effects of supply chain bottlenecks, particularly through AI-based optimization algorithms, firms may develop new material flow pathways, and they may find their business practices changing accordingly.

The DPP orchestration process includes the involvement of (6) regulatory bodies as the DPPs are used to assess compliance with regulations on material flows, energy emissions, waste management, including recycling, etc. Governmental regulation of minimum standards may be augmented by industry-wide agreements or individual firms' self-regulation, such as adherence to the principles of the circular economy by maintaining the highest value for components and materials and decoupling products' manufacture and use from their environmental impact. Orchestration requires insight into the effects of DPPs through (7) impact assessment to measure the holistic effects on social, environmental, and economic indicators. This will consider not just the direct effects made visible through a product's DPP but also the indirect and rebound effects. This poses a significant challenge for orchestrators, as such indirect effects may be difficult to identify or measure. The final orchestration step is (8) the continual improvement of the DPPs and their governance through close cooperation with multiple stakeholders,

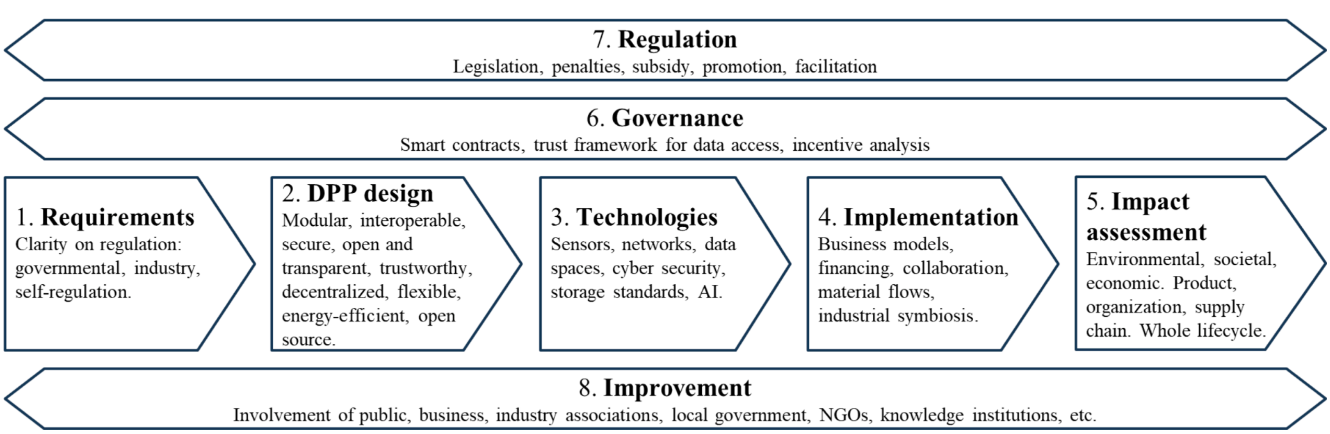

Fig. 3. A framework for the orchestration process in the design and implementation of Digital Product Passports throughout industrial ecosystems.

including public bodies, firms, industry associations, local governments, consumer groups, knowledge institutes, and others.

These eight key steps for orchestrating DPPs have been distilled through a process of interdisciplinary dialogue and leveraging relevant insights from the numerous streams of literature that address this topic (see Fig. 1 in Section 2, Research approach).

Building upon the *trans*-disciplinary analysis presented above, in this section, we propose a set of guiding principles for designing and implementing a DPP from the perspective of managers in firms that are involved in producing products. At the same time, the guiding principles provide a theoretical basis for scholars on the implementation of DPP toward a CE, as multiple scientific and societal views are recognized and condensed (Brennan et al., 2021).

4.1. DPP requirements principle

Specify the requirements for the DPP at the system level, making both its objectives and the reasoning behind them clear to all stakeholders.

A DPP is a collaborative endeavor that will only lead to sustainability benefits if all relevant parties work together. A necessary first requirement here is that each firm understands what is required of them, how that fits into the wider product production process, and the basis for these requirements. Indicatively, with regard to the use of ICT, this need for clarity pertains to understanding the functional requirements of a system; e.g., what types of data need to be collected and what processes need to be monitored. If any lack of clarity is allowed to cloud interpretations, then members of the industrial ecosystem may take steps to the detriment of the DPP, such as withholding important information. For example, a small metalworking factory may already use offcuts of high-grade steel for purposes where low-grade steel would be sufficient. This firm needs to understand the system-level requirement of maintaining the highest possible material value. Clarity on requirements is therefore a necessary but insufficient component of the DPP design and implementation process.

4.2. DPP design principle

Use data spaces to create decentralized, open infrastructures that are modular, interoperable, transparent (open source), and ensure data sovereignty and security.

The implementation of DPPs needs to follow a design that allows for their widespread use across multiple sectors, prevents power centralization, and maximizes their impact. In this context, the implementation of DPPs needs to assume a decentralized architecture and enable the self-sovereign identification of actors to provide and access data without the need for intermediaries. This is a significant challenge in the current digital landscape, where a small number of large tech firms provide highly competitive cloud services with a centralized architecture. DPPs also need to employ open ontologies and standardize data formats to make stored data and information discoverable and open. Open and platform-agnostic approaches to implementing DPP interfaces will ensure interoperability between the systems of different actors and make data security transparent, thereby facilitating the widespread and scalable adoption of DPPs.

4.3. DPP technology principle

Collaboratively decide which democratizing digital technologies to use that are readily available to and implementable by all parties across the industrial ecosystem.

For a fully functioning DPP that has a meaningful impact at the system level, the digital maturity of all parties needs to be brought up to a suitable level. For this to happen without having detrimental effects on those parties situated in contexts with less advanced digital infrastructure, there needs to be a collaborative decision-making process with respect to technology choices. This pertains to the technical requirements of DPP infrastructure; i.e., which technologies are used and how (note the difference to functional requirements mentioned in section 4.1 DPP Requirement Principle). For example, suppliers in developing countries may be willing to commit to one specific DPP implementation as long as it aligns with alternatives for other customers, thus reducing any fear of lock-in. Adhering to this DPP technology principle can form an inclusive boost to the willingness of all parties to commit to the DPP, rather than an exclusive barrier to participation. For advanced AI technologies, for example, it is the responsibility of the parties in more developed regions to support implementation in less developed regions.

4.4. DPP implementation principle

Define business models that fully align with the objectives and workings of the DPP, as verifiable improvements to the efficiency of material flows will result in a commercial advantage.

Business models specify the strategy of a firm's product development, taking into account both upstream supplier concerns and downstream customer requirements, and they lay out what forms of value are created and captured. As the DPP will have potentially far-reaching consequences for many firms in an industrial ecosystem, its implementation requires all participants to revisit their business models and realign them with the objectives and workings of the DPP. Some firms' business models may change dramatically, requiring forward-looking leadership. Particularly the firms that provide virgin raw materials, such as mining exploitation companies, face the challenge of redefining their value creation by pursuing alternative sourcing options, or they will be excluded. Any waste produced during the production process may be commercialized, such as through local industrial symbiosis, where new partners may be sought beyond the traditional supply chain. For example, experiments are underway in a Swedish steel factory, to provide nitrogen-rich waste gases for firms involved in fertilizer production. Best practice in the CE prescribes maintaining the highest value for materials. This means that a business model that includes refurbishing components has a higher value than one that includes recycling raw materials.

4.5. DPP impact assessment principle

Measure holistic impact, including rebound effects, to assess the true sustainability impact of a product.

For a production system as a whole to show a positive sustainability impact, the DPP needs to be clear about all knock-on or rebound effects, as this will enable sustainability innovations to be commercially viable and, by extension, partial solutions to be evaluated appropriately. For example, e-scooters have been hailed as being environmentally friendly because a single vehicle is used by multiple people instead of each person buying their own. However, in practice, e-scooter trips in congested cities often replace trips that would otherwise have taken place by bicycle, public transport, or on foot. The environmental cost of collecting and distributing e-scooters is far higher than that of charging their batteries. Similarly, lifecycle analysis techniques must be expanded to account for the complexities of closing material flow loops, such as novel symbiotic relationships found across industrial ecosystems. Indeed, a full range of stakeholders need to be included in determining the scope of impact assessment, including citizens, businesses and public organizations, as meaningful impact can mean different things to different stakeholders.

4.6. DPP governance principle

Develop a collaborative trust framework setting out which parties provide access to their data to which users, for what purposes, and under what conditions, codified into contractual agreements.

A DPP will provide detailed insight into material flows and related production processes and may be seen as a commercial risk to some parties that have justified concerns about who gains access to their data and the potential for competitive misuse of that data. Through a collaborative trust framework, all participant incentives, restrictions, and obligations are laid out, ensuring—alongside the technical design—that the DPP does not form a commercial risk and that power in the industrial ecosystem does not reside with a single DPP-owner. In fact, with a strong trust framework in which all parties have an appropriate stake and clear rights, the DPP will become a strong incentive for system-wide innovation toward sustainable production practices.

4.7. DPP regulation principle

Create relationships with regulators to promote the need for support in developing fair and meaningful DPPs.

Firms are not passive observers in the development of legislation and other regulations but can engage in open, transparent discussions with regulators and policymakers in order to explain the implications of regulations and the implications of differences in regulations between regions or territories. As the European Union appears to be taking the lead in enforcing the use of DPP, it is logical for firms situated outside of the EU but involved in products for sale within the EU to persuade their regulators to base their legislation on similar sustainability objectives. This will result in penalties or subsidies that incentivize firms to work with DPPs. Additionally, leading firms can assist regulators in developing appropriate promotion and facilitation to help other firms in their region comply with DPP regulations. Regulations emphatically transcend the different fields concerning DPPs. A strong regulatory framework should encompass regulations about product design, a facilitating set of rules for urban planners to advance and strengthen physical infrastructure, and regulations about governance issues inherent to industrial ecosystems that transcend institutional entities (e.g., municipality, province). This paper shows potential links between legal aspects and different research fields; however, this needs to be explored more in-depth by researchers in the legal field.

4.8. DPP improvement principle

Involve all relevant stakeholders and give them a shared mandate to improve the DPP.

Through the involvement of multiple stakeholders in discussing the findings of the holistic impact analysis, each iteration of the DPP design and implementation cycle can be improved upon. Relevant stakeholders include firms, industry associations, public bodies, local governments, knowledge institutions, consumer groups, non-governmental organizations, investment brokers, innovation intermediaries, and more. For example, digital platform cooperatives have emerged to govern and encourage data sharing as one step in achieving CE. This DPP improvement principle has a multi-stakeholder focus that will allow for a broad perspective on any negative social or environmental impacts, including potential geographical inequality, and stimulate agreement for continual support of and optimization of the DPP. Discussions on potential trade-offs need to be managed in an open process, with acknowledgement of differences of opinion about optimizing the overall value for all parties, a fair distribution among parties, or a pure focus on the ecological footprint.

5. Conclusions

5.1. Critical reflection on the function, relevance and boundary conditions of the guiding principles

The guiding principles developed through the integration of several discipline-specific expertise serve as a roadmap for industrial ecosystems and public bodies as they approach the implementation of DPP. The guiding principles favor outcomes at the system level, which is a key requirement for DPP to effectively drive the changes needed to address environmental concerns. While the current analysis attempts to consider multiple factors and dimensions relevant to DPPs, research in this area should continue and test whether the developed principles and orchestration framework are mutually exclusive and collectively exhaustive. The orchestration framework focuses strongly on the implementation of DPPs with emphasis on operational guidelines, adoption and use across and within IEs with the purpose of enabling the transition to the CE. Realizing CE outcomes as a main purpose of DPP is a view we adopted in this study, yet, DPP are a broader development which most likely will entail broader implications, including intended and unintended consequences.

The implementation of DPP can be further enhanced by learnings from implementing other standards, technologies, and certifications at the global level, such as ISO or EPR models. ISO certification schemes have been widely adopted in practice on a global level, but their implementation is firm-specific with a strong internal focus (e.g., internal engagement of management and employees) and does not explicitly consider external stakeholders. Yet, a key learning from implementing ISO 9001 and 14001 is that managers tend to focus too much on the auditing and certification processes and less on continuous improvement and internalization of learning (Boiral, 2011). With a strong focus on technology, the implementation of DPP should also consider the risk of overemphasizing the technology at the expense of the actual outcomes to be achieved through the technology. EPR models are an example of standards implemented beyond individual firms. The increasing interest in EPR models has shown that implementation on a wider scale, across national boundaries, requires harmonized legislation and the development of a coordinating framework that can enable the proper enforcement of recycling standards and the role of orchestrators such as Producer Responsibility Organizations (Kunz et al., 2018). Thereby, the orchestration framework proposed in this study as a linking glue for the guiding principles follows this narrative and emphasizes a multitude of relevant actors to be engaged and the emerging governance, regulatory, and implementation challenges.

While the guiding principles provide valuable managerial and theoretical implications, we acknowledge that many boundary conditions apply. We propose an implementation approach that is collaborative and incremental, whereby we acknowledge that DPP are a normative instrument by nature, driven by the EU in order to enable circularity in the EU market.

While this research has not explicitly considered the legal requirements and implications of implementing and using DPP, a thorough legal analysis needs to be conducted in future studies. The changing legal framework in the context of the European Union around data protection and privacy can pose significant risks and implementation challenges for DPP (European Parliament, 2016). Governance and usage of data by different stakeholders should be thoroughly examined, and there should be systems in place to ensure that the right data is shared in a secure and reliable manner and that the sharing complies with any relevant regulations, such as the General Data Protection Regulation (GDPR) and the Data Governance Act, in the European Union (Janssen et al., 2020).

5.2. Contribution to the field of DPP

Despite increasing acceptance and integration of circular business principles, CE systems have not yet been implemented at any meaningful scale. Research in the direction of CE systems is required from multiple scientific communities in order to assist private individuals, business managers, investors, and policymakers in making informed decisions (Hofstetter et al., 2021).

A key difficulty in informed decision-making in the context of a successful transition to a CE is the discovery of and access to data. In particular, data needs to be collected that will cover multiple stages of the product life cycle (from sourcing production materials to monitoring production processes, use of the product, and reclaiming material) and multiple scales (from individual items to entire value chains and multiple markets). Furthermore, different actors in the value chain will continually generate related data throughout the product lifecycle and will need to be provided with mechanisms and tools providing certain guarantees regarding data attribution, immutability, access rights, and use. At the same time, any technical solutions will need to scale with respect to the number of actors, products, markets, and data access rights derived from relevant policies and legislation. While recent advancements in digital technologies now make it possible to efficiently address and overcome these challenges (e.g., communication networks providing seamless, pervasive connectivity; the Internet of Things and Edge Computing enabling the cyber-physical continuum; and AI and Machine Learning identifying underlying patterns and trends), they rely heavily on the corresponding data being structured, voluminous, and accessible in a controlled manner. Digital Product Passports seem to bridge the gap between a technical solution with the abovementioned characteristics and decision- and policy-making processes and activities. A DPP infrastructure providing the methods for managing and accessing DPPs both individually and at scale is likely to play a central role in enabling the CE by enabling connectivity both within and between complex industrial ecosystems and their diverse set of actors (Serna-Guerrero, Ikonen, Kallela, & Hakanen, 2022).

The proliferation of emerging ICT, particularly Artificial Intelligence and Machine Learning, has facilitated the conceptualization of innovative paradigms within industrial ecosystems (e.g., Industry 4.0 and 5.0 and smart manufacturing). So far, however, these paradigms are only implemented in a fragmented way in isolated islands of innovation, in spite of significant advances in AI and knowledge engineering systems. The barriers hindering their implementation are multifaceted, ranging from corresponding actors being reluctant to share or provide access to their data to a lack of a legislative framework regulating the field as well as technical barriers. Regarding the latter, AI technologies heavily rely on the availability of structured and regularly updated data that are used in order to extract knowledge by identifying underlying trends and patterns and performing nowcasting and forecasting. The introduction of DPPs and the development of a DPP infrastructure with the desirable properties (attribution and immutability of data, access control mechanisms, scalability) will facilitate the collection, curation, and use of structured data at scale, thus further promoting the adoption of AI and knowledge engineering by relevant actors and stakeholders.

The literature on DPP is only in its infancy, and following recent regulatory pressures, there is increasing interest both theoretically and practically in better understanding the nature and functions of DPP as well as its technological underpinnings and implementation requirements for knowledge engineering (e.g., Adisorn et al., 2021; Berger et al., 2022; Cetin et al., 2022; King et al., 2022). Our intention with this paper is to contribute to this growing stream of research by assessing what is needed to orchestrate the implementation of DPPs within and between industrial ecosystems. The focus on orchestration between and within IEs as a means to deliberately and purposefully implement DPPs while considering a wide range of stakeholders, motivations, requirements and technological infrastructure makes our contribution interesting and novel. This is both societally relevant and urgently required, as DPPs are intimately linked to the transition to the CE, the main theoretical stance attempting to enable economic growth without causing environmental degradation. We attempt to conceptualize how DPP can contribute to the CE vision as a solution approach. Our contribution may help to lead scholars toward impactful research as we employ a transdisciplinary approach to integrate insights from different disciplines to provide a better and more complete understanding of DPPs, the knowledge engineering that underpins them, and how their implementation may be enhanced. In terms of managerial significance, our orchestration framework and guiding principles for the implementation of DPPs, which are based on the transdisciplinary analysis, provide guidance on how to make relevant choices that can inform both managers within industrial firms and orchestrators guiding inter-organizational implementation.

5.3. Summary

Following the European Union's proposal for DPPs as the most promising approach to making production systems sustainable, the main message of this paper is that multiple perspectives must be considered when DPPs are designed and implemented to achieve the overarching goal of sustainable material flows, energy use, and reduced emissions. The *trans*-disciplinary analysis described in this paper has highlighted key barriers and challenges relating to knowledge engineering at the micro-, meso-, and macro-economic levels, and this has led to the formulation of guiding principles for managers of firms involved in product production industrial ecosystems. There is a global imperative to transform our economies away from their damaging past and into a regenerative future, and DPPs are likely to form a cornerstone of this transformation; as such, they must be carefully designed and implemented.

CRediT authorship contribution statement

David J. Langley: Writing – original draft, Supervision, Formal analysis, Conceptualization. **Eugenia Rosca:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Marios Angelopoulos:** Writing – original draft, Formal analysis, Conceptualization. **Oscar Kamminga:** Writing – original draft, Formal analysis, Conceptualization, Methodology. **Christa Hooijer:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. .

Emerging Theme	1st Order Theme	Brief explanation based on the expert discussions
Requirements analysis	Clarity on the problem and required solution	While discussing businesses their experience with sustainability policy measures similar to DPP's it became apparent that businesses often think policy to be unclear and ambiguous. That is why clarity about the implementation is needed. In addition, the expert panel stressed that for businesses to move towards implementing DPP's, businesses need to have a clear understanding and awareness about the sustainability problems underlying the transition.
Implementation	Need for incremental approach in the implementation	Several times in the discussion, the need for an incremental approach was emphasized mostly due to the global and complex nature of the current IEs.

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Emerging Theme	1st Order Theme	Brief explanation based on the expert discussions
Regulation	Open discussions and exchange between regulators and firms involved	The policies developed are often top-down imposed on companies and other stakeholders and there is limited understanding of what they entail as well as their intricacies.
Improvement	Shared efforts for improvement, collective engagement, improvement cycles, incorporation of wide range of stakeholders for input, broad perspectives and agreements for continuous improvement efforts	Implementation of DPP's continual and iterative learning process in which multiple stakeholders are involved. DPP's are still a developing technology which will have to go through multiple iterations in various forms to be adequate for achieving CE goals. In addition, transparent and open communication between actors is required to collectively engage relevant stakeholders.

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