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Digital Product Passport: A Pathway to Circularity and Sustainability in Modern Manufacturing

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Abstract: The primary aim of this study is to explore and understand the potential benefits and applications of the Digital Product Passport (DPP) system within the modern manufacturing industry. To achieve this, we developed a unique methodology, model, and a template for creating a DPP, identifying the key characteristics essential for effective implementation. Our approach involved an analysis of the literature and the formulation of a unified DPP framework, tailored to enhance supply chain transparency and support sustainable manufacturing practices. The empirical findings from our research demonstrate the DPP's impact on supply chain transparency, providing crucial product lifecycle information that bolsters decision-making and facilitates optimal resource management. Additionally, our study suggests that the DPP model, when applied to sectors such as electronics manufacturing, promises transformative results. This research underpins the pivotal role of DPPs in the future of manufacturing, highlighting their potential to catalyze a shift towards greater transparency and sustainability. Actionable guidelines are provided for manufacturers considering the adoption of this innovative system.

Keywords: digital product passport; DPP; manufacturing industry; circularity; supply chain transparency; data standardization; sustainability; industry 4.0

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1. Introduction

In a world witnessing unprecedented resource depletion, shifting climatic patterns, and a rapidly increasing global population, the conventional, linear model of consumption—take, make, and dispose—is untenable in the long run [1]. Addressing this issue, there is a growing movement towards the concept of circularity [2].

The circular economy represents a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits [3]. It employs reuse, sharing, repair, refurbishment, remanufacturing, and recycling to create closed-loop systems, thereby minimizing waste and making the most of resources [4]. This regenerative approach contrasts with the traditional linear economy, which has a 'take, make, dispose' model of production [5]. Circularity aims to move beyond the idea of making 'less bad' products to creating systems that are regenerative and restorative by design [6].

At the heart of the circular economy lies the principle of sustainability [7]. True sustainability is not merely about reducing harm but endeavors to bring positive impacts to the planet and the communities that inhabit it [8]. Sustainable product lifecycle management embodies this concept. It strives to mitigate environmental impacts while balancing economic viability and social equity throughout a product's lifecycle. The lifecycle approach considers all stages of a product's life, from raw material extraction, production, and use, to disposal and the potential for reuse or recycling [9].

Fundamental to realizing circularity and sustainability is the understanding that products and equipment can, and should, be reused and repurposed [10]. A product's end of life is not a terminal state, but rather a stage in its continuous lifecycle [11]. For instance, a disused smartphone can be disassembled, its valuable components repurposed for new electronic devices, and its less valuable parts recycled for their base materials [12]. In industries with high-value equipment, such as manufacturing or aviation, the practice of the refurbishment and remanufacturing of equipment is already common [13]. Embracing this not only reduces waste but also the demand for newly extracted raw materials, thus saving costs and conserving natural resources [14].

However, the practice of reuse and repurposing is not without its challenges. One of the significant barriers is the lack of information on the composition, usage, and end-of-life handling of products [15]. That is where the concept of traceability comes into play [16]. Traceability, at its core, is the ability to trace and verify the history, distribution, location, and application of products, parts, and materials. Its benefits span various facets of the product lifecycle [17].

In the production phase, traceability can enhance supply chain transparency, enabling manufacturers to source responsibly and minimize their environmental footprint [18]. For consumers, traceability provides insights into a product's origins and impacts, empowering them to make more informed purchasing decisions [19]. As for the end-of-life stage, traceability can facilitate the recycling and repurposing process, ensuring valuable materials are recovered and harmful substances are safely managed [20].

The European Commission suggests implementing digital product passports (DPPs) in the European Single Market as part of its Green Deal. This will promote circular business practices that reduce CO_2 emissions and maximize material efficiency [21]. In order to help consumers and businesses make informed purchasing decisions, the proposed regulation would require that a DPP, which provides an accurate and verifiable set of information about the products' environmental sustainability, be available before they can be sold or used in the European Union. DPPs also aim to increase openness regarding the environmental impact of items throughout their production and throughout their whole lifecycle, as well as to simplify repairs and recycling. Because DPPs include data that allows for the tracking of any compounds of concern throughout the product's lifecycle, they will also make it possible for public authorities to evaluate whether products comply with legislation pertaining to sustainable production and usage [22].

Bridging these interconnected themes of the entire product life cycle, from manufacturing and product usage to circularity, sustainability, reuse and repurposing, and traceability, is the DPP. Therefore, in this paper, we explore how DPP can be a pathway to circularity and sustainability in modern manufacturing, enhancing transparency and efficiency throughout the product lifecycle. More specifically, the current paper develops a standardized framework for DPP design and development, encompassing all the key characteristics of a DPP. Additionally, we have created a standardized template to assist in the design and documentation of DPPs.

The structure of this paper is as follows: Section 2 delves into a literature review, analyzing the existing research on DPPs and identifying gaps in knowledge. Section 3 presents the DPP model, whereas Section 4 presents our results and discussion, providing insights into the application and impact of DPPs. Finally, Section 5 concludes the paper, summarizing our findings and suggesting future avenues of research.

2. Literature Review

The Digital Product Passport (DPP) is a concept that embodies a digital representation of a product's information throughout its lifecycle, from creation to disposal. It serves as a repository of data that includes a product's origins, materials, usage guidelines, environmental impacts, and more. The DPP is envisioned to play a pivotal role in enhancing product traceability, promoting sustainability, and facilitating a circular economy. As we delve into the current literature on DPPs, it underscores the existence of a broad range of understandings and use cases. The lack of an overarching, comprehensive framework is evident in the diverse conclusions that studies arrive at. Simultaneously, the analysis of DPPs in the context of the circular economy, traceability, and product lifecycle reveals substantial gaps in knowledge and calls for further research.

A key theme across the literature is the urgent need for a standardized framework for DPPs. Jensen et al. (2023) enumerate seven clusters of data crucial for a DPP: usage and maintenance, product identification, products and materials, guidelines and manuals, supply chain and reverse logistics, environmental data, and compliance [23]. Adisorn et al. (2021) advocate that the preliminary design of a DPP should primarily consist of product-related data provided by manufacturers to stimulate a more circular economy [24]. King et al. (2023) corroborates the need for effective data capture and processing, particularly in sectors with data-intensive operations [25]. Nonetheless, the diverging perspectives across studies signal a lack of a comprehensive, universally accepted framework for DPPs—a pressing issue that needs to be addressed for enhancing DPPs' effectiveness across diverse stakeholders.

Circularity is another recurring concept in the literature. Both Plociennik et al. (2022) and Koppelaar et al. (2023) view DPPs as essential tools in enabling the circular economy by offering key data about the product lifecycle [26,27]. However, they also highlight the ubiquitous absence of vital information among stakeholders, hindering the successful implementation of circular economy practices. This state of affairs underscores the pressing need for DPPs that can effectively bridge these information gaps.

The role of DPPs in product lifecycle management is also stressed in several studies. Both Plociennik et al. (2022) and Koppelaar et al. (2023) highlight the critical role DPPs play across the entire product lifecycle, from manufacturing to disposal [26,27]. However, the literature often lacks a detailed breakdown of the different stages of the product lifecycle and how DPPs operate within them, signifying an avenue for further research.

Additionally, the literature reveals common challenges in implementing DPPs. Key issues include a lack of standardization [28], data sensitivity and availability concerns [29], and the need to incentivize manufacturers [24]. Addressing these challenges is crucial to improve the adoption and effective use of DPPs.

The practical aspects of DPPs are discussed by Walden et al. (2021) and Berger et al. (2023), with the former delving into DPP implementation within a circular economy, and the latter discussing steps for creating and effectively using DPPs [30,31]. These works highlight the need for more comprehensive strategies and guidelines for efficient DPP creation and utilization.

In this study, we contribute novel insights by providing an in-depth analysis of existing DPP applications, identifying critical knowledge gaps, and proposing a comprehensive framework for DPPs. Our goal is to broaden discussions on DPPs' roles in facilitating a circular economy and managing product lifecycles, thus offering fresh insights into the potential and challenges of DPPs. Table 1 synthesizes the key contributions and shortcomings of each paper in the pertinent literature:

Table 1. Key contributions and shortcomings of the pertinent literature.

Author(s)	Contributions (+)	Shortcomings (−)
Jensen et al. (2023) [23]	Comprehensive exploration of data needs for DPPs, offering a significant contribution to the understanding of DPP structures.	The discussion on data sensitivity and availability is underdeveloped.
Adisorn et al. (2021) [24]	Offers insight into potential design options for DPPs and how these may benefit various stakeholders in a product's value chain.	More research is needed to understand how to incentivize manufacturers to deliver the required information.
Plociennik et al. (2022) [27]	Proposes a DLCP that can improve the sorting process of electronic waste, contributing to the practical application of DPPs.	Lacks an in-depth discussion on the challenges faced during the DLCP implementation process.

Table 1. *Cont.*

Author(s)	Contributions (+)	Shortcomings (−)
Koppelaar et al. (2023) [26]	Presents a conceptual design of a DPP for critical raw materials' reuse and recycling.	The study's focus is narrow and does not consider other types of products and materials.
Jansen et al. (2022) [28]	Provides a structured overview of the current development of DPPs, a useful resource for researchers and practitioners.	Empirical studies on the use of DPPs in real-world contexts are needed to substantiate the arguments.
King et al. (2023) [25]	Emphasizes the significance of robust data capture and processing methods.	Lacks a focus on standardization and uniform data structure.
Jansen et al. (2023) [29]	Underscores the need for empirical research to substantiate theoretical frameworks and conjectures about DPPs.	More practical examples and case studies are needed.
Walden et al. (2021) [30]	Analyzes DPP's implementation within a circular economy.	Requires a more comprehensive discussion of potential challenges in DPP implementation.
Berger et al. (2023) [31]	Discusses the steps for creating and utilizing DPPs effectively.	Requires further research on the broader applicability of these steps across different sectors.

While our analysis predominantly centers on peer-reviewed scientific papers, the contributions of projects like CIRPASS (https://cirpassproject.eu/; accessed on 10 December 2023) are noteworthy. Though not a peer-reviewed article, CIRPASS, known for its comprehensive approach to data collection and DPP screenings, offers the advantage of a structured framework for DPP implementation, particularly in sectors like electronics, textiles, and batteries. Its structured approach provides a clear roadmap for DPP integration. Concluding with key findings and recommendations, CIRPASS offers valuable perspectives on DPPs and their industry implications. However, one limitation of CIRPASS is that it may not fully address the diverse and dynamic needs of all manufacturing sectors, especially in rapidly evolving industries. In contrast, our methodology expands upon the foundation laid by CIRPASS by incorporating a more flexible and adaptable framework. We focus on customizability and scalability, ensuring that our DPP model can be tailored to fit a wider range of manufacturing scenarios, including those with rapidly changing technology and production processes. This adaptability is a key differentiator, as it allows our methodology to stay relevant and effective in the face of industry advancements and varying sector-specific requirements. Furthermore, our methodology places a stronger emphasis on integrating advanced data analytics and real-time data processing capabilities, enhancing the DPP's efficacy in decision-making and resource optimization.

In recent years, the European Commission's Sustainable Products Initiative (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en; accessed on 10 December 2023), endorsed by the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC), has emerged as a cornerstone in achieving the EU Green Deal and the UN Sustainable Development Goals. The European Commission's Ecodesign Regulation stresses the significance of products that are long-lasting, repairable, and reusable. This expansion encompasses a majority of market products, with the DPP at its core, aiming to standardize product-related data. This shift highlights the European market's move towards a sustainable and digital approach to product management, emphasizing the need for unified standards and collaboration among European entities.

In the context of emerging EU sustainability and circular economy initiatives, particularly the Ecodesign for Sustainable Products Regulation (ESPR) (https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en; accessed on 10 December 2023) and the EU's Circular Economy Action Plan (CEAP) (https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en; accessed on 10 December 2023), our study on the DPP holds significant relevance. While our work is independent and not a direct contribution to these frameworks, the principles of ESPR and the objectives of CEAP resonate with the goals of our DPP model. The ESPR's focus on sustainable product design and the CEAP's drive towards a circular economy align closely with the DPP's aim to enhance transparency and sustainability in product lifecycle management. This alignment highlights the importance and timeliness of our research in the broader context of EU regulatory and policy developments.

Based on the literature review conducted, we have identified several research gaps in the literature concerning DPPs. Although there are some research studies and research projects, there is still confusion around the DPP topic, and the following questions have not been answered yet. What exactly is a DPP, what the key design parameters are for a DPP, and how it has been used. Also, there is no methodological approach for developing a DPP, except for the CIRPASS project, where a very basic method is presented. Furthermore, the studies on DPPs available in the literature are based on specific use cases rather than presenting a generic approach towards DPP.

3. Digital Product Passport Model

Based on the literature review conducted in Section 2, it became evident that there is no unified framework or understanding of DPP implementation. Therefore, this section presents a holistic framework and model for developing DPPs, designed for use by researchers and industries. Additionally, a DPP template is provided to assist in the development and standardization phase of DPPs.

In order to define the basic principles of a DPP, it is essential to have a clear understanding of what a DPP is and how it will be used. More specifically, a DPP is a centralized data store that has information for a specific product instance [22]. This information encompasses the entire lifecycle of a product and needs to be accessible to different actors, each requiring specific information [31]. The development of the DPP model is based on the analysis of six key areas, as identified from the literature and the authors' vision for DPP implementation. These areas include the connectivity of the DPP, how it exchanges data, the update frequency of data, the relation of the DPP in various product life cycle steps, the actors that will be using the DPP, the level of details of the DPP and the accessibility options of the information of the DPP. Additionally, the proposed model and DPP specifications were designed to be understandable and user-friendly to facilitate broader adoption within the industry and research community.

DPP definition:

DPP is a centralized data storage system aggregating key data across a product's lifecycle, designed to enhance manufacturing transparency, traceability, circularity, and sustainability, while meeting the specific information needs of various actors including manufacturers, distributors, regulators, and end-users.

As the name suggests, the DPP does not possess a physical presence; it is a digital entity meant to capture and store essential data throughout the product life cycle, tailored according to the manufacturer's requirements. The manufacturer designs the DPP with several purposes in mind, either for internal use or for usage across different nodes throughout the product life cycle and even beyond the product's end of life. When creating a product's DPP, the manufacturer's initial critical decision involves identifying the DPP's key specifications, as these parameters will also shape its type, purpose, and capabilities. The role of the DPP is informative, instructive, corrective, or predictive. This means it serves as a source of information for the product, provides instructions for specific actions on the product, or uses the information for correcting any product issues or predicting future product failures or production optimization.

Products fall into two categories: those composed of a single component and those assembled from multiple components. Figure 1 illustrates these product types and how their respective DPPs are structured. In the case of a single-component product, the process is straightforward, with the DPP referring specifically to that component. Conversely, in an assembly, each component possesses its own DPP, and all the data contained within these individual DPPs is passed on to the assembled product. Thus, these DPPs are merged into a new, comprehensive DPP that not only includes information from the component DPPs but also stores new data from the assembly process and throughout the product life cycle. Different components in an assembly may have varying levels of detail in their DPPs. This level of detail is controlled by the owner of the DPP.

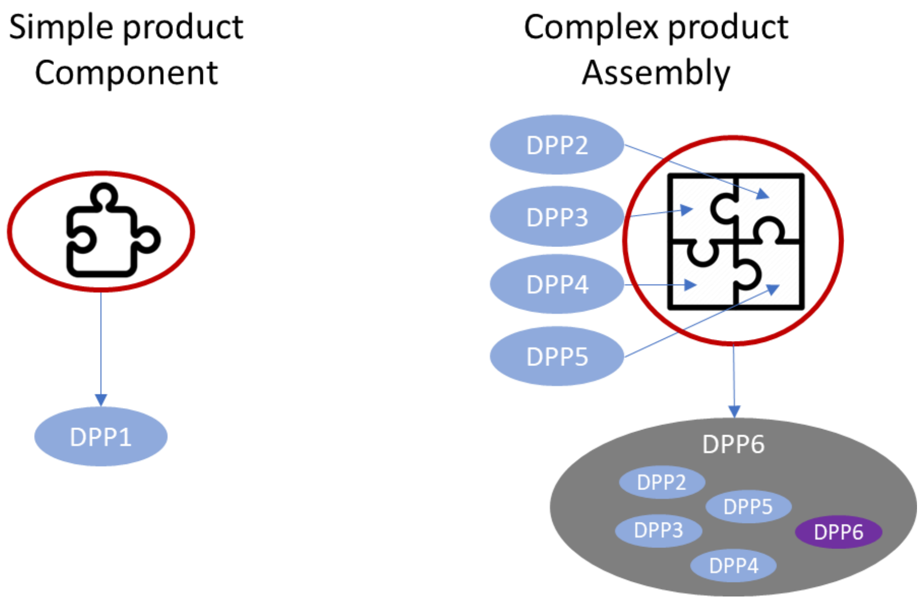

Figure 1. DPP for different types of products and DPP inheritance.

Figure 2 illustrates also the behavior of DPPs in a supply chain. More specifically, as mentioned before, DPPs are unique for each product and, if integrated into another product, their information is inherited by the DPP of the integrated product.

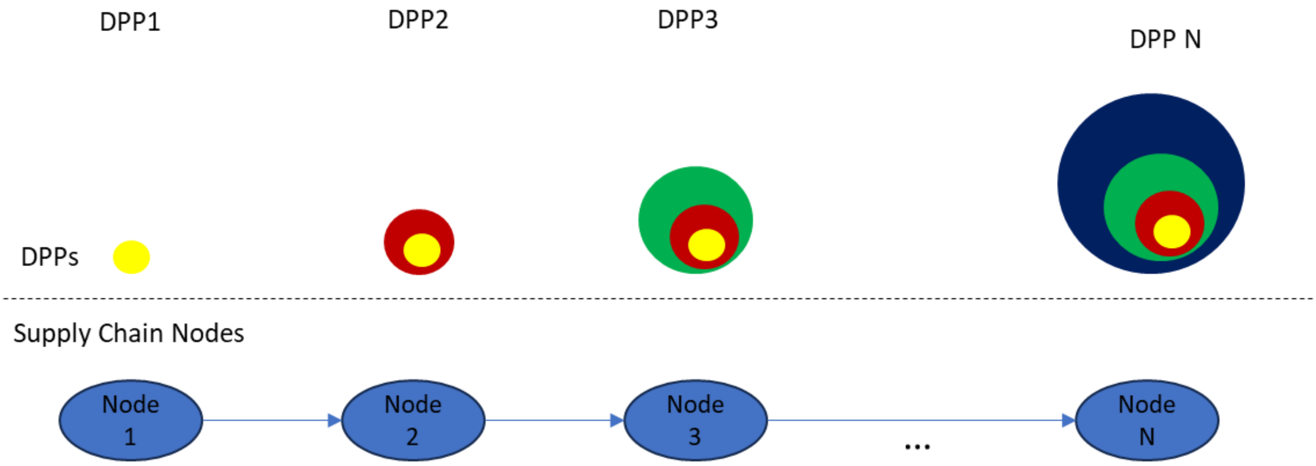

Figure 2. DPPs in supply chain.

3.1. Digital Product Passport Connectivity

Figure 3 illustrates the first key aspect of a DPP: its connectivity type. We can identify three categories of connectivity: (a) local, (b) cloud, and (c) hybrid. This aspect pertains to the method, frequency, and volume of data that are incorporated into the DPP, underlining the need for different DPP types to meet the various needs of manufacturers. Specifically, a cloud-based DPP is a dedicated cloud data space housing various data types concerning the product. The information can either be automatically or manually updated on the cloud, but the most important feature of this type of DPP is the fact that the DPP data can be accessed from anywhere. Conversely, a local DPP requires physical proximity or contact for access. Data updates to the local DPP can also be automatic or manual. In this case, data is stored in a physical drive attached to the product. For example, an elementary form of a local DPP is an RFID tag holding key information [32]. The size of the storage required for the DPP is dependent of the type of information and data the manufacturer needs to store to the DPP. Last, the hybrid connectivity type entails having a DPP instance on the cloud and another locally on the product. These instances do not store identical information. If a manufacturer opts for a hybrid DPP, it suggests that some of the DPP data should be universally accessible for use by other manufacturers or applications, while some data should be locally stored on the product's DPP instance.

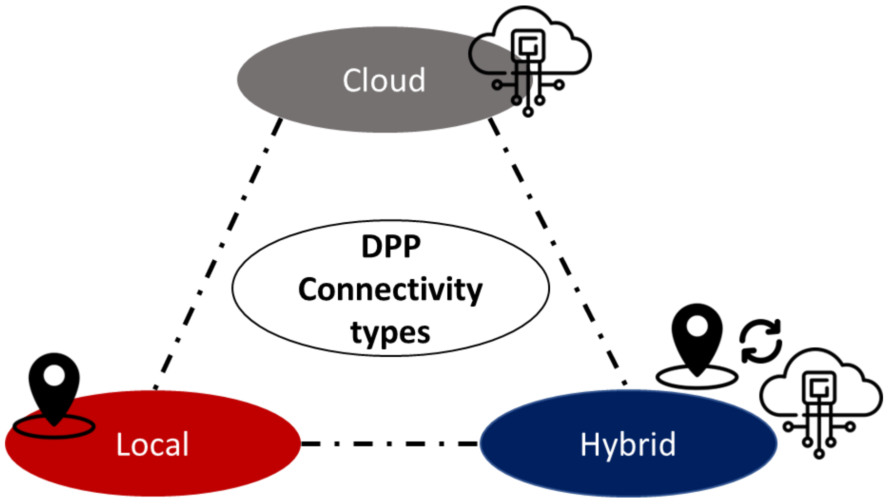

Figure 3. DPP different types of connectivity.

3.2. Digital Product Passport Data Update Frequency

Another key feature of the DPP that creators should consider is the frequency of data storage. Generally, there are three categories: (a) no data update, which implies that once the DPP is created and populated with initial data, this information neither changes nor becomes enriched over time; (b) fixed time period updates, where data is stored in the DPP at intervals defined by the manufacturer; (c) individual data updates as and when available, meaning the DPP is updated whenever there is new data.

Data can be input into the DPP manually, semi-automatically, or automatically. Manual data entry entails someone physically inputting the data into the DPP. As such, when manual data update type is selected, the volume of data in the DPP will be considerably lower compared to the other two types and typically involves only basic information. Semi-automated data update still requires human involvement, but, unlike manual update, data can be directly uploaded from other systems or data sources, subject to user approval. This method offers control over the data uploaded to the DPP without concerns about data volume. Automatic data storage implies the DPP is connected to various data sources, and the DPP updates autonomously when data becomes available.

3.3. Digital Product Passport in Relation to the Product Life Cycle

The DPP plays a crucial role in storing data from various stages of a product's life cycle. Using the product lifecycle steps as a guide [9], we have identified eight stages where DPP can be effectively deployed, as illustrated in Figure 4. The DPP's owner, typically the OEM (though not exclusively, as discussed in Section 3.4), can decide at which stages the DPP will be utilized, depending on its intended purpose. The DPP is responsible for storing data for a single instance of a product, hence the design or prototype stages included in the product life cycle are omitted [9,33]. The recommended steps cover the product from its manufacturing process until its end of life, culminating in recycling.

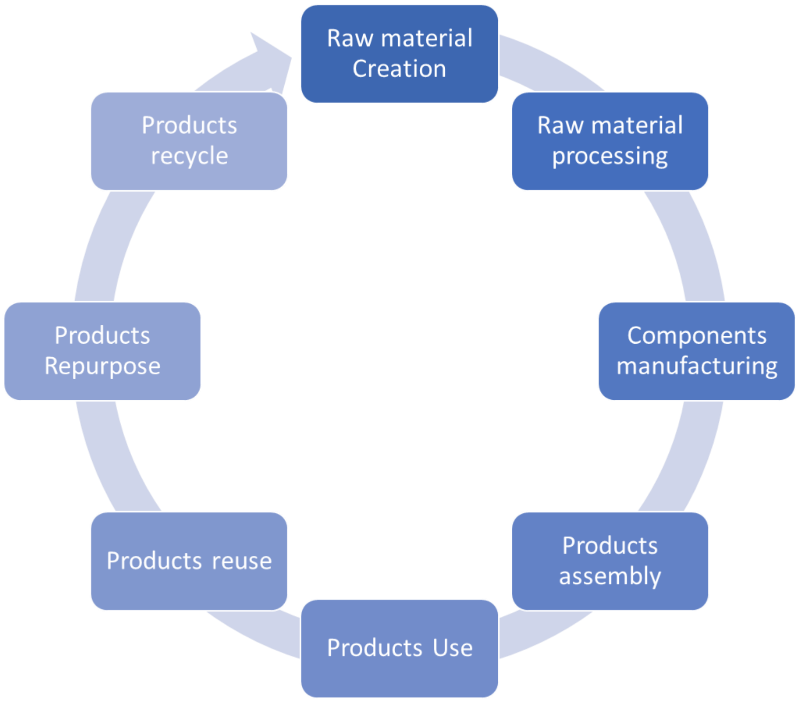

Figure 4. Product life cycle steps involved in DPP.

Another feature of the DPP is information inheritance, which determines whether some or all of the data from the DPP will be passed on to another product at the end of its life or if the information will be lost. This characteristic is bidirectional, implying that a DPP should facilitate the inheritance of information and, conversely, the receiving DPP should be capable of inheriting data from other DPPs; the notion of information sharing/inheritance is well-known in the applications of cloud manufacturing and manufacturing as a service [34,35]. The subject of information inheritance will be explored further in this paper.

3.4. Actors Involved in Digital Product Passport and Data Types

The scope of DPP is to accompany a product throughout its entire life cycle, as illustrated in Figure 3. The purpose of the DPP is to assist at each corresponding stage. This means that the information available in the DPP from earlier stages can be used in future steps to enhance the associated process or simply to inform the user about a product's crucial details. Depending on the life cycle stage, different actors interact with the DPP. In total, seven distinct actors have been identified and are listed below. These actor categories encompass all individuals or digital systems that can interact with the DPP.

The actors represent overarching entities, Implying that the actor interacting with the DPP could be either a human or a digital system corresponding to that actor. The Original Equipment Manufacturer (OEM) is both the owner and creator of the DPP. A value chain partner is defined as any node in the product's value chain that adds value through various manufacturing processes. In contrast, the distributor's role is to bring the product to market, hence the separation of these actors, which can correspond to the different access rights to the DPP.

1. OEM;
2. End user;
3. Maintenance;
4. Distributor;
5. Value chain partner;
6. Recycler;
7. DPP data analyzer.

Each actor is responsible for either retrieving or adding different types of data to the DPP. Consequently, different actors will have varying access rights to the DPP. Specifically, the DPP's creator and manager will define the access rights for each actor who will access the DPP. The access options include either "read only" or "read/write". By doing so, the DPP's owner can effectively control and manage it. The access rights should not apply to the actor level but to specific information within the DPP.

There are seven distinct generic data type categories involved in the DPP, as illustrated in Figure 5. These categories cover the entire spectrum of the product and all the steps of its life cycle. Some data may fit into more than one category, or different data may depend on data from other categories. Each DPP data category corresponds to specific stages in the product's lifecycle, though some categories may contain information from across the entire product life cycle. The DPP's owner is responsible for deciding the level of detail that enters the DPP. The various types of DPP detail levels will be discussed further in this section.

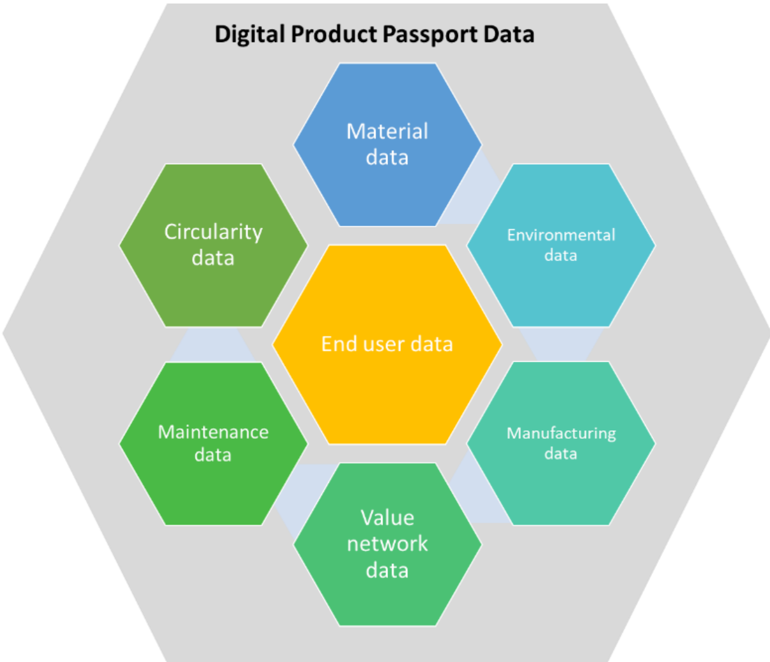

Figure 5. DPP different data type categories.

Material data: This category pertains to any information about the materials involved in the respective product that the DPP will store. More specifically, the basic information should include the types of materials used in the product (e.g., steel, aluminum, etc.) and details on the material specifications. Also, the amount of material is important to note because such information can be beneficial at a later stage of the product, such as the recycling process or otherwise. Additionally, this specific DPP data type could function as the bill of materials for the product and beyond.

Environmental data: This category of the DPP is tasked with storing any information related to the environmental aspects of the product. More specifically, it includes data about the environmental friendliness of the different materials involved in the product, or the environmental characteristics of the manufacturing processes applied to the product. This information can serve two purposes: monitoring the environmental impact of the manufacturing process, and determining the environmental implications of the product's usage once it is manufactured. In this manner, the product's entire life cycle can be monitored in terms of its environmental impact.

Manufacturing data: This category stores all manufacturing-related data. Manufacturing data encompasses all the different information generated during a product's manufacturing process. This includes data from various sensors, different machine PLC systems and operators' reports or notes, etc. This information could be highly useful for manufacturers for traceability and optimization purposes. Generally, all data generated during the manufacturing process should be categorized under this heading. As one can understand, there is some overlap between each category. For instance, the power consumption of a machine during manufacturing is both manufacturing and environmental information. Furthermore, re-manufacturing data will also be part of the manufacturing data.

Value network data: This category is tasked with storing all information generated by the various nodes in the product's value network. Some of this data might be related to the manufacturing processes for the product, so such information would be present in both categories. Furthermore, details regarding logistics and product tracking until it reaches the end user will be stored under this category.

Maintenance data: This category will house all information related to maintenance. Once the product has begun being used by its owner, any form of maintenance or intervention on the product is stored under this category.

Circularity data: This category is tasked with storing data related to the implementation of circularity, such as product re-use, re-purposing, or recycling data. More specifically, when a change occurs in the product's life cycle after its initial use, this change should be logged in order to keep track of the exact steps that were followed for each product. Such data should aid in both the better and more efficient implementation of circularity but also assist in the precise evaluation of the effectiveness of circularity. Additionally, the manufacturer should include information regarding protocols or procedures for the re-use, re-purposing, or recycling of a product here. For example, such data could be a disassembly sequence for more efficient disassembly. Also, the manufacturer should specify which components should be returned to the manufacturer after the product's end of life for re-use purposes.

End user data: In this category, all data produced by the use of the product or by the owner of the product are stored. Additionally, the manufacturer should include information regarding the product meant for the end user in this section, such as product instructions, maintenance requirements, and any other information that the manufacturer wishes to communicate to its final customers.

The previous list explains in detail the different types of data that the DPP should contain. Figure 6 shows when each set of data could be generated or is being generated. Material, environmental, and value network data will be populated with information across the entire product life cycle. Manufacturing data are generated only during the manufacturing process, as well as during the product's re-use and re-purposing. Maintenance occurs from the beginning of a product's use until the recycling stage.

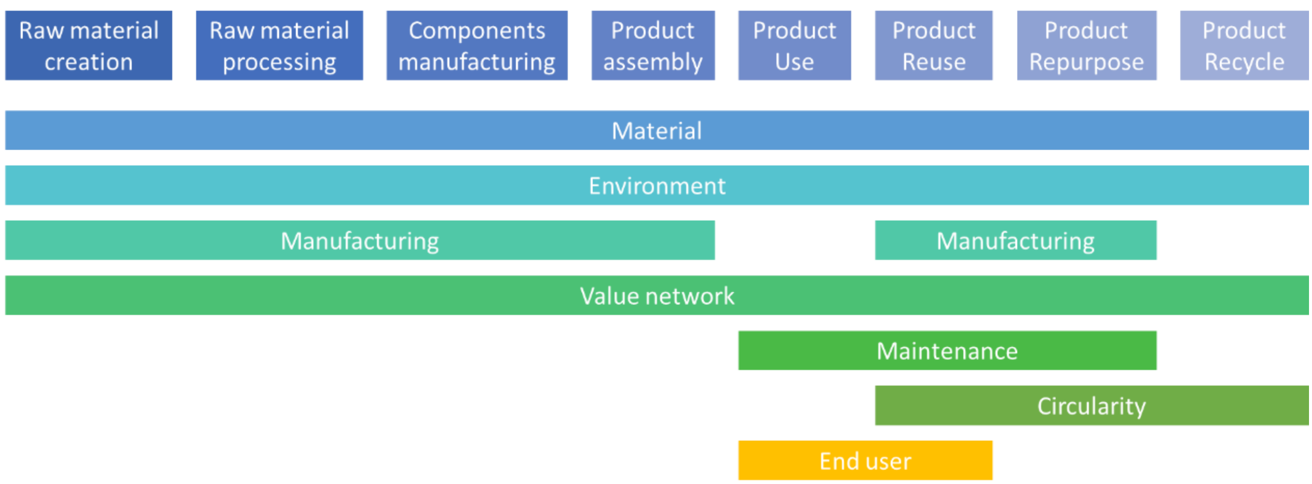

Figure 6. Timing at which the different types of data in DPPs are generated.

3.5. Digital Product Passport Level of Detail

As explained in the previous sections, there are multiple potential data sources for the DPP. The critical question DPP owners should answer is what level of detail of data should be stored in the DPP. Defining this is not a straightforward process. Again, we refer to the different product life cycle steps defined in Figure 3. All these steps can be categorized into three major groups: the manufacturing stage, the product operation stage, and the product circularity stage.

The manufacturing stage involves all the different manufacturing steps until the product reaches the end user and begins to operate. The operation stage refers to the period during which the product operates. The product circularity stage refers to all the stages after the use of the product and involves actions such as product reuse or repurposing actions in order to fully exploit the remaining useful life of the products or some of their components. This step also includes the recycling process.

This classification into different stages of the product life cycle is used to determine the DPP's level of detail. These categories are independent and can have varying levels of detail, depending on the DPP owner's requirements. We have defined the specific levels of detail for each category to aid DPP owners in understanding the potential of using the available information, as detailed in Table 2 for the manufacturing stage, Table 3 for the product operation stage, and Table 4 for the product circularity stage. All categories include a Level 0, indicating that no information is being collected for the selected topic, thus rendering the application of DPP impractical. In such cases, additional investment in data collection infrastructure is required before DPP deployment. The defined levels serve a dual purpose: they help existing data collection infrastructures identify deployable DPP levels, and for those without such infrastructures, they act as a guide for selecting the appropriate equipment to collect the necessary data.

Table 2. Manufacturing information levels of detail.

Levels	Name	Description
Level M0	No DPP	No information for the manufacturing of the product is saved.
Level M1	Generic batch information	Level M1 implies that only generic information for a specific batch of products is saved. This includes basic information such as the batch number, date, time started and finished, number of products, and batch destination. The machines used in the process should also be listed.
Level M2	Specific batch information	Level M2 contains all the information from M1, along with more specific data regarding the manufacturing of this specific batch. This may include data about the processing of the different products in the batch, quality inspection reports, and a generic list of the materials used in the product. Interactive data, such as the next manufacturing station or other information that operators or automated systems will update, and a detailed tracking of the personnel who handled the batch and manufacturing steps are also included.
Level M3	Generic individualized product information	The M3 level includes information similar to M1, but for each single product rather than a batch. Additionally, it includes the product bill of processes and bill of materials.
Level M4	Specific individualized product information	The M4 level includes information similar to M2, but for each single product rather than a batch, and M3. This level provides the most comprehensive information possible for the manufacturing process of a product. For example, it may also include time series directly from the sensors or PLC of machines related to the specific product instance.

Table 3. Product operation phase levels of detail.

Levels	Name	Description
Level P0	No DPP	No information for the product operation phase is saved.
Level P1	Basic information for the product family	In Level P1, basic information about the product family, such as an owner's manual and generic maintenance plan, is included. In this level, no update of the information of the DPP will be made during the life of the product.
Level P2	Basic information for the specific product	Level P2 includes all the information from P1, along with more specific data about the individual product. These data include the manufacturing date, seller details, purchase date, warranty information, and owner details. In this level, no updates to the DPP will be made after the sale of the product.
Level P3	Detailed information on the specific product	Level P3 includes all the information from P2, plus additional data added during the product's operation, such as maintenance records or other information defined by the product OEM. These data are meant to be manually entered when there is a change to the product.
Level P4	Interactive information on the specific product	Level P4 includes all the information from P3. In addition, the product can interactively store operational data in the DPP and, vice versa, retrieve historical data from the DPP.

Table 4. Product circularity phase levels of detail.

Levels	Name	Description
Level C0	No DPP	No information for the product circularity phase is saved.
Level C1	Basic recycling information	This level includes different materials involved in the product to facilitate recycling. In this level, no updates to the DPP will be made; the DPP information is fixed.
Level C2	Basic product reuse information	Level C2 includes all the information from C1, plus instructions on how to reuse the product, including generic checklists with common problems and practices for reusing the specific product. No updates to the DPP will be made in this level; the DPP information is fixed.
Level C3	Detailed product reuse information	Level C3 includes all the information from C2. In addition, it provides disassembly sequences and procedures for the proper repair or upgrade of the product. It also specifies where the product should go to be remanufactured for reuse. Any change performed on the product in the reuse process is documented in the DPP.
Level C4	Detailed product repurpose information	Level C4 includes all the information from C3. In addition to all this information, if the product is repurposed, detailed instructions on what should happen to each of the product's components according to their individual DPPs are included. Any change made to the product in the repurposing process is documented in the DPP.
Level C5	Interactive product circularity	Level C5 includes all the information from C4. In this level, data from the product is sent to the DPP interactively. The product owner is informed about the product status and suggested solutions, maintenance for reuse, or any other information the OEM wants to communicate to the product owner related to circularity.

The previously mentioned tables detail the different levels of specificity for each of the three defined categories: manufacturing, product use, and circularity information. When an OEM designs a DPP, it must pay close attention to the dependencies that exist among these levels. This means that a selection from one category will influence the available compatible options in the other two categories. More specifically, Table 5 outlines the dependencies among the different levels. The table utilizes three symbols: "o", "-", and "X". The symbol "o" signifies that the selected level (row, first column) incorporates the information from the level in the first row and corresponding column. The symbol "-" signifies that the selected level does not support the corresponding level, and finally, the "X" symbol indicates compatibility. Furthermore, Table 6 showcases the different aspects defined in the previous sections, such as DPP connectivity, data update frequency, and involved actors, in relation to the different levels of detail for each of the three categories. In Table 6, the minimum requirements are outlined. Specifically, for connectivity, the hybrid approach is considered the most advanced, as it merges both concepts. While the hybrid approach can be implemented in all cases, it may not be cost-effective if it is not necessary.

Table 5. Implementation dependencies for different levels.

	M1	M2	M3	M4	P1	P2	P3	P4	C1	C2	C3	C4	C5
M1													
M2	o												
M3	o	o											
M4	o	o	o										
P1	X	X	-	-									
P2	-	-	X	X	o								
P3	-	-	X	X	o	o							
P4	-	-	X	X	o	o	o						
C1	-	X	X	X	X	X	X	X					
C2	-	X	X	X	-	X	X	X	o				
C3	-	-	X	X	-	X	X	X	o	o			
C4	-	-	X	X	-	X	X	X	o	o	o		
C5	-	-	-	X	-	-	X	X	o	o	o	o	

Table 6. Detail levels vs. connectivity, DPP data update frequency, and involved actors.

	Minimum DPP Connectivity Capabilities	DPP Data Update Frequency	Involved Actors
M1	Local	Once	OEM
M2	Local	During manufacturing process	OEM
M3	Cloud	During manufacturing process	OEM, value chain actor
M4	Cloud	During manufacturing process	OEM, value chain actor
P1	Local	Once	OEM, end user
P2	Local	Once	OEM, end user, distributor
P3	Local	Every time changes happen to the product	OEM, end user, distributor, maintenance
P4	Cloud	Continuously	OEM, end user, distributor, maintenance, recycler
C1	Local	None	OEM, recycler
C2	Local	None	OEM, recycler
C3	Local	Every time changes happen to the product	OEM, recycler, maintenance
C4	Local	Every time changes happen to the product	OEM, recycler, maintenance, distributor
C5	Cloud	Continuously	OEM, recycler, maintenance, distributor

3.6. Digital Product Passport Access

All information saved by the different actors to the DPP is intended to serve as an assistive tool when an actor requires some data for the product and for improving the traceability of changes to the product. As has been made clear by now, there are many different variations of a DPP according to the needs of the OEM who owns the DPP. Once the OEM has defined all the above information, the selection of the DPP access method should be the next step. Since the DPP, as the name suggests, is "digital", it contains digital information, which implies that it must be accessible by digital means. More specifically, there are six different ways to access the DPP:

1. Local access to the DPP using some of the product's systems.
2. Local access to the DPP using a wireless or wired connection to a laptop, smart phone, or tablet.
3. The product has a QR code or similar, and, by using the DPP application (laptop, smart phone, or tablet), the QR code is scanned, and basic information about the product appears.
4. The product has a QR code or similar, and the user is redirected to the product's DPP online.
5. The OEM has developed a DPP platform for the product, and the corresponding actor enters some credentials (e.g., serial number, etc.) and they access the DPP online.
6. If the product is using an RFID, the user scans the RFID and reads the information saved in the DPP.

3.7. Digital Product Passport Template

The design of a DPP should be executed in a standardized manner to ensure repeatability and consistency across different products. This consistency will be significantly beneficial in cases where assembly occurs and multiple DPPs must be combined into one. Therefore, in this section, a DPP design template is proposed to be used during the design and documentation of a DPP. The proposed template aims to appropriately document the various pieces of information that will be stored in the DPP. Two different templates have been developed: one that will contain all the generic information of the DPP (Table 7), and another (Table 8) for defining and documenting the details of each variable specified in the generic DPP template. Table 7 is organized into three sections. The first section covers fundamental DPP information related to the product, including who will have access to the DPP and to which specific information. It also indicates whether the DPP inherits information from other DPPs. The second section defines the variables to be used and stored in the DPP, detailing their shareability and the potential recipients. The final section addresses variables inherited from other DPPs at previous stages in the product lifecycle.

Table 7. DPP generic design template.

DPP Overall Design Template	
1	**DPP fundamental information**
DPP name:	[Enter DPP name]
DPP code:	[Enter DPP code]
Product Name:	[Enter Product Name]
Product Code:	[Enter Product Code]
Product type:	[Single component/Assembly]
Overall connectivity:	[Define the overall connectivity of the DPP. The specific connectivity of each variable will be defined at a later stage]
DPP static or dynamic	Static: The DPP is read-only and it is present only for informative reasons. Dynamic: The DPP information is updated at given periods.
Involved actors for saving information to the DPP	[Define all the actors that will save information to the DPP]
Involved actors for reading information from the DPP	[Define all the actors that will read information from the DPP]
Inherits information from other DPP	[Yes/No]

Table 7. *Cont.*

DPP Overall Design Template		
2	**Overall DPP variable information**	
Total number of DPP variables:	[Define the total number of variables that will be stored in the DPP]	
Detailed list with the different variables of the DPP	[Create a detailed list with the variables in the DPP. These variables should exclude the variables that will be inherited from other DPPs]: • Variable 1 (short description of variable 1) (sharable or not) • Variable 2 (short description of variable 2 (sharable or not) • …	
3	**DPP information inheritance from other DPPs**	
Detailed list with the DPPs that will be inherited by the current DPP	DPP1	• Variable 1 (short description of variable 1) • Variable 2 (short description of variable2) • …
	DPP2	• Variable 1 (short description of variable 1) • Variable 2 (short description of variable2) • …
	…	…

Table 8. Details of a variable.

DPP Specific Variable Template	
Variable Name	[Enter Variable Name]
Variable code	[Enter Variable code]
Inherited?	[Yes/No]
If inherited, from which DPP?	[Provide Name and details of the DPP]
Variable type	[Read, Write, or Read/Write]
Which actors can read?	[Define actors according to the list in Section 3.4]
Which actors can write?	[Define actors according to the list in Section 3.4]
Life cycle steps to write	[Define in which life cycle steps an actor can write to the variable]
Lifecycle steps to read	[Define in which life cycle steps an actor can read the variable]
Frequency to read	[Define the frequency for each of the actors, if not the same]
Frequency to write	[Define the frequency for each of the actors, if not the same]
Connectivity type	[Local, Cloud, or Hybrid]
Type of data to store	[End user data, Maintenance data, Manufacturing data, (refer to Figure 4)]
Type of variable	[Single variable, a set of variables for a specific cause, etc.]
Estimated size of saved information	[The size in terms of MB]
Owner of the data	[Define who the owner of the specific data that will be saved in this variable is]

3.8. Blockchain Technology and Data Carrier in DPP

In the DPP model, blockchain technology plays a pivotal role in ensuring the security, integrity, and transparency of product data. Blockchain's decentralized and immutable ledger system allows for the secure and verifiable tracking of product information across the supply chain, enhancing trust among stakeholders. This technology is particularly crucial in scenarios where data authenticity and protection against tampering are paramount.

Furthermore, data carriers, such as QR codes or RFID tags, are essential components of the DPP system. They facilitate the easy storage and retrieval of product data. By encoding product information, data carriers enable quick access to the DPP, thus streamlining the product identification and information retrieval processes across different stages of the product lifecycle.

4. Results and Discussion

The primary aim of this paper is to establish foundational guidelines for explaining and standardizing the DPP concept. At present, the DPP domain is relatively immature, lacking a clear, unified direction. Our proposed model is intended to shed light on this field and bring a sense of unity among researchers and industry professionals working with DPP.

4.1. Implications of the DPP Model

The proposed DPP model stands to profoundly impact the industrial manufacturing ecosystem by offering a digitized, centralized, and standardized product information management system. This new model aims to transform the way manufacturers, consumers, and stakeholders interact with the product and its associated data throughout its lifecycle.

With the DPP model, we can expect a remarkable improvement in manufacturing efficiency. The model allows for an enhanced decision-making process based on the accurate and detailed data it provides. As such, manufacturers could drastically reduce waste and improve product quality. In the automobile industry, for instance, DPPs could provide real-time information on each vehicle component, enabling manufacturers to anticipate potential issues, streamline production lines, and enhance overall output.

Except the implication of the DPP in the manufacturing stage of a product, it has many other implications in the steps after the manufacturing. The distribution actors have will be able to monitor and manage in a better and more efficient way their products and also will allow them to implement more sophisticated optimization strategies. At the same time, the end-users of the products will be able to have a better overview of the product and, using the potential services from the manufacturers, be able to take full advantage of their product and avoid unnecessary costs and contribute to the minimization of the environmental impact.

4.2. Enhanced Product Lifecycle Management

The lifecycle of a product, from inception to disposal, could be significantly improved through the application of DPPs. Service personnel would have immediate access to essential information about the product, allowing for more effective maintenance and repair strategies [36]. This could result in extended product longevity, reducing the frequency of new product purchases, and, thereby, contribute to a more sustainable economy [9].

The DPP model also shines in the context of recycling. Effective recycling or repurposing strategies are possible by leveraging the information stored within the DPP. This fosters a circular economy, especially pertinent given the increasing complexity of materials in modern manufacturing.

4.3. Potential Challenges and Mitigation Strategies

Despite the evident benefits, implementing a DPP system is not without hurdles. Data privacy and security pose a significant challenge [37]. With sensitive consumer and product information at stake, robust cybersecurity measures must be in place to prevent unauthorized access or misuse. This can be tackled through encryption, strict access control mechanisms, and regular security audits [38].

Integrating the DPP system into existing processes is another considerable challenge. It demands substantial coordination among all stakeholders. Resistance could stem from those viewing the DPP as an unwelcome complexity or a cost burden [26]. Here, the key lies in transparently communicating the DPP system's benefits, such as improved efficiency, cost reduction, product longevity, and its role in fostering sustainability.

For the DPP concept to function effectively and for companies to fully leverage its advanced capabilities, it is essential that all nodes in a value chain utilize the DPP concept. Without widespread adoption, the benefits of implementing DPP on a global scale are diminished. From a business perspective, DPP is not a short-term solution but is designed to yield benefits in the mid to long term.

4.4. Guidelines for Implementing DPP

For manufacturers aiming to transition into this new era of data-centric operations by implementing DPP, the following detailed guidelines should be thoroughly considered:

1. **Standardization:** Begin by ensuring the DPP model follows current industry standards for data management, security, and privacy. This is a prerequisite to ensure interoperability between different systems and stakeholders, while concurrently safeguarding sensitive data against potential threats. Additionally, conforming to standardized practices can assist in attaining certifications or qualifications that may be required in certain industries or regions, further enhancing the product's marketability.
2. **Integration:** DPP implementation should be planned and executed as a seamless extension of the existing manufacturing and operational processes. To accomplish this, one needs to map out the current processes, identify the points where DPP interactions would occur, and design systems to minimize disruption and maximize value addition. Remember, the DPP is not meant to replace existing processes but to augment them by providing rich, comprehensive, and accessible data.
3. **Training:** Ensuring that employees across the organization, from shop-floor workers to top-level management, understand the DPP system and its benefits is crucial. Training programs must be comprehensive and ongoing, providing instruction on how to access, input, interpret, and secure data. By fostering a deep understanding and comfort with the system, employees will be able to harness the DPP's full potential.
4. **Stakeholder Communication:** Effective and transparent communication with all stakeholders, including suppliers, distributors, and customers, is paramount. This entails highlighting the benefits that the DPP system offers, such as improved product traceability, quality assurance, and the potential for cost reduction. Open dialogues can mitigate resistance and encourage adoption, fostering a shared vision for a more efficient, sustainable manufacturing landscape.
5. **Gradual Implementation:** Implementing a DPP system is a complex process that involves significant changes to existing operations. To manage this transition effectively, it could be beneficial to phase in the DPP, starting with a pilot project on a single product line or component. This allows for real-time adjustments and the fine-tuning of the system before full-scale implementation, minimizing potential disruptions to the operation.
6. **Continuous Evaluation:** After implementation, it is critical to continuously evaluate and improve the system based on performance metrics and stakeholder feedback. Leveraging the metrics proposed in this paper can provide insights into the DPP's effectiveness and guide its optimization.

Implementing these guidelines will facilitate a smoother transition to a DPP system, equipping manufacturers to leverage the potential of data in fostering efficiency, sustainability, and value creation in their operations.

In addition to the guidelines outlined, the following strategies are proposed to further enhance the adoption and effective use of DPP among stakeholders:

Partnership Development: Forge partnerships with industry leaders and influencers to showcase successful DPP integrations, creating case studies that highlight tangible benefits.

Demonstration Projects: Implement DPPs in pilot projects or flagship products, allowing stakeholders to witness firsthand the advantages and operational improvements.

Regulatory Alignment: Engage with policymakers to align DPP implementation with emerging regulations and standards, ensuring compliance provides a direct incentive for adoption.

Technology Integration Support: Provide technical assistance and toolkits to integrate DPPs with existing enterprise systems, lowering the barrier to adoption due to technological challenges.

Feedback Mechanisms: Establish channels for regular feedback from stakeholders, using their insights to continuously refine the DPP system.

By implementing these additional promotional tools alongside the guidelines previously mentioned, manufacturers can create a robust ecosystem that not only supports the technical implementation of DPPs but also fosters a culture of adoption and sustained use throughout the product lifecycle.

4.5. Application Framework

The application of a DPP system could be systematically executed following the expanded framework below:

1. **Requirement Analysis:** The first step involves a comprehensive understanding and documentation of product information requirements. This includes identifying the necessary product data, desired functionalities of the DPP system, and all potential stakeholders. Additionally, it is essential to assess the current operational workflow, IT infrastructure, and compatibility requirements to ensure the seamless integration of the DPP system later on.
2. **System Design:** Once the requirements are clear, designing the DPP system can commence. This involves creating an architecture that meets the requirements identified in the analysis phase while aligning with industry standards. The design should prioritize usability and security, facilitating efficient and safe data handling. A user-friendly interface can encourage stakeholder acceptance and expedite the learning curve.
3. **Integration:** The implementation of the DPP system into the existing manufacturing process is a critical phase. Given the magnitude of the change, it is recommended to adopt a gradual approach. Start by integrating the DPP system in less critical operations or smaller product lines. This approach allows for real-time feedback and adjustments without major disruptions to existing operations.
4. **Testing:** Once integrated, extensive testing should be conducted to validate the system's functionality. This step involves stress testing, regression testing, and user acceptance testing to identify and fix bugs, validate data integrity, and ensure that the system aligns with user expectations and requirements.
5. **Training and Rollout:** After thorough testing, training programs should be established for all relevant employees and stakeholders. A clear understanding of the system's functionality and benefits can mitigate resistance and promote usage. The system can then be officially launched, starting with smaller scales or pilot areas before a full-scale rollout, thus ensuring that the system functions effectively under operational conditions.
6. **Monitoring and Evaluation:** Post-launch, the DPP system should be continuously monitored and evaluated against set performance metrics and user feedback. This iterative process will guide necessary tweaks and enhancements to optimize the system over time.
7. **Continuous Improvement:** The application framework does not end at launch. Given the dynamic nature of data and technologies, it is crucial to maintain an attitude of continuous improvement. Regular system reviews should be conducted, technological advancements should be continually integrated, and user training should be refreshed periodically to ensure the DPP system remains relevant and beneficial.

Following this application framework provides a systematic roadmap for manufacturers to implement a DPP system effectively, ensuring they are well-prepared to navigate the challenges and harness the immense potential that DPP offers.

4.6. Real-World Applications

To further illustrate the applicability and benefits of the DPP model, let us delve into the electronics manufacturing industry, particularly, the smartphone segment. A smartphone is a perfect exemplar of a complex product with numerous components sourced from various suppliers across the globe.

4.6.1. Supply Chain Transparency

Implementing a DPP system in this context could provide unprecedented transparency into the supply chain. With each component assigned a digital passport detailing its origins, manufacturers, consumers, and regulators would have access to a product's complete backstory. Such visibility can allow manufacturers to better manage their supply chain, reducing the risk of delays and promoting ethical sourcing by avoiding suppliers associated with unsustainable practices or unfair labor conditions [39].

4.6.2. Process Optimization and Quality Assurance

The detailed product information derived from DPP could aid manufacturers in optimizing processes. For instance, if a component regularly fails quality checks, the DPP could help trace the issue back to a specific batch or supplier, allowing the manufacturer to address the issue directly and efficiently. Such preventive and corrective actions could lead to improved product quality, decreased waste, and enhanced customer satisfaction. The adoption of DPP will significantly positively affect the performance of Zero Defect Manufacturing (ZDM) implementation, as more information will be available, which is the key for the implementation of approaches like ZDM to be implemented [39]. Furthermore, the data in the DPP could also significantly help with the maintenance of all the different artificial intelligence, machine learning, and digital twin models in order to adapt to the changes over time.

4.6.3. Improved After-Sales Services

For after-sales service providers, DPPs can serve as comprehensive product histories, outlining the precise specifications, the history of repairs or modifications, and even the conditions under which the product was used [40]. This can expedite the troubleshooting process, making repairs more efficient, and extending the product's lifespan.

4.6.4. Streamlined Recycling Processes

Furthermore, the DPP model could dramatically simplify the recycling process by providing accurate and detailed material composition information [41]. For example, smartphones contain precious metals like gold and rare earth elements that could be recovered and reused. Currently, identifying and extracting these materials can be a complex and costly process. With DPP, recyclers could access a precise blueprint of the materials in a given product, enabling more effective and profitable recycling.

4.6.5. Consumer Engagement

For consumers, the DPP can offer insights into a product's entire lifecycle—from the sourcing of its components and the conditions of its assembly to the product maintenance and condition of use. This level of transparency could empower consumers to make more informed, sustainable purchasing decisions, favoring products with responsible supply chains, and high recycling potential. By extrapolating from this smartphone example, the benefits of DPP implementation could extend across industries, contributing to more efficient and sustainable manufacturing landscapes [42]. In conclusion, while the DPP model poses some challenges, the benefits, which range from enhanced manufacturing efficiency to improved lifecycle management and a strengthened circular economy, present a strong case for adoption. With detailed planning, strict security measures, and open communication among all stakeholders, the DPP system could be a game-changer for product lifecycle management.

4.7. Practical Challenges and Barriers in DPP Adoption

While the DPP offers transformative potential for the manufacturing industry, its implementation is not without challenges. Key barriers include the following:

- **Integration Complexity:** Incorporating DPPs into existing manufacturing systems can be technically complex and costly, particularly for smaller enterprises. Developing user-friendly, scalable DPP platforms could mitigate this challenge.
- **Stakeholder Resistance:** Resistance from various stakeholders, including manufacturers and suppliers, may arise due to perceived complexity or cost implications. Targeted educational campaigns and demonstrable benefits can be instrumental in overcoming this resistance.
- **Data Privacy and Security:** Handling sensitive data in DPPs raises concerns about privacy and cybersecurity. Implementing robust encryption and strict access controls is crucial for maintaining data integrity and trust.
- **Standardization and Interoperability:** The lack of standardized DPP formats may hinder interoperability between systems. Collaborative efforts towards standardization are essential for seamless integration across different platforms and industries.
- **Cost Implications:** The initial setup and maintenance costs of DPP systems could be a significant barrier, especially for smaller manufacturers. Financial incentives or support from regulatory bodies may encourage wider adoption.

To overcome these barriers, a multi-faceted approach involving technological innovation, stakeholder engagement, policy support, and education is necessary. By addressing these challenges proactively, the manufacturing industry can fully leverage DPPs to achieve enhanced transparency, efficiency, and sustainability.

4.8. DPP's Relevance to Modern Manufacturing

The DPP model is particularly relevant in the context of modern manufacturing, which is increasingly characterized by digitalization, sustainability, and interconnected supply chains. The DPP framework aligns with these contemporary trends by providing a digital means to track and manage product lifecycle data efficiently. This capability is crucial for modern manufacturing processes that require high levels of transparency, compliance with sustainability standards, and efficient resource utilization. By integrating DPPs, manufacturers can not only enhance operational efficiency but also contribute to more sustainable and circular manufacturing practices.

4.9. Proposed Methodology for Industry-Specific DPP Development

Recognizing the critical role of DPPs in various sectors, we propose a generalized methodology to guide the development of industry-specific DPPs. This approach encompasses the following steps:

Industry Analysis: Conduct a thorough analysis of the target industry to understand the unique operational processes, supply chain dynamics, and regulatory requirements.

Stakeholder Identification: Identify all relevant stakeholders within the industry, including suppliers, manufacturers, regulators, and end-users, to understand their data needs and interactions.

Data Requirements Mapping: Map out the specific data requirements for each stakeholder, ensuring the DPP captures all the necessary information for a product's lifecycle within the industry.

Technology Assessment: Evaluate the current technology landscape of the industry to determine the best data carriers and platforms for DPP integration.

Regulatory Compliance: Ensure that the DPP framework aligns with industry-specific regulations and standards, facilitating compliance and adoption.

Pilot Testing: Develop and test a pilot DPP with a select group of industry participants to gather feedback and refine the DPP model.

Implementation Guidelines: Create detailed guidelines for full-scale DPP implementation, including integration strategies, training programs, and evaluation metrics.

This proposed methodology provides a blueprint for future research and practical applications, allowing for the adaptation of the DPP framework to meet the nuanced needs of different industries.

5. Conclusions

This research has offered valuable insights into the development and implementation of a DPP system, proposing a unique model tailored for the manufacturing industry. More specifically, all the aspects of a DPP have been analyzed and explained alongside a standardized DPP template for creating DPPs in a structured way. The study, rooted in a comprehensive literature review, has sought to bridge the gap in our understanding of DPP and its potential in revolutionizing manufacturing supply chains. The DPP model was designed to provide in-depth product lifecycle information, offering unparalleled supply chain transparency that can significantly enhance decision-making and resource management.

In total, six key aspects of a DPP have been identified and explained in detail: the DPP connectivity types, the DPP update frequency, the use of the DPP in different product lifecycle steps, the different actors involved in the DPP and how each interacts with the DPP, the level of details of a DPP, and the access rights of the DPP.

Our key metrics, formulated to evaluate the DPP model's effectiveness, address crucial aspects such as data accuracy, ease of integration, stakeholder acceptance, cost-effectiveness, and the potential for process improvements. A qualitative evaluation through the application of hypothetical manufacturing scenarios has shed light on the strengths of our model, as well as areas where adaptations might be needed to ensure its seamless integration into existing systems.

Addressing the concerns about the validation of our DPP model, it is paramount to emphasize the depth and comprehensiveness of our literature review. While our qualitative approach provided insights into potential applications and challenges, we acknowledge the absence of empirical validation through hands-on case studies or experiments. This research serves as a foundational study, setting the stage for future empirical investigations in real-world manufacturing settings.

The anticipated benefits of the DPP model include greater visibility into supply chains, increased efficiency, improved recycling processes, a potential reduction in costs, and significant improved information traceability. The last one is the key towards circular economy and sustainable manufacturing. Manufacturers that adopt the DPP concept will have a significant competitive advantage on the market, because they will be able to offer better and more sustainable products and services for their customers.

In light of our findings, several implications arise. Practically, the DPP system offers manufacturers a robust mechanism to navigate the intricate web of supply chains, thereby enhancing decision-making and resource allocation. Theoretically, our research bridges existing knowledge gaps, presenting a coherent structure that future studies can pivot around. On a policy front, the DPP model underscores a global commitment to sustainable and transparent manufacturing practices. As nations worldwide grapple with the challenges of sustainability, such systems offer a roadmap for industries to align with global objectives. Embracing the DPP model not only positions manufacturers at the forefront of innovation but also reinforces their commitment to global sustainability goals.

However, challenges such as the need for standardization, secure data handling, and stakeholder resistance were identified. We provided guidelines to manufacturers interested in implementing DPP and suggested a simple framework for its integration.

Notwithstanding the expected resistance from different stakeholders, our research indicates that the potential benefits of implementing a DPP system far outweigh the initial apprehensions. With appropriate strategic planning, stakeholder communication, and the provision of adequate training, these challenges can be effectively managed.

Our research contributes a significant step forward in our understanding of DPP. However, further research is needed to refine the model, develop detailed industry-specific DPP systems, and explore their potential application in various other sectors. As digital transformation continues to reshape the manufacturing industry, DPP systems hold promise to be a vital component in the journey towards achieving greater transparency, efficiency, and sustainability. Additionally, future research will aim to quantify the actual benefits of the DPP in real industrial scenarios. Measuring the DPP performance presents challenges due to its dependency on various factors and the time required to observe tangible results post-implementation. For that reason, the current paper focused on defining and standardizing the DPP concept, aiming to increase adoption rates and create favorable conditions for its practical application in products and value chains.

In conclusion, while the DPP presents a promising pathway towards sustainable and efficient manufacturing practices, its successful implementation hinges on overcoming significant practical challenges. Key among these are the complexities of integration, stakeholder resistance, data security concerns, the need for standardization, and cost implications. Addressing these barriers requires a collaborative effort involving technological advancements, policy support, stakeholder engagement, and education. By proactively tackling these challenges, the industry can unlock the full potential of DPPs, leading to a more transparent, sustainable, and economically viable manufacturing future.

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References

1. Neves, S.A.; Marques, A.C. Drivers and Barriers in the Transition from a Linear Economy to a Circular Economy. *J. Clean. Prod.* **2022**, *341*, 130865. [CrossRef]
2. Morseletto, P. Targets for a Circular Economy. *Resour. Conserv. Recycl.* **2020**, *153*, 104553. [CrossRef]
3. Liu, L.; Ramakrishna, S. (Eds.) *An Introduction to Circular Economy*; Springer: Singapore, 2021; ISBN 9789811585098.
4. Cappelletti, F.; Rossi, M.; Germani, M. How De-Manufacturing Supports Circular Economy Linking Design and EoL—A Literature Review. *J. Manuf. Syst.* **2022**, *63*, 118–133. [CrossRef]
5. Kanellou, E.; Alexakis, K.; Kapsalis, P.; Kokkinakos, P.; Askounis, D. The DigiPrime KPIs' Framework for a Circular Economy Transition in the Automotive Industry. *Procedia Manuf.* **2021**, *54*, 302–307. [CrossRef]
6. Barford, A.; Ahmad, S.R. A Call for a Socially Restorative Circular Economy: Waste Pickers in the Recycled Plastics Supply Chain. *Circ. Econ. Sust.* **2021**, *1*, 761–782. [CrossRef] [PubMed]
7. Valverde, J.-M.; Avilés-Palacios, C. Circular Economy as a Catalyst for Progress towards the Sustainable Development Goals: A Positive Relationship between Two Self-Sufficient Variables. *Sustainability* **2021**, *13*, 12652. [CrossRef]
8. Kelly, M.; Howard, T. *The Making of a Democratic Economy: Building Prosperity for the Many, Not Just the Few*; Berrett-Koehler Publishers: Oakland, CA, USA, 2019; ISBN 978-1-5230-9993-1.
9. Psarommatis, F.; May, G. Achieving Global Sustainability Through Sustainable Product Life Cycle. *IFIP Adv. Inf. Commun. Technol.* **2022**, *663 IFIP*, 391–398. [CrossRef]
10. Al-Alawi, M.K.; Cugley, J.; Hassanin, H. Techno-Economic Feasibility of Retired Electric-Vehicle Batteries Repurpose/Reuse in Second-Life Applications: A Systematic Review. *Energy Clim. Change* **2022**, *3*, 100086. [CrossRef]
11. Porzio, J.; Scown, C.D. Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Adv. Energy Mater.* **2021**, *11*, 2100771. [CrossRef]
12. Charles, R.G.; Douglas, P.; Dowling, M.; Liversage, G.; Davies, M.L. Towards Increased Recovery of Critical Raw Materials from WEEE– Evaluation of CRMs at a Component Level and Pre-Processing Methods for Interface Optimisation with Recovery Processes. *Resour. Conserv. Recycl.* **2020**, *161*, 104923. [CrossRef]
13. Chatziparaskeva, G.; Papamichael, I.; Voukkali, I.; Loizia, P.; Sourkouni, G.; Argirusis, C.; Zorpas, A.A. End-of-Life of Composite Materials in the Framework of the Circular Economy. *Microplastics* **2022**, *1*, 377–392. [CrossRef]

14. Bongers, A.; Casas, P. The Circular Economy and the Optimal Recycling Rate: A Macroeconomic Approach. *Ecol. Econ.* **2022**, *199*, 107504. [CrossRef]
15. Rajaeifar, M.A.; Ghadimi, P.; Raugei, M.; Wu, Y.; Heidrich, O. Challenges and Recent Developments in Supply and Value Chains of Electric Vehicle Batteries: A Sustainability Perspective. *Resour. Conserv. Recycl.* **2022**, *180*, 106144. [CrossRef]
16. Anastasiadis, F.; Manikas, I.; Apostolidou, I.; Wahbeh, S. The Role of Traceability in End-to-End Circular Agri-Food Supply Chains. *Ind. Mark. Manag.* **2022**, *104*, 196–211. [CrossRef]
17. Santana, S.; Ribeiro, A. Traceability Models and Traceability Systems to Accelerate the Transition to a Circular Economy: A Systematic Review. *Sustainability* **2022**, *14*, 5469. [CrossRef]
18. Maretto, L.; Faccio, M.; Battini, D. The Adoption of Digital Technologies in the Manufacturing World and Their Evaluation: A Systematic Review of Real-Life Case Studies and Future Research Agenda. *J. Manuf. Syst.* **2023**, *68*, 576–600. [CrossRef]
19. Leng, J.; Sha, W.; Wang, B.; Zheng, P.; Zhuang, C.; Liu, Q.; Wuest, T.; Mourtzis, D.; Wang, L. Industry 5.0: Prospect and Retrospect. *J. Manuf. Syst.* **2022**, *65*, 279–295. [CrossRef]
20. Meegoda, J.N.; Malladi, S.; Zayas, I.C. End-of-Life Management of Electric Vehicle Lithium-Ion Batteries in the United States. *Clean Technol.* **2022**, *4*, 1162–1174. [CrossRef]
21. European Commission Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Establishing a Framework for Setting Ecodesign Requirements for Sustainable Products and Repealing Directive 2009/125/EC 2022. Available online: https://data.consilium.europa.eu/doc/document/ST-7854-2022-INIT/en/pdf (accessed on 10 December 2023).
22. Langley, D.J.; Rosca, E.; Angelopoulos, M.; Kamminga, O.; Hooijer, C. Orchestrating a Smart Circular Economy: Guiding Principles for Digital Product Passports. *J. Bus. Res.* **2023**, *169*, 114259. [CrossRef]
23. Jensen, S.F.; Kristensen, J.H.; Adamsen, S.; Christensen, A.; Waehrens, B.V. Digital Product Passports for a Circular Economy: Data Needs for Product Life Cycle Decision-Making. *Sustain. Prod. Consum.* **2023**, *37*, 242–255. [CrossRef]
24. Adisorn, T.; Tholen, L.; Götz, T. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. *Energies* **2021**, *14*, 2289. [CrossRef]
25. King, M.R.N.; Timms, P.D.; Mountney, S. A Proposed Universal Definition of a Digital Product Passport Ecosystem (DPPE): Worldviews, Discrete Capabilities, Stakeholder Requirements and Concerns. *J. Clean. Prod.* **2023**, *384*, 135538. [CrossRef]
26. Koppelaar, R.H.E.M.; Pamidi, S.; Hajósi, E.; Herreras, L.; Leroy, P.; Jung, H.-Y.; Concheso, A.; Daniel, R.; Francisco, F.B.; Parrado, C.; et al. A Digital Product Passport for Critical Raw Materials Reuse and Recycling. *Sustainability* **2023**, *15*, 1405. [CrossRef]
27. Plociennik, C.; Pourjafarian, M.; Nazeri, A.; Windholz, W.; Knetsch, S.; Rickert, J.; Ciroth, A.; Precci Lopes, A.d.C.; Hagedorn, T.; Vogelgesang, M.; et al. Towards a Digital Lifecycle Passport for the Circular Economy. *Procedia CIRP* **2022**, *105*, 122–127. [CrossRef]
28. Jansen, M.; Gerstenberger, B.; Bitter-Krahe, J.; Berg, H.; Sebestyén, J.; Schneider, J. Current Approaches to the Digital Product Passport for a Circular Economy: An Overview of Projects and Initiatives. In *Wuppertal Institute for Climate, Environment and Energy*; Wuppertal Institut für Klima, Umwelt, Energie gGmbH: Wuppertal, Germany, 2022.
29. Jansen, M.; Meisen, T.; Plociennik, C.; Berg, H.; Pomp, A.; Windholz, W. Stop Guessing in the Dark: Identified Requirements for Digital Product Passport Systems. *Systems* **2023**, *11*, 123. [CrossRef]
30. Walden, J.; Steinbrecher, A.; Marinkovic, M. Digital Product Passports as Enabler of the Circular Economy. *Chem. Ing. Tech.* **2021**, *93*, 1717–1727. [CrossRef]
31. Berger, K.; Baumgartner, R.J.; Weinzerl, M.; Bachler, J.; Schöggl, J.-P. Factors of Digital Product Passport Adoption to Enable Circular Information Flows along the Battery Value Chain. *Procedia CIRP* **2023**, *116*, 528–533. [CrossRef]
32. Kang, K.; Zhong, R.Y. A Methodology for Production Analysis Based on the RFID-Collected Manufacturing Big Data. *J. Manuf. Syst.* **2023**, *68*, 628–634. [CrossRef]
33. Raihanian Mashhadi, A.; Behdad, S. Optimal Sorting Policies in Remanufacturing Systems: Application of Product Life-Cycle Data in Quality Grading and End-of-Use Recovery. *J. Manuf. Syst.* **2017**, *43*, 15–24. [CrossRef]
34. Wang, G.; Zhang, G.; Guo, X.; Zhang, Y. Digital Twin-Driven Service Model and Optimal Allocation of Manufacturing Resources in Shared Manufacturing. *J. Manuf. Syst.* **2021**, *59*, 165–179. [CrossRef]
35. Hasan, M.; Starly, B. Decentralized Cloud Manufacturing-as-a-Service (CMaaS) Platform Architecture with Configurable Digital Assets. *J. Manuf. Syst.* **2020**, *56*, 157–174. [CrossRef]
36. Psarommatis, F.; May, G.; Azamfirei, V. Envisioning Maintenance 5.0: Insights from a Systematic Literature Review of Industry 4.0 and a Proposed Framework. *J. Manuf. Syst.* **2023**, *68*, 376–399. [CrossRef]
37. Psarommatis, F.; Dreyfus, P.A.; Kiritsis, D. The Role of Big Data Analytics in the Context of Modeling Design and Operation of Manufacturing Systems. *Des. Oper. Prod. Netw. Mass Pers. Era Cloud Technol.* **2022**, 243–275. [CrossRef]
38. Tuptuk, N.; Hailes, S. Security of Smart Manufacturing Systems. *J. Manuf. Syst.* **2018**, *47*, 93–106. [CrossRef]
39. Psarommatis, F.; May, G.; Dreyfus, P.-A.; Kiritsis, D. Zero Defect Manufacturing: State-of-the-Art Review, Shortcomings and Future Directions in Research. *Int. J. Prod. Res.* **2020**, *7543*, 1–17. [CrossRef]
40. Liu, X.; Deng, Q.; Gong, G.; Lv, M.; Jiang, C. Service-Oriented Collaboration Framework Based on Cloud Platform and Critical Factors Identification. *J. Manuf. Syst.* **2021**, *61*, 183–195. [CrossRef]

41. Hapuwatte, B.M.; Seevers, K.D.; Jawahir, I.S. Metrics-Based Dynamic Product Sustainability Performance Evaluation for Advancing the Circular Economy. *J. Manuf. Syst.* **2022**, *64*, 275–287. [CrossRef]
42. Afshar-Bakeshloo, M.; Jolai, F.; Bozorgi-Amiri, A. A Bi-Objective Manufacturing/Remanufacturing System Considering Downward Substitutions between Three Markets. *J. Manuf. Syst.* **2021**, *58*, 75–92. [CrossRef]