A Review on Digital Product Passports as Drivers of Digital Transformation in Industry

Grigorios Tzionis
Information Technologies Institute
Centre For Research and
Technology Hellas
Thessaloniki, Greece
gtzionis@iti.gr

Georgia Kougka
Information Technologies Institute
Centre For Research and
Technology Hellas
Thessaloniki, Greece
kougka@iti.gr

Ilias Gialampoukidis
Information Technologies Institute
Centre For Research and
Technology Hellas
Thessaloniki, Greece
heliasgj@iti.gr

Stefanos Vrochidis
Information Technologies Institute
Centre For Research and
Technology Hellas
Thessaloniki, Greece
stefanos@iti.gr

Ioannis Kompatsiaris
Information Technologies Institute
Centre For Research and
Technology Hellas
Thessaloniki, Greece
ikom@iti.gr

Maro Vlachopoulou
University of Macedonia
University of Macedonia
Thessaloniki, Greece
mavla@uom.edu.gr

Samuel Olaiya Afolaranmi
Future Automation Systems &
Technologies Laboratory
Tampere University
Tampere, Finland
samuel.afolaranmi@tuni.fi

Jose Luis Martinez Lastra
Future Automation Systems &
Technologies Laboratory
Tampere University
Tampere, Finland
jose.martinezlastra@tuni.fi

***Abstract*—Digital Product Passports (DPPs) are emerging as pivotal tools *driving* the digital transformation across industries by providing standardized, interoperable, and detailed digital records of products. This enhances tracking, transparency, and lifecycle management, fostering sustainable and efficient digital ecosystems. While the potential of DPPs is recognized, existing reviews often lack a specific focus on their role as active enablers of industrial digital transformation. This paper addresses that gap by presenting a comprehensive review of the state-of-the-art in DPP research and applications, critically examining how they facilitate this transformation. We outline the methodology used to gather the literature, propose a taxonomy of DPP types based on technology and function (illustrated visually and summarized in a comparative table), present an evaluation framework with relevant metrics, and analyze their implications across various industrial sectors. Key contributions include this structured taxonomy, the evaluation framework, and a critical discussion of challenges (e.g., interoperability, standardization, readiness gaps) and opportunities, offering recommendations for leveraging DPPs effectively.**

***Index Terms*—Digital Product Passport, Digital Transformation, Industry 4.0, Industry 5.0, Circular Economy, Sustainability, Literature Review.**

I. Introduction

The accelerating pace of digital transformation necessitates innovative tools to enhance industrial transparency, traceability, and sustainability. DPPs have emerged as a critical solution, acting as comprehensive digital records that store standardized, interoperable information about a product's entire lifecycle—from raw material sourcing through manufacturing, usage, and end-of-life [4], [5]. By leveraging technologies like blockchain, digital twins, and IoT, DPPs actively *drive* improvements by enabling real-time monitoring, secure data sharing, and enhanced supply chain accountability [6], [7].

Recent industrial paradigms, particularly circular economy models, rely heavily on the capabilities provided by DPPs. Tracking materials, carbon footprints, and compliance metrics through DPPs facilitates sustainable practices in sectors like manufacturing, fashion, automotive, and construction [8], [9]. For example, integrating digital twins with DPPs demonstrably improves process efficiency and waste reduction in smart manufacturing [10], [11]. In textiles, DPPs enhance traceability, crucial for complying with regulations like the EU's Green Deal and Circular Economy Action Plan [3], [5].

Furthermore, in an era prioritizing supply chain resilience, DPPs enabled by blockchain and AI analytics empower businesses to optimize operations and meet Environmental, Social, and Governance (ESG) standards [1], [14]. Industries like automotive and aerospace utilize RFID and sensor integration with DPPs for predictive maintenance, component authentication, and end-of-life management [12], [13].

While several reviews exist on DPPs [3], many focus broadly on technology or specific sectors. This paper distinguishes itself by providing a critical review focused specifi-

This research was funded by European Union's Horizon Europe Research and Innovation program AIDEAS under Grand Agreement No 101057294.

cally on *how DPPs act as drivers of digital transformation* across diverse industries. We synthesize the state-of-the-art based on a targeted literature search (detailed in Section II), propose a structured taxonomy and evaluation framework, analyze implementation across sectors, and critically examine the associated challenges and opportunities. The aim is to provide stakeholders with actionable insights into leveraging DPPs not just as record-keeping tools, but as active agents of change towards more transparent, efficient, and sustainable industrial ecosystems.

II. Methodology

This review synthesizes current research on Digital Product Passports (DPPs) concerning their role in the digital transformation of industry. To gather relevant literature, a targeted search was conducted using the OpenAlex database (https://openalex.org/) on February 11, 2025 [21].

The primary search focused on identifying works with the exact phrase "Digital Product Passport" in the title or abstract. To narrow the focus to relevant industrial contexts, an additional filter for the OpenAlex primary topic ID 't10763' (related to Industrial Engineering and Operations Research) was applied. While the OpenAlex interface did not allow for a direct filter on "Digital Transformation in Industry" alongside the primary topic, the relevance of papers to this theme was assessed during the manual analysis stage.

This search strategy yielded a set of [Insert Number] publications. All retrieved publications were considered for inclusion in this review. While this approach does not constitute a full systematic literature review across multiple databases (e.g., following PRISMA guidelines), it provides a focused snapshot of the research landscape within the OpenAlex index based on the specified keywords and topic filter as of the search date.

The analyses presented in this paper, including the proposed taxonomy (Section IV-A), the discussion of industrial applications (Section IV-B), and the data presented in Figures 2 through 7 (publication trends, distribution by DPP type, distribution by industrial sector), are based entirely on this corpus of [Insert Same Number] retrieved papers. Categorization of papers for Figures 3, 4, 6, and 7 was performed through manual analysis of the title, abstract, keywords, and main content of each included paper to determine its primary DPP type focus and relevant industrial sector(s).

III. Background: Evolution and Context of DPPs

The concept of the DPP has evolved significantly, spurred by digital transformation, regulatory pressures (e.g., EU Green Deal, Circular Economy Action Plan [3], [5]), and the demand for circular economy models. Early efforts focused on supply chain traceability for quality assurance, anti-counterfeiting, and ethical sourcing [7], [9]. With Industry 4.0 and the emerging Industry 5.0 paradigms, the scope expanded dramatically. DPPs now integrate sustainability metrics, carbon tracking, and lifecycle assessments, positioning them as key enablers for climate-neutral, resource-efficient industries [8], [10].

Technically, DPPs function as comprehensive digital records containing standardized data about a product's lifecycle (composition, origin, manufacturing, usage, repair, end-of-life) [5], [6]. Key components often include:

- Unique Product Identifiers (e.g., RFID, QR codes, NFC tags).
- Data Carriers & Storage (e.g., Blockchain/DLT, centralized/decentralized databases).
- Data Exchange Protocols & APIs for interoperability.
- Analytics (e.g., AI-driven) for insights, integrity checks, and compliance verification [1], [14].

DPPs are integral to realizing the goals of Industry 4.0 (automation, connectivity) and Industry 5.0 (human-centricity, sustainability, resilience). They facilitate:

- **Predictive Maintenance**: Via real-time monitoring using integrated sensors (IoT) and digital twins [12], [13].
- **Resource Optimization**: By tracking material flows, emissions, and waste, enabling data-driven reduction strategies [10], [11].
- **Enhanced Traceability**: Improving supply chain resilience, ensuring regulatory compliance, and fostering customer trust [6], [16].
- **Circular Economy Enablement**: Providing data needed for repair, refurbishment, remanufacturing, and recycling [3], [8].

However, significant challenges impede widespread adoption. Interoperability remains a major hurdle, stemming from diverse, often proprietary, data formats, legacy systems, and the lack of universally agreed-upon data exchange standards across complex supply chains [15], [19]. Ensuring robust cybersecurity and data privacy is paramount, especially with sensitive data shared across multiple stakeholders, often using decentralized technologies like blockchain; this requires strong encryption, access control, and compliance with regulations like GDPR [16]–[18]. Furthermore, the absence of globally harmonized standards for DPP structure, content, and governance leads to fragmentation and hinders seamless cross-border operation [2]. Addressing these requires collaborative efforts in standardization, policy alignment, and technological development [19], [20].

IV. Types of Digital Product Passports

DPPs serve as structured digital records facilitating traceability, compliance, and circularity. They can be categorized based on their primary technological enabler, functional focus, or specific industry application [5], [6]. Understanding these types helps clarify their diverse roles in digital transformation.

A. A Taxonomy of DPPs

Based on an analysis of the reviewed literature (gathered as described in Section II), DPPs can be classified into several types, primarily distinguished by their core technology or dominant functional objective. It is important to note that these categories are not always mutually exclusive; a single DPP implementation might combine elements from multiple types (e.g., a Blockchain-based DPP focused on the Circular Economy). The taxonomy presented below aims to structure the landscape based on prevalent characteristics identified in current research and applications. DPPs can also be viewed through functional lenses such as lifecycle orientation, supply chain focus, regulatory compliance, data-driven insights, industry-specificity, or hybrid models, which often map onto the technology-centric types described here. Figure 1 provides a visual overview of the main categories discussed below. To further clarify the distinctions and relationships between these types, Table I offers a comparative summary, highlighting key technologies, primary functions, and example industrial sectors for each category identified in the reviewed literature.

- **Blockchain-based DPPs:** Utilize DLT for tamper-proof, decentralized data storage, enhancing security, authentication, and anti-counterfeiting [14]. Common in luxury goods, pharma, electronics recycling, textiles, and automotive for authenticity and compliance [5], [16].
- **Digital Twin-Based DPPs:** Integrate real-time virtual models for lifecycle management and predictive analytics [10]. Enable simulation, monitoring, and optimization of performance, maintenance, and sustainability [11]. Applied in aerospace, industrial automation, smart manufacturing [12], [13].
- **Circular Economy-Focused DPPs:** Prioritize resource efficiency and closed-loop lifecycles [8]. Track material flows, recyclability, and carbon footprints to support regulations (e.g., EU Circular Economy Action Plan [5]). Critical in packaging, textiles, e-waste, renewable energy [3].
- **Industry 4.0 DPPs:** Leverage automation, robotics, AI analytics for smart manufacturing and real-time data exchange [9]. Enable predictive maintenance, supply chain automation, process optimization in high-tech manufacturing, automotive, industrial IoT [19].
- **Industry 5.0 DPPs:** Extend Industry 4.0, focusing on human-centric, sustainable, resilient transformation [4]. Integrate AI personalization, circularity goals, ethical AI governance [18]. Used in adaptive manufacturing, digital supply ecosystems, sustainable production.
- **IoT-Based DPPs:** Use smart sensors, RFID, real-time tracking for enhanced monitoring, automation, lifecycle management [12]. Enable remote diagnostics, inventory tracking, energy monitoring in logistics, smart cities, consumer electronics [13].
- **Supply Chain-Focused DPPs:** Emphasize traceability, transparency, regulatory compliance across global networks [15]. Provide insights into sourcing, transport, quality assurance in fashion, pharma, food safety, electronics [1].
- **RFID-Based DPPs:** Incorporate RFID tags for automated tracking and authentication [14]. Effective in automotive, aerospace, high-value asset tracking requiring secure, real-time identification [11].
- **Sustainability-Focused DPPs:** Integrate carbon tracking, LCAs, ESG reporting for climate-conscious manufacturing [8]. Assist construction, energy, material recycling in meeting green regulations and net-zero targets [5].
- **Smart Grid & Energy DPPs:** Tailored for energy infrastructure tracking, optimizing distribution, enhancing renewable integration [12]. Monitor solar panels, wind turbines, batteries for grid management and compliance.
- **Data Sharing DPPs:** Facilitate secure, cross-industry data exchange ensuring privacy, interoperability, compliance [7]. Used in automotive, finance, government for digital identity and inter-company collaboration.
- **Big Data-Enabled DPPs:** Integrate AI, ML, advanced analytics for insights from large datasets [19]. Improve supply chain optimization, failure prediction, fraud detection in finance, healthcare, predictive maintenance [18].
- **Digital Business DPPs:** Enhance transparency, compliance, digital service integration in B2B/B2C contexts [19]. Valuable in e-commerce, software licensing, enterprise sustainability tracking.
- **Digital Repair DPPs:** Support Right to Repair initiatives by providing access to repair data, software compatibility, component sourcing [17]. Gaining traction in electronics, automotive, white goods to extend lifespans and reduce e-waste.

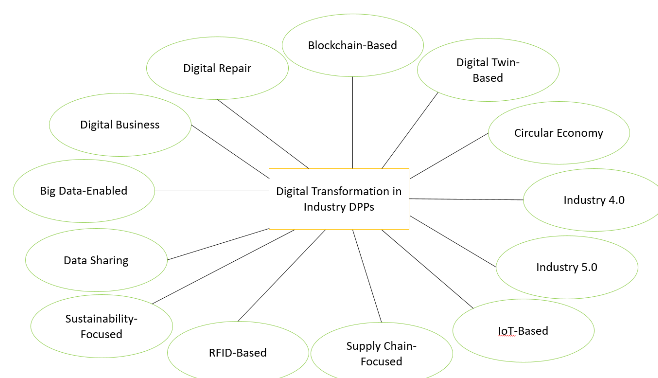

Fig. 1: Visual Overview of DPP Categories based on Technology and Function

The analysis of publication trends, derived from the literature corpus described in Section II, provides insights into the evolving research landscape. Figure 2 highlights a steady rise in DPP-related publications from 2013 to 2024 within this corpus, with a marked acceleration in recent years, suggesting growing academic and industrial interest.

TABLE I: Comparative Analysis of DPP Types (Based on Reviewed Literature)

DPP Type	Key Technology Example(s)	Primary Function/Goal Example(s)	Example Industrial Sector(s)
Digital Twin-Based DPP	Virtual Models, IoT, AI	Lifecycle Mgmt, Simulation, Optimization	Food Supply Chain, Fashion Industry, etc.
Dynamic DPP	Real-time Data Integration	Up-to-date Info, Adaptability	Organic & Geographic Indication Food Sector
Circular Economy DPP	Various (IoT, Blockchain)	Resource Efficiency, Closed-loop Lifecycle	Manufacturing & Supply Chain, Various Industries
Ontology-Based DPP	Semantic Models, Ontologies	Structured Data Representation, Automation	Instrument-Making Industry
Knowledge Graph-Based DPP	Various	Various	Construction Industry
Standardized DPP Framework	Various	Various	Manufacturing Industry
Regulatory & Policy-Based DPP	Various	Various	Textile Industry
Blockchain-Based DPP	DLT/Blockchain	Security, Transparency, Traceability	Smart Manufacturing & Supply Chains, Smart Manufacturing, etc.
AAS-Based DPP	Various	Various	Manufacturing & Circular Economy
Regulatory-Driven DPP	Various	Various	Manufacturing Industry
Textile Industry DPP	Various	Various	Textile Industry
Transparency-Focused DPP	Various	Various	Fashion & Textile Industry
Green Digital Twin-Based DPP	Virtual Models, IoT, AI	Lifecycle Mgmt, Simulation, Optimization	Industrial Manufacturing
Cloud-Native DPP	Various	Various	Industry 4.0
Blockchain-based DPP	DLT/Blockchain	Security, Transparency, Traceability	Circular Economy, Manufacturing
Value Chain DPP	Various	Various	Automotive, Circular Economy
Cyber-Physical Machine Tools	Various	Various	Manufacturing
Human-Centric DPP	Various	Various	Manufacturing & Digital Economy
Industry 4.0-Based DPP	Automation, AI, IoT	Smart Manufacturing, Process Optimization	Circular Economy & Smart Manufacturing, Various Industries
RFID-Integrated DPP	RFID Tags/Readers	Identification, Tracking, Authentication	Supply Chain & Logistics
MaaS-Enabled DPP	Various	Various	Automotive Industry
Sustainability-Focused DPP	LCA Tools, Carbon Tracking	ESG Reporting, Green Compliance	Various Industries, Manufacturing & Green Design
Supply Chain-Focused DPP	Various (Blockchain, IoT)	Traceability, Compliance, Network Visibility	Logistics & Supply Chain
Big Data-Enabled DPP	AI/ML, Advanced Analytics	Insights, Optimization, Prediction	Consumer Goods
Platform-Based DPP	Various	Various	Manufacturing & Industrial Production
Risk Management-Focused DPP	Various	Various	Digital Manufacturing & Supply Chain
IoT-Enabled DPP	Sensors, RFID, Connectivity	Monitoring, Automation, Tracking	Textile & Fabric Industry
Circular Fashion DPP	Various	Various	Fashion Industry
Industry 5.0 DPP	AI, Robotics, Human-Centric Tech	Resilience, Sustainability, Human Augmentation	Various Industries
IoT-Based DPP	Sensors, RFID, Connectivity	Monitoring, Automation, Tracking	Marine Industry, Smart Manufacturing
Digital Transformation DPP	Various	Various	Digital Society & Industry 4.0, Higher Education
Industry 4.0 DPP	Automation, AI, IoT	Smart Manufacturing, Process Optimization	Aviation & Airport Management, Various Industries, etc.
Big Data-Driven DPP	AI/ML, Advanced Analytics	Insights, Optimization, Prediction	Consumer Goods Industry
Digital Business DPP	Various Digital Platforms	B2B/B2C Integration, Compliance	Various Industries
RFID-Based DPP	RFID Tags/Readers	Identification, Tracking, Authentication	Automotive Industry
Smart Grid & Energy DPP	Various	Various	Energy Sector
Digital Thread DPP	Various	Various	Smart Manufacturing
Data Sharing DPP	APIs, Data Standards	Interoperability, Secure Collaboration	Construction Industry
Digital Repair DPP	Data Access Standards	Repairability, Lifecycle Extension	Consumer Electronics
Circular Economy-Based DPP	Various (IoT, Blockchain)	Resource Efficiency, Closed-loop Lifecycle	Various Manufacturing Industries
Big data (Industry 4.0) DPP	Automation, AI, IoT	Smart Manufacturing, Process Optimization	Fast moving consumer goods (FMCG), Clothing and Cosmetics
Digital Twin and Circular Economy-Based DPP	Virtual Models, IoT, AI	Lifecycle Mgmt, Simulation, Optimization	Manufacturing industry
Supply chain & Blockchain-based DPP	DLT/Blockchain	Security, Transparency, Traceability	Fashion Industry
Industry 4.0 and 5.0 DPP	Automation, AI, IoT	Smart Manufacturing, Process Optimization	Construction industry
Digital platform DPP	Various	Various	Construction industry
Battery Digital Twin DPP	Virtual Models, IoT, AI	Lifecycle Mgmt, Simulation, Optimization	Battery Industry

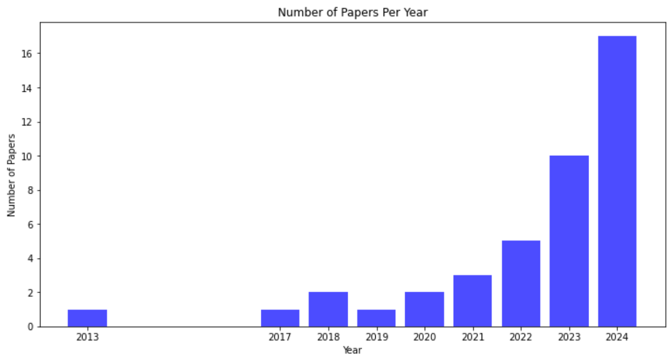

Fig. 2: DPP papers through the years (Based on literature identified in Section II)

Examining the distribution of publications across different DPP types within the identified literature, as shown in Figure 3, reveals current research concentrations. Digital Twin-Based and Blockchain-Based DPPs appear most frequently, followed by Circular Economy and Industry 4.0 focused types.

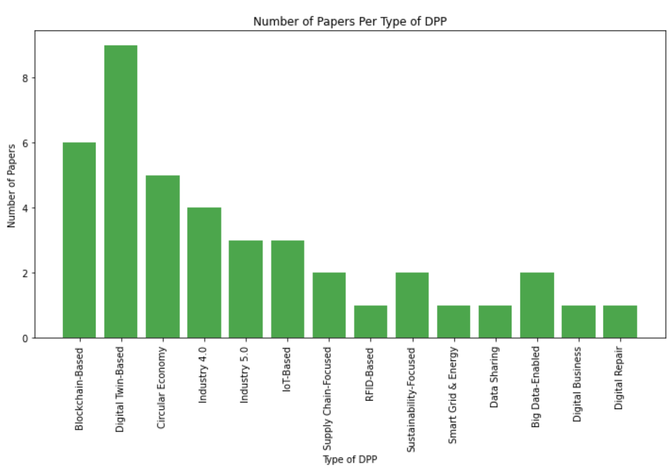

Fig. 3: Number of Papers per Type of DPP (Based on literature identified in Section II)

Figure 4 further breaks down these publication trends by DPP type over time. It confirms the recent prominence of Blockchain-Based and Digital Twin-Based solutions within the reviewed papers and indicates growing momentum in areas like Sustainability-Focused and Smart Grid & Energy DPPs.

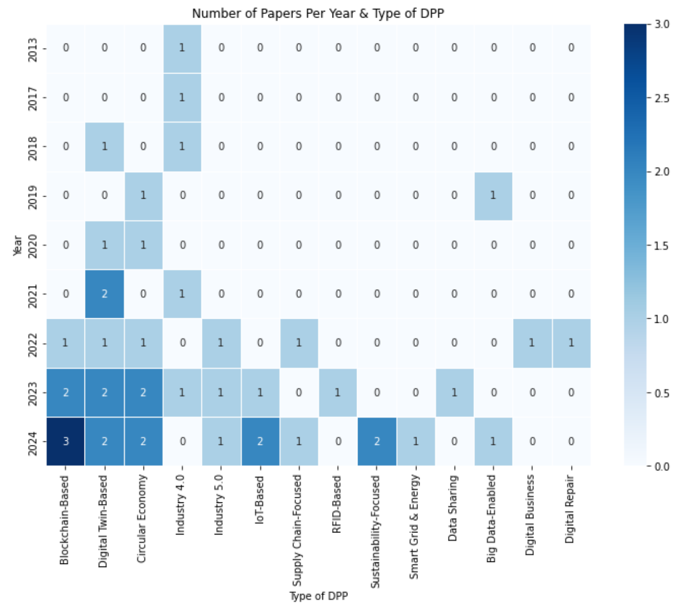

Fig. 4: Number of Papers per Year & Type of DPP (Based on literature identified in Section II)

B. Industrial Sectors and Applications

DPPs are being implemented across diverse industrial sectors, driving transparency, compliance, and sustainability, accelerated by digital transformation trends and regulatory mandates [5], [6]. Figure 5 illustrates the key sectors identified in the literature gathered for this review. Below are examples of DPP applications within these sectors:

- **Manufacturing (General & High-Tech):** Real-time production monitoring, quality control, resource efficiency, waste minimization [10], [19]. Integration of IoT, AI, digital twins tracks material flows, carbon footprints, machine health [12]. Enhances lifecycle management, predictive maintenance, circular strategies [11]. Use Case: Monitoring resource utilization for efficiency [2].
- **Circular Economy Initiatives:** Enabling closed-loop lifecycles via traceability, material recovery tracking, carbon assessments [5], [8]. Used in packaging, e-waste, construction to track recyclability, optimize reuse, comply with regulations [3]. Aligns with EU Circular Economy Action Plan and SDGs.
- **Fashion & Textiles:** Transparency in sourcing, ethical production tracking, waste reduction [16]. Blockchain/digital twins provide garment authenticity, repairability insights, circularity scores [3]. Validates sustainability claims, meets EU Green Deal/Textile Strategy requirements [5]. Use Case: Tracking fabric composition and recycling pathways [5].
- **Automotive:** RFID/AI-driven DPPs monitor components, enhance recyclability, ensure emissions compliance [11], [14]. Track battery lifecycles, material origins, second-life applications, promoting circularity in EV production [12]. Use Case: Monitoring component lifecycle for compliance and circularity [3].

- **Smart Manufacturing/Factories:** Integrate digital twins, AI automation, IoT for streamlined operations, minimized downtime [10], [19]. Enhance predictive maintenance, cyber-physical system coordination, human-robot collaboration [4].
- **Retail & Consumer Goods:** Ensure product traceability, ethical sourcing, consumer transparency [1], [15]. QR codes/blockchain passports give access to sustainability credentials, repair details, origin tracking [16]. Use Case: Providing consumers detailed product origin and sustainability info [1].
- **Energy (Renewable & Smart Grid):** Lifecycle tracking of solar panels, wind turbines for performance optimization, end-of-life recycling [12], [13]. Smart grid DPPs monitor battery degradation, efficiency, compliance [10]. Use Case: Lifecycle tracking of renewable energy equipment [1].
- **Supply Chain & Logistics:** Improve efficiency, reduce counterfeiting, enhance shipment security [1], [15]. RFID/IoT DPPs enable real-time cargo tracking, inventory automation, streamlined trade compliance [14].
- **Construction:** Integration with BIM tracks material lifecycles, structural integrity, embodied carbon [7]. Ensures compliance with sustainability certifications (LEED, BREEAM), promotes circular practices [5].
- **Research & Higher Education:** Promote open data sharing, research integrity, knowledge dissemination [18]. Used in smart manufacturing/sustainability research for lab management, project tracking, industry collaboration.
- **Aviation:** Component authentication, safety compliance, predictive maintenance [12]. Blockchain DPPs track part histories, repair records, secondary market transactions for regulatory transparency [11].
- **Maritime:** Ship lifecycle tracking, fuel monitoring, regulatory compliance [13]. IoT DPPs enable real-time diagnostics, vessel efficiency analysis, predictive maintenance [10].
- **Digital Society & Governance:** Role in cybersecurity, decentralized identity management [4]. In Industry 4.0/5.0, facilitate AI-driven ecosystems, digital service tracking, human-machine collaboration [18].

Figure 5 presents a visual overview of the primary industrial sectors identified in the literature where DPPs are being applied or researched.

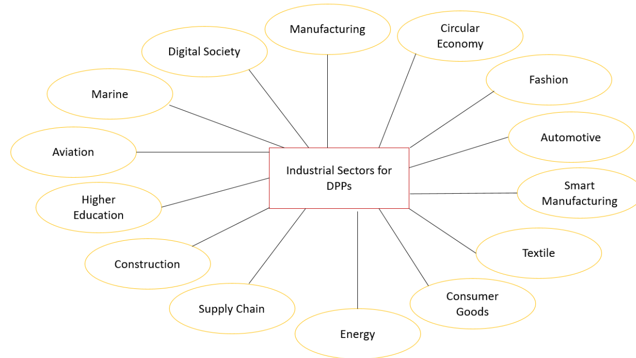

Fig. 5: Industrial Sectors Leveraging DPPs for Digital Transformation

The distribution of research publications across these industrial sectors within the identified corpus, depicted in Figure 6, shows a strong focus on Manufacturing, followed by Circular Economy initiatives. Fashion, Automotive, and Smart Manufacturing also represent significant areas.

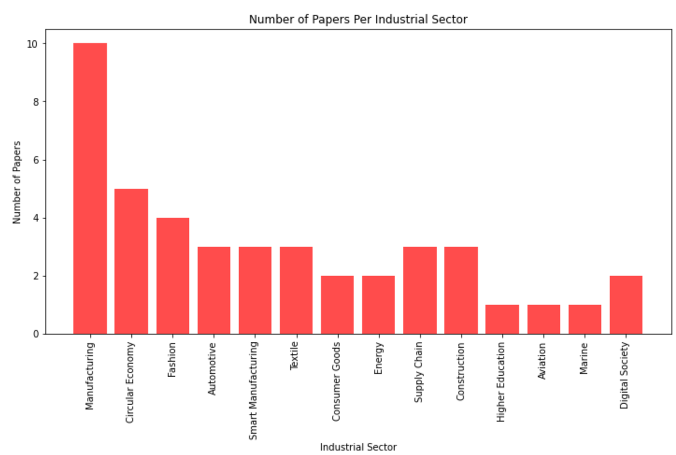

Fig. 6: Number of Papers per Industrial Sector for DPPs (Based on literature identified in Section II)

Analyzing the publication trends per sector over time, as visualized in Figure 7, reinforces the recent surge of interest in Manufacturing and Circular Economy within the reviewed literature, alongside growing activity in Fashion, Automotive, and Supply Chain sectors.

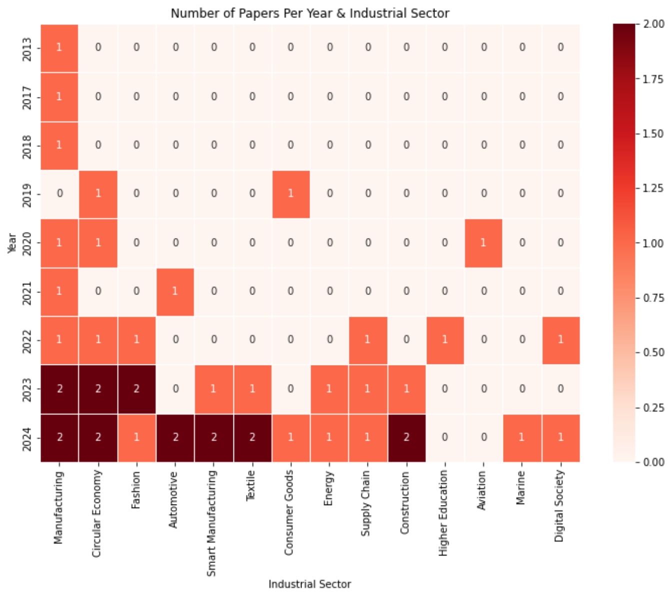

Fig. 7: Number of Papers per Year & Industrial Sector (Based on literature identified in Section II)

V. Evaluation of Digital Product Passports

Evaluating DPP effectiveness requires structured frameworks and relevant metrics assessing their technological robustness, regulatory alignment, usability, and impact [5], [6]. In Table II, we map evaluation criteria to metrics for DPP.

A. Evaluation Criteria Framework

A comprehensive evaluation framework should encompass the following key criteria:

- **Lifecycle Transparency and Circular Economy Alignment:** Assesses the completeness of lifecycle tracking (sourcing to end-of-life) and the degree to which the DPP supports closed-loop systems, material traceability, and environmental impact assessments (e.g., carbon footprint) [1], [5], [8].
- **Data Integrity, Security, and Privacy:** Evaluates the robustness of mechanisms ensuring data authenticity, tamper resistance (e.g., via blockchain [12], [14]), confidentiality (encryption), and compliance with privacy regulations (e.g., GDPR). Checks effectiveness in preventing fraud and unauthorized access [3].
- **Interoperability and Standardization:** Measures the ability to seamlessly integrate with existing enterprise systems (ERP, SCM) and regulatory databases, adherence to open standards, API availability, and cross-platform usability [11], [15], [16].
- **Regulatory Compliance and Policy Adherence:** Assesses alignment with relevant global/regional regulations (e.g., EU Green Deal, Circular Economy Action Plan) and industry-specific mandates (e.g., emissions reporting, material traceability, EPR) [5], [7], [8].
- **User Accessibility and Usability:** Focuses on the ease of access and use for all stakeholders (manufacturers, regulators, consumers), including intuitive interfaces, multi-language support, and clarity of presented data [1], [10], [16].
- **Environmental and Economic Impact:** Quantifies the DPP's contribution to sustainability goals (waste reduction, energy efficiency) and economic benefits (cost savings from logistics, material recovery, compliance) [4], [12], [18].
- **Scalability and Long-Term Viability:** Evaluates the framework's capacity to scale across product categories, regions, and evolving regulatory landscapes, adapting to supply chain complexities and technological advancements [11], [19].

B. Metrics for Evaluation

To operationalize the evaluation criteria presented in Section V-A, specific quantitative and qualitative metrics are employed. These metrics provide measurable indicators of DPP performance against the desired standards, helping to assess effectiveness, compliance, and impact on sustainability and efficiency [5], [6], [8], [14]. Table II provides a summary mapping criteria to example metrics.

Below are key metrics used in DPP evaluation, expanding on the examples in the table:

- **Traceability Index:** Measures the extent to which a product's lifecycle can be accurately traced. Higher scores indicate comprehensive tracking [1], [8]. Critical in fashion, automotive, electronics for provenance and authenticity [3], [16].
- **Sustainability Score:** Assesses environmental/social impact via carbon footprint, material circularity, ethical sourcing compliance [5], [8]. Used in manufacturing, construction, energy for LCA and compliance (e.g., EU Green Deal) [7], [10].
- **Data Accuracy Rate:** Percentage of correct, verifiable data entries, ensuring integrity and reliability [12], [14]. Blockchain enhances accuracy via tamper-proof records [11].
- **Compliance Metrics:** Evaluates adherence to specific regulations (e.g., EU Circular Economy Action Plan [5], GDPR [18], EPR frameworks [16]).
- **Stakeholder Adoption Rate:** Percentage of manufacturers, suppliers, retailers, consumers actively using the DPP system [1], [15]. High adoption indicates acceptance and collaboration [4], [16].
- **Interoperability Score:** Evaluates seamless integration with external databases, platforms, agencies [7]. Assesses API connectivity, cross-platform access, standardized data exchange [11].
- **Economic Efficiency Index:** Assesses cost savings from reduced compliance costs, better inventory management, lower fraud risks [4]. Used in automotive, logistics for resource optimization [12].

TABLE II: Mapping Evaluation Criteria to Metrics for DPP Assessment

Evaluation Criterion (from V-A)	Example Metric	Type (Qn/Ql)	Description / Focus
Lifecycle Transparency & CE Alignment	Traceability Index [1], [8] Sustainability Score [5], [8]	Qn/Ql Qn/Ql	Completeness of lifecycle tracking (source-to-grave). Environmental/social impact (carbon, circularity, ethics).
Data Integrity, Security, Privacy	Data Accuracy Rate [12], [14] Security Breach Incidents	Qn Qn	Percentage of correct/verifiable data entries. Number/severity of security incidents related to DPP data.
Interoperability & Standardization	Interoperability Score [7] Standards Compliance Rate	Qn/Ql Qn	Ease of integration with external systems (APIs, standards). Adherence to relevant data/communication standards.
Regulatory Compliance & Policy Adherence	Compliance Metrics [5], [16], [18] Audit Pass Rate	Qn/Ql Qn	Adherence rate to specific regulations (e.g., CEAP, EPR). Success rate in regulatory/compliance audits.
User Accessibility & Usability	Stakeholder Adoption Rate [1], [15] User Satisfaction Score	Qn Ql	Percentage of target users actively using the DPP. Qualitative feedback on ease of use, clarity.
Environmental & Economic Impact	Carbon Footprint Reduction Economic Efficiency Index [4]	Qn Qn	Measured reduction attributable to DPP insights/actions. Cost savings (compliance, inventory, fraud reduction).
Scalability & Long-Term Viability	System Scalability Test Results Adaptability Assessment	Qn Ql	Performance under increasing load (data volume, users). Qualitative assessment of ability to adapt to changes.

Note: Qn = Quantitative, Ql = Qualitative. Citations indicate sources discussing the relevance of the metric type.

VI. Challenges, Opportunities, and Future Directions

The implementation and scaling of DPPs face significant hurdles but also unlock substantial opportunities for industrial innovation and sustainability.

A. Persisting Challenges

Key technical and organizational challenges must be overcome for widespread DPP success:

- **Interoperability and Standardization:** Achieving seamless data exchange across heterogeneous systems and supply chain partners remains a primary obstacle due to proprietary formats and lack of universal standards [1], [2]. This fragmentation hinders end-to-end visibility and collaboration.
- **Data Security and Privacy:** Protecting sensitive product, process, and business data stored and shared via DPPs is critical. Robust encryption, granular access control, and secure infrastructure (potentially leveraging blockchain's immutability) are essential but complex to implement at scale [3], [16]. Compliance with evolving privacy regulations (like GDPR) adds complexity [17].
- **Scalability and Cost:** Developing and deploying DPP systems that can handle vast amounts of data from numerous products and stakeholders across global supply chains can be technologically demanding and costly, particularly for SMEs.
- **Data Quality and Governance:** Ensuring the accuracy, completeness, and reliability of data entered into DPPs throughout the lifecycle requires clear governance structures, defined responsibilities, and potentially automated verification mechanisms.
- **Regulatory Fragmentation:** While frameworks like the EU's provide direction, the lack of globally harmonized regulations creates compliance challenges for international companies [2].
- **Digital Readiness Gap:** A significant gap often exists between regulatory mandates for DPPs and the actual digital maturity of industries, especially SMEs, potentially hindering adoption and effective utilization [18].

B. Opportunities for Growth and Innovation

Despite challenges, DPPs offer significant opportunities:

- **Driving Transparency and Trust:** DPPs provide verifiable data on product origins, composition, and sustainability practices, enhancing consumer confidence and brand reputation [1].
- **Accelerating the Circular Economy:** By providing detailed lifecycle data (materials, repairability, disassembly), DPPs are fundamental enablers for recycling, refurbishment, and remanufacturing, closing material loops [2], [3].
- **Enabling Data-Driven Innovation:** Aggregated and analyzed DPP data offers valuable insights for optimizing operations (e.g., predictive maintenance), improving product design, identifying supply chain bottlenecks, and developing new data-centric business models [1], [19].
- **Streamlining Compliance:** Automating data collection and reporting through DPPs can simplify and reduce the cost of compliance with environmental, safety, and trade regulations.
- **Fostering Collaboration:** Standardized DPP frameworks can facilitate better information sharing and collaboration among supply chain partners, leading to more resilient and efficient value chains [2].

C. Future Directions

Future work should focus on developing globally accepted standards for DPP data models and interoperability protocols. Research into advanced security techniques (e.g., zero-knowledge proofs for privacy-preserving data sharing) and AI-driven data validation is crucial. Furthermore, exploring incentive mechanisms and support structures, particularly for

SMEs, will be vital for accelerating adoption and bridging the digital readiness gap. International collaboration will be key to harmonizing regulations and unlocking the full potential of DPPs in creating sustainable global industrial ecosystems.

VII. Conclusion

This review has critically examined the multifaceted role of Digital Product Passports (DPPs) as active drivers of digital transformation within industry. DPPs are not merely static records but dynamic tools enhancing transparency, traceability, and sustainability across diverse sectors. Our analysis synthesized the state-of-the-art based on a targeted literature search (Section II) and proposed a taxonomy categorizing DPPs based primarily on their core technology and function (Section IV-A, illustrated in Figure 1 and summarized in Table I), acknowledging that implementations often blend these types.

We presented evaluation frameworks (Section V-A) and associated metrics (Section V-B, summarized in Table II) providing a structured approach to assess DPP effectiveness regarding lifecycle management, data integrity, interoperability, usability, and regulatory compliance. While significant technical and organizational challenges persist (Section VI-A)—notably interoperability, data security, the lack of global standards, and varying levels of digital readiness across industries—DPPs offer immense opportunities (Section VI-B). They are crucial for fostering transparency, enabling data-driven innovation, and operationalizing circular economy practices.

Moving forward (Section VI-C), realizing the full potential of DPPs requires concerted effort from stakeholders. Developing and adopting standardized protocols, establishing robust data governance, ensuring scalable and secure technological solutions, and addressing the digital readiness gap are paramount. Cross-industry and cross-regional collaboration is essential to create a unified, interoperable ecosystem for DPPs, thereby solidifying their role in shaping more sustainable, efficient, and resilient digital industrial landscapes globally. The key contribution of this review lies in its focused analysis of DPPs as transformation drivers, the structured taxonomy, and the comprehensive evaluation framework presented, all grounded in the described literature search methodology.

Match & Contribution to IEEE TEMS Objectives

This contribution aligns well with the theme of the ICE IEEE 2025 conference on ”AI-driven Industrial Transformation: Digital Leadership in Technology, Engineering, Innovation & Entrepreneurship”. The paper explores Digital Product Passports (DPPs), an emerging technology central to industrial digital transformation, particularly in the context of sustainability and circular economy mandates driven by initiatives like the EU Green Deal.

Our work directly addresses key IEEE Technology and Engineering Management Society (TEMS) research objectives:

- **Addressing the Management of Emerging Technology:** We analyze DPPs as a pivotal emerging technology, examining their types, applications, and the managerial challenges associated with their adoption (e.g., standardization, interoperability, data governance).
- **Providing Practical Frameworks:** The paper proposes a taxonomy to categorize DPPs (Section IV-A, Figure 1, Table I) and an evaluation framework with specific criteria and metrics (Section V, Table II). These frameworks offer practical guidance for organizations seeking to understand, implement, and assess the effectiveness of DPP solutions.
- **Analyzing Implementation Challenges:** We dedicate significant discussion to the technical, organizational, and regulatory challenges hindering DPP implementation (Section VI-A), including interoperability, security, cost, data quality, and the digital readiness gap, providing insights relevant to engineering management.
- **Focusing on Value Creation:** The review highlights how DPPs create value by enhancing transparency, enabling circular economy business models, driving data-driven innovation, improving supply chain resilience, and streamlining regulatory compliance (Section VI-B).

By synthesizing the state-of-the-art (based on the methodology outlined in Section II), proposing structured frameworks, and critically analyzing the role, challenges, and opportunities of DPPs in driving industrial transformation towards sustainability and efficiency, this paper contributes relevant insights for technology leaders, engineers, innovators, and entrepreneurs navigating this evolving landscape.

MATCH & CONTRIBUTION

This contribution aligns well with the theme of the ICE IEEE 2025 conference on ”AI-driven Industrial Transformation: Digital Leadership in Technology, Engineering, Innovation & Entrepreneurship”. The paper explores the integration of SCRUM elements, a popular agile project management framework, into service prototyping processes for technology and service innovation. By incorporating SCRUM principles into the service prototyping process, the authors emphasize the importance of agile methodologies in driving innovation and entrepreneurship. The research sheds light on how data-driven engineering practices can be enhanced through the adoption of agile frameworks, enabling organizations to respond effectively to evolving market demands. This contribution addresses the conference’s focus on utilizing data-driven approaches to foster innovation and entrepreneurship, making it a relevant and valuable addition to the conference proceedings.

ACKNOWLEDGEMENTS

This research was funded by European Union’s by Horizon Europe Research and Innovation program AIDEAS under Grand Agreement No 101057294.

References

[1] T. Götz, H. Berg, M. Jansen, T. Adisorn, and D. Cembrero, “Digital product passport: the ticket to achieving a climate-neutral and circular European economy?,” Wuppertal Institute, 2022. [Online]. Available: https://epub.wupperinst.org/files/8049/8049_Digital_Product_Passport.pdf.

[2] J. Walden and A. Steinbrecher, "Digital product passports as enabler of the circular economy," *Chemie Ingenieur Technik*, vol. 93, no. 11, pp. 1779-1788, 2021. DOI: 10.1002/cite.202100121.

[3] A. Zhang and S. Seuring, "Digital product passport for sustainable and circular supply chain management: a structured review of use cases," *International Journal of Production Research*, pp. 1-23, 2024. DOI: 10.1080/13675567.2024.2374256.

[4] J. Barata and I. Kayser, "Industry 5.0–past, present, and near future," *Procedia Computer Science*, vol. 219, pp. 778–788, 2023.

[5] J. Legardeur and P. Ospital, "Digital product passport for the textile sector," Study requested by the ITRE committee, European Parliament, Policy Department for Economic, Scientific and Quality of Life Policies, Brussels, 2024.

[6] P. Ospital, D. H. Masson, C. Beler, and J. Legardeur, "A digital product passport to support product transparency and circularity," in *Proc. Global Fashion Conference*, 2022, pp. 11–p.

[7] A. Tezel, D. Kifokeris, C. Formoso, L. Koskela, and C. Koch, "A conceptual framework for lean construction and blockchain synergy," in *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC 30)*, 2022, pp. 576–587.

[8] J. Mügge, A. Seegrün, T.-K. Hoyer, T. Riedelsheimer, and K. Lindow, "Digital Twins within the Circular Economy: Literature Review and Concept Presentation," *Sustainability*, vol. 16, no. 7, p. 2748, 2024.

[9] O. Bongomin et al., "Industry 4.0 disruption and its neologisms in major industrial sectors: A state of the art," *Journal of Engineering*, vol. 2020, Article ID 8090521, 20 pages, 2020.

[10] J. Deuse et al., "Green digital twins in the product life cycle," in *Advanced Manufacturing and Sustainable Productivity: Proceedings of the WGAB Doctoral Colloquium 2023*, J. Deuse, B. Kuhlenkötter, K. Lindow, R. Stark, G. Seliger, Eds. Springer Vieweg, Berlin, Heidelberg, 2023, pp. 167–186.

[11] F. Schöppenthau et al., "Building a Digital Manufacturing as a Service Ecosystem for Catena-X," *Sensors*, vol. 23, no. 17, p. 7396, 2023.

[12] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.

[13] S. N. Masaev, A. N. Minkin, E. Yu. Troyak, and A. L. Khrulkevich, "Digital twin of woodworking enterprise," in *IOP Conference Series: Earth and Environmental Science*, vol. 806, no. 1, p. 012022, 2021.

[14] F. Stodt, N. Maisch, P. Ruf, A. Lechler, O. Riedel, and C. Reich, "Collaborative Smart Production Supply Chains with Blockchain Based Digital Product Passports," *Preprints.org*, 2024021194, 2024. DOI: 10.20944/preprints202402.1194.v1.

[15] M. Zaki, B. Theodoulidis, P. Shapira, A. Neely, and M. F. Tepel, "Redistributed manufacturing and the impact of big data: a consumer goods perspective," *Production Planning & Control*, vol. 30, no. 7, pp. 568–581, 2019.

[16] C. Chrimes and H. Heim, "The Fashion Product Passport: In Search of the "Killer App"," in *Fashion and Environmental Sustainability*, S. S. Muthu, Ed. Springer, Singapore, 2023, pp. 149-169.

[17] K. de Vries and S. Abrahamsson, "A Digital Right to Repair? How new EU legislation could open up data and software in connected products to enhance their lifespan," *De Lege*, vol. 2022, pp. 1-28, 2022.

[18] R. Agrawal, V. A. Wankhede, A. Kumar, S. Luthra, and D. Huisingh, "Progress and trends in integrating Industry 4.0 within Circular Economy: A comprehensive literature review and future research propositions," *Business Strategy and the Environment*, vol. 31, no. 1, pp. 559–579, Jan. 2022.

[19] H. Kohl, G. Seliger, and F. Dietrich, Eds., *Manufacturing Driving Circular Economy: Proceedings of the 18th Global Conference on Sustainable Manufacturing (GCSM), October 5-7, 2022, Berlin, Germany*, Springer Nature Switzerland, 2023.

[20] V. Jesus, D. Kalaitzi, L. Batista, and N. L. Lopez, "Digital Twins of Supply Chains: A Systems Approach," *IEEE Transactions on Engineering Management*, pp. 1-15, 2024. DOI: 10.1109/TEM.2024.3369441.

[21] OpenAlex Search. "Works filtered by 'Digital Product Passport' in Title/Abstract and Primary Topic ID t10763." [Online]. Available: https://openalex.org/works?page=1&filter=title_and_abstract.search%3ADigital%20Product%20Passport,primary_topic.id%3At10763. [Accessed: February 11, 2025].

[22] F. Stodt, N. Maisch, P. Ruf, A. Lechler, O. Riedel, and C. Reich, "Collaborative Smart Production Supply Chains with Blockchain Based Digital Product Passports," *Preprints*, 2024. DOI: 10.20944/preprints202402.1194.v1.