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Digital Product Passports: Where Yesterday's Product Informs Tomorrow's Process

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Abstract

European Industry is facing a number of challenges. Firstly, to improve competitiveness, companies need to digitalize and move to more Autonomous Factories that are able to make use of product and production data to optimize their processes in real time. Secondly, industry needs to become more sustainable and report on this to an ever increasing degree. In this contribution we present how these two developments are not at odds with each other, but instead investments in one directly contribute to success in the other challenge. Specifically, by integrating the Digital Product Passport (DPP) in your production environment to provide access to the Autonomous Factory, as well as using DPPs to meet various reporting requirements including those on sustainability. In this way, sustainability and competitiveness go hand in hand, while enabling far reaching optimization and lowering reporting burden.

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1. Introduction - The Rationale Behind Digital Product Passports

When former ECB President Mario Draghi presented his 2024 report: The Future of European Competitiveness [1], he warned that Europe must rebuild a world-class industrial base that is simultaneously green, digital, and strategically independent. Competitiveness, he argued, no longer depends on cost reduction alone but on mastering the clean-tech age by securing the know-how, raw materials, and data that underpin the value of future products.

This message resonated across Europe where most countries have already set goals to become more sustainable and decarbonize their industry. One of the European Commission's flagship instruments in this transition is the Digital Product Passport (DPP) [2], designed to structure product information and improve access to it. DPPs aim to support a circular economy by optimizing product design, use, and end-of-life handling. In doing so, they not only advance

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environmental goals but also reduce the dependence on imported materials, placing DPPs squarely within the broader ambitions of Europe for strategic autonomy and industrial resilience.

In parallel, industry is advancing toward the fourth industrial revolution. Manufacturers are moving beyond digitalization toward smart and autonomous systems capable of operating with minimal human intervention. Such systems promise efficiency gains, resilience against labor shortages, and new value streams. Industry is looking for new ways to leverage increasingly connected products, equipment, and processes to further improve manufacturing efficiency and earning power, and improve the returns on the investments made in digitization. For European manufacturers facing structural challenges, such as high energy costs, scarce raw materials, and labor constraints, autonomy may be essential for maintaining competitiveness while ensuring sustainable resource use [3].

Although DPPs and Autonomous Factories have emerged from different contexts, they are now converging. Both rely on digitization, structured data, and intelligent (interoperable) system design. Both promise increased efficiency, reduced waste, and a more sustainable, strategically independent industrial future. Yet despite their shared goals, development often proceeds in isolation, risking duplication, misalignment, and missed opportunities.

This paper examines how DPPs and Autonomous Factories can reinforce one another. Drawing on ongoing research and applied work, we clarify their synergies, highlight open challenges, and propose directions to accelerate informed development. Section 5 outlines emerging trends and critical gaps. We then discuss how convergence can be advanced through pragmatic validation and strategic alignment, before concluding with recommendations for policymakers, industry, and researchers.

2. Background

DPPs are motivated by sustainability efforts and legislation such as the *Ecodesign for Sustainable Products Regulation* (ESPR) [2] or Green Deal [4]. On the other hand, Autonomous Factories are needed to keep European Industry globally competitive [5]. At first glance it appears these two developments are competing with each other, by forcing companies to pick either transparency, or efficiency. However, in this paper we argue that they can also strengthen each other: With DPPs informing Autonomous Factories and Autonomous Factories logging its data in DPPs. In this section we will first provide background on the three main concepts of this paper: DPPs, Autonomous Factories, and interoperability. How these combine will be described in the following sections.

2.1. Digital Product Passports

In the ESPR, DPPs are defined as: “a set of data specific to a product that includes the information specified in the applicable delegated act, and that is accessible via electronic means through a data carrier” [2]. It will depend on the product whether a DPP “should be specific to the item, batch or product model” [2]. Meaning that a pair of jeans might have a DPP unique to its batch and an electric car might have a unique DPP for each individual car. More information on the specific information they contain can be found in Section 3.1.

DPPs have been developed primarily to support sustainability and circular economy initiatives, particularly within the European Union [2, 6]. They bring transparency to supply chains because DPPs must be accessible and shareable between different platforms. This allows for insight into where products come from, what they are made of, and how they impact the environment. Some research also points to making Causal AI-powered DPPs, which are also able to give insight into key performance indicators (KPIs) [7].

While the primary motivation for DPPs is environmental sustainability, their implementation also addresses key geopolitical considerations. Ongoing wars and conflicts highlight the urgency of resource independence in Europe and the importance of long-term resilience. By enhancing supply chain transparency, DPPs also reduce dependence on critical raw materials from unstable regions, mitigating supply risks [8, 3]. Additionally, they help ensure compliance with international trade regulations and standards, fostering more stable and predictable trade relationships.

Within the manufacturing sector, DPPs can be the key for supporting circularity and sustainability. It can bring a variety of benefits to industry, improving not only internal processes and traceability, but also supply chain transparency [9] and production time reduction [10]. DPPs can be the way to digitalize product information [11] or be used for production control input [12]. Haase et al. [13] look at DPP services as a product, which has to create value for company, market and users. New services must align with the purpose of the company, boost its competitiveness and

impact, and solve long-lasting issues for customers (see Figure 2 of [13]). In support of that Götz et al. [11] discuss that DPPs are not only one of the key solutions to support circularity, but can also enable new business models and optimization strategies.

However, implementing DPPs into existing systems can still be a challenge. Within industry, metamodels such as the Asset Administration Shell (AAS) [14] are used to gather key information about different assets on the production floor. Jung et al. propose to use the AAS structure for development of DPP submodels, which can extract production data directly from established manufacturing systems [15].

Another question is the type of information that a DPP must contain as it follows a product, as this is not yet clearly defined [16, 10]. Psarommatis and May identify seven broader categories in the context of modern manufacturing: material, circularity, maintenance, environmental, manufacturing, value network, and end user [9]. Alternatively Stratmann et al. identify four categories: product, utilization, value-chain, and sustainability [17].

2.2. DPPs: Current Developments

Current DPP developments focus on the design, development, standardization, and implementation of interoperable DPP system, which can ensure legal compliance, create a secure reliable ecosystem and guarantee the expected business and legislative value. Some of the major drivers of these developments are the European standardization initiative by CEN/CENELEC in JTC24, and large scale European CIRPASS2 project, where user-stories [18], reference architectures [19], foundational frameworks, systems and definitions are being developed, which are going to shape the DPP future. Current developments are aimed primarily at keeping the DPP system open for various technologies, and able to scale across domains and sectors, while standardizing and locking down enough aspects to ensure interoperability. However, as of the moment of writing this work, most of the work is in development, but not yet released and implemented. Additionally, tools, applications and other solutions providing DPPs are still ramping up in numbers and capabilities.

2.3. Autonomous Factories

The current industry innovation is advancing towards autonomy. More specifically, more and more jobs within a factory are aimed to move from manual to automated execution, handing more responsibility to systems. The new capabilities that a factory gets, often referred to as self-X, are focused on what a system can do on its own and create a new set of requirements for systems. Starting from automation, in the context of Industry 4.0 (the new industrial revolution happening right now), factories are advancing toward semi-autonomous and fully autonomous systems [20]. A system is considered fully autonomous when it can operate without the need of human intervention or interaction and is able to take decisions on its own. The need for this high level of system control is dictated by the overall goals of factories: to increase productivity while decreasing the required effort, all while dealing with challenges such as product complexity, personnel shortage, and more [5]. However, achieving this goal is far from straight forward, as it requires not only aligning between different innovation focuses (technology, ecosystem and business model), but also collaboration with various stakeholders [21]. AI is a promising solution, which can bring a lot of benefits to a factory, but at the same time faces challenges such as data availability and data security [22] among others. This is what makes availability of information in the correct standardized shape so critical, as its lack can have significant negative effect [23].

2.4. Autonomous Factories: Current Developments

Autonomous Factory development has seen steady progress over recent years. Although full autonomy is still out of reach for many manufacturers, significant advances are being made in factory equipment interoperability, integration of OT (Operational Technology) and IT (Information Technology) systems, use of intelligent decision-making, and modeling tools. Projects like the Dutch *Next Gen High Tech* (<https://nxtgenhightech.nl/en/>) initiative showcase collaborative efforts between academia and industry to push these frontiers forward, focusing on use cases that enable smart, self-adapting, and digitally integrated manufacturing operations. What can be observed is that autonomy, while broadly considered important, is a goal which is complicated, ambiguous and overall too massive to achieve at a single step. Most current generally adopted solutions and applications still focus on creating digital and

smart solutions and have yet to push towards autonomous. Nevertheless, industry has been busy with innovating and actively developing standards, frameworks and solutions.

2.5. Interoperability: the Intersection of DPPs and Autonomous Factories

While DPPs and Autonomous Factories are advancing along seemingly separate trajectories, both hinge on one critical capability: interoperability. Without interoperable data, systems, processes, the benefits, and adoption can significantly diminish. While there is plenty of literature on the timeless topic of interoperability, there is little up-to-date research on Autonomous Factories, likely due to industries perceiving expertise on this topic as a company secret. On the topic of DPPs and traceability systems in general there is research. However, this is often not able to stay relevant for long with the quickly developing legal, technical and organizational landscape. As such, it proves difficult to find up-to-date research on the combination between DPPs and Autonomous Factories.

In the context of DPPs, “*manufacturers are the most important source of product information*” [16]. A DPP follows a product throughout its complete lifecycle, from design phase to end-of-life. During that process it passes through many different stakeholders, all of which operate in different environments. For this process to be effective, DPPs must be interoperable (among other requirements such as accessibility, stability and more specified in Table 1 of [24]) in order to communicate across systems, comply with regulations, ensure data integrity, and be understood by diverse stakeholders. This is not just a technical need, it is also a strategic one. The Draghi Report on European Competitiveness [1] highlights that fragmented digital infrastructures and data silos are holding back innovation, efficiency, and trust across European industries. To remain globally competitive, Europe must streamline how systems and stakeholders interact.

At the same time, Autonomous Factories relay on seamless integration of different technologies across machines from different vendors, legacy and new systems, external services and supply-chain ecosystem. If all of those systems are unable to properly connect to each other and understand the context, then autonomy breaks down. Moreover, for autonomy, there is a need for complete, product-specific information, data that could be supplied by a DPP if made available in a usable, semantic, and machine-readable format.

More specifically, DPPs can help manufacturing industries in more ways than one. The legislation on machine safety requires that specific information, such as manuals and certifications, be made available [25]. This can be achieved by making this information part of the DPP of the machines. To highlight the importance of this, the following two sections dive into why and how this importance manifests.

3. DPPs as a Foundation for Autonomy

Before discussing how DPPs can support various functions within an Autonomous Factory, it is important to first understand what a DPP typically contains in the manufacturing context.

3.1. DPP content

The exact content of a DPP remains an evolving area of research, as legislation and standards are still being developed. Adoption itself is in its infancy stage, providing little guidance. While in sectors such as batteries there are already more concrete guidelines [26], other industries lack this. Therefore, due to the diversity of product types, domains, intended use cases and lack of established specifics, it is more appropriate to consider general categories of DPP content rather than define specific data schema at this point of research.

Several types of information can justifiably belong in a DPP, depending on the specific context and influencing factors (see Figure 1). Unlike the work of [17] or [9], which focuses on concrete content categorization of information, we take a different approach focusing instead on the way the data would be used. We consider three broader categories (1) Legally Required, (2) Essential, and (3) Future-Useful. This differentiation is not focused on the data based on its type (e.g. circularity, environmental, material), but instead looks at its purpose and requirements. We consider whether the data **must** be there by law, can be there due to value or should be there based on potential future benefits it can bring.

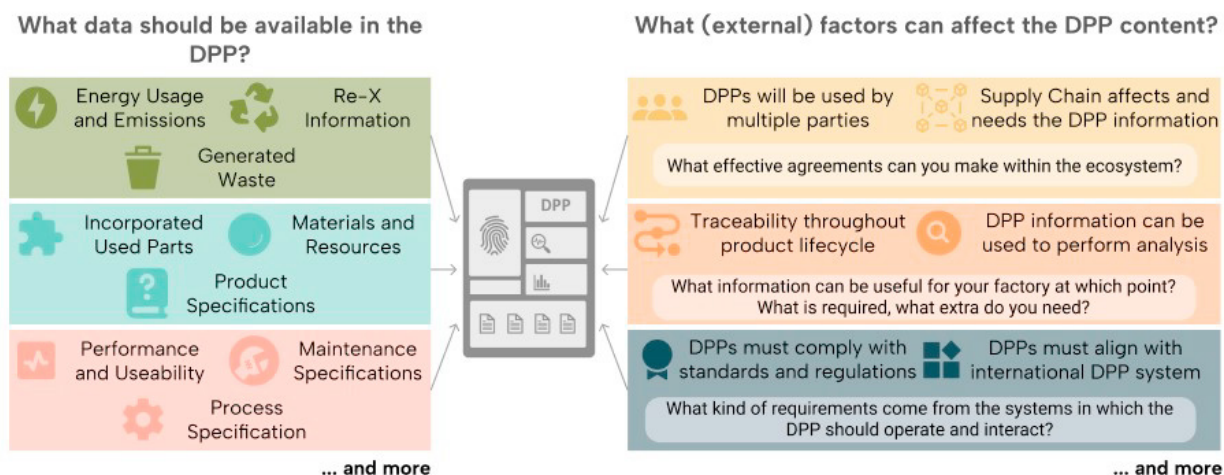


Fig. 1. Example of DPP content. The left side of the figure shows types of information, following guidelines in [2], while the right side lists relevant factors that can influence DPP content.

Legally Required Information in DPPs. As discussed in Section 2.1, various regulations relevant to DPPs are emerging or being finalized. For manufacturers, this includes legislation such as the ESPR [2], which outlines mandatory data requirements including material composition, energy efficiency, and carbon footprint. Manufacturing-specific regulations like the Battery Regulation [27] require even more targeted disclosures, such as raw material sourcing or hazardous content. While some frameworks remain under development or show inconsistencies.

Essential Information for DPPs. In the manufacturing context, essential DPP information extends beyond legal requirements to include data critical for efficient production, automation, and quality assurance. This encompasses process parameters, component specifications, supplier certifications, and part traceability. Manufacturers increasingly rely on standardized data models. For example the Battery Pass data model [27] or Asset Administration Shell (AAS) submodels [14] to harmonize data flows across factories and supply chains. Including this data in DPPs facilitates automated configuration, digital twins, and system-wide interoperability, all vital for enabling autonomous factory operations.

Future-Useful Information in DPPs. Manufacturers also benefit from including data in DPPs—data that supports future use cases such as predictive maintenance, remanufacturing, and aftermarket services. For example, storing machine-readable repair instructions, performance logs, or lifecycle events enables autonomous systems to make informed decisions about disassembly, part reuse, or recycling. However, overloading the DPP with excess data can hinder adoption and complicate integration. Manufacturers must therefore consider future use cases and the associated data needed. Potentially including cryptographically secure elements like Decentralized Identifiers (DIDs) to enable secure data transactions and ensure access control.

3.2. DPPs in Autonomous Factory

While DPPs are originally intended to support traceability and regulatory compliance, their value within Autonomous Factories extends significantly beyond that. In these environments, DPPs can function as information carriers, semantic enablers, quality and compliance facilitators, lifecycle trackers, and more. To illustrate this added value, we describe, in this subsection, how DPPs can be used in the broader context of autonomy.

At the core of an Autonomous Factory lies the seamless flow of accessible, understandable, standardized information across different processes, systems and machines. One can consider four stages, which encapsulate the reasoning processes: (1) connect, (2) understand, (3) reason, and (4) act. At each stage, DPPs can act as facilitators, as shown in Figure 2. They can enable standardized data transfer, providing real-time access to relevant product details (e.g., for robotic configuration or AI-based decisions), and supporting modular manufacturing cells where machines recognize new components instantly.

Information carrier. At the first step a DPP is not just a passive documentation, which is required by law. It can instead be actively used to transfer needed information between different processes (within and outside the borders of the factory). Here the DPP can be a central point for information that is critical to understanding a product and a process.

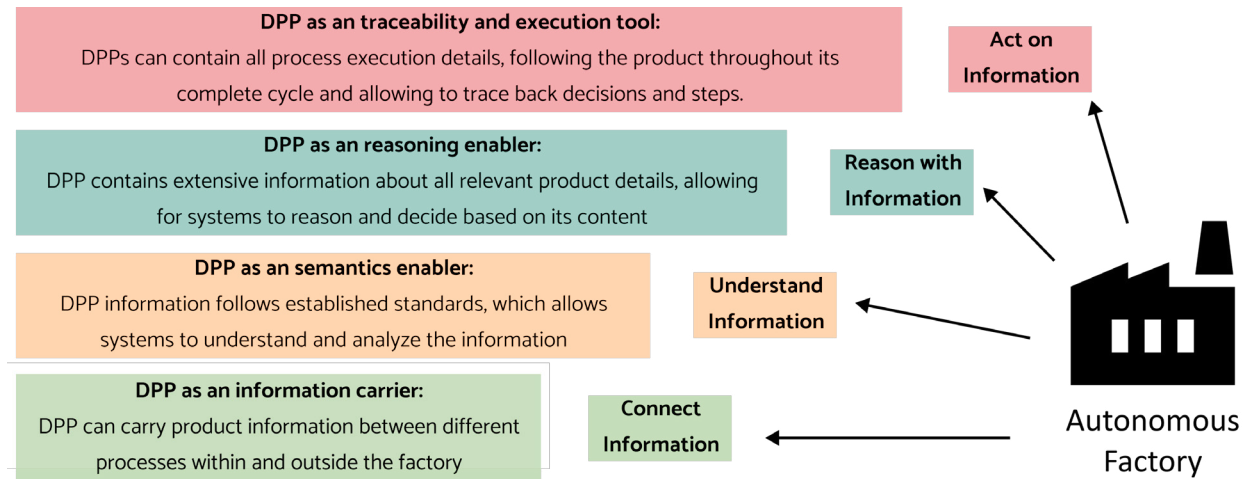


Fig. 2. The process within an autonomous factory can be seen as one following four main steps regarding information - (1) connect, (2) understand, (3) reason, (4) act. For every step the DPP can play a critical role, enabling a particular functionality.

Semantic Enabler. Once information is available, a system needs to also be able to understand it. Here the implementation of DPPs can contribute to achieving semantic interoperability. Semantics is essential in an Autonomous Factory, as it helps make factory operations understandable through a unified common metamodel. Though still maturing, semantic frameworks are vital for enabling plug-and-play production systems. Implementing DPPs can support this through their underlying usage and connection to ontologies, standard data models, and shared vocabularies, thereby fostering interoperability across platforms and enabling deeper factory integration.

Reasoning Enabler. An Autonomous Factory needs to be able to make decisions about different processes and tasks within its production. This requires access to sufficiently detailed and reliable information regarding a product. This can for example be specifics about the product composition, previous manufacturing steps, regulatory and certification records, quality specifications, and more. In this context DPPs are an enabler of reasoning, as they carry the different types of information about a product. An Autonomous Factory can access all that information and use it to reason and determine next actions. As machines gain access to structured compliance information, they can take proactive steps in validation and reporting, reducing the need for manual intervention, perform root-cause analysis, adapt.

Traceability and Execution Tool. The DPPs add value across the entire product life-cycle. They track every step of the production process and record any relevant information. This can be at different moments of the product life-cycle, from product creation, to maintenance, to steps such as re-manufacturing, repair, recycling (or the rest of the ReX processes [28]). In all those steps, autonomous decision-making relies on sufficient and complete product information. Here, DPPs can provide data on material composition, usage, lifetime performance, previous repairs, which may be crucial in determining how to execute a concrete production step. Or a DPP can be used as the tool to record any performed changes on the product. It can support processes such as Causal AI [7]. This information enables autonomous systems to determine end-of-life actions independently, supporting circular economy goals and enhancing long-term operational efficiency.

4. The Loop Between DPPs and the Autonomous Factory

DPPs and Autonomous Factories form a bi-directional relationship: what one needs, the other can provide. This reciprocity creates a loop of increasing efficiency, transparency, and scalability (Figure 3). To make this dynamic clear, it is useful to consider the needs and contributions of each.

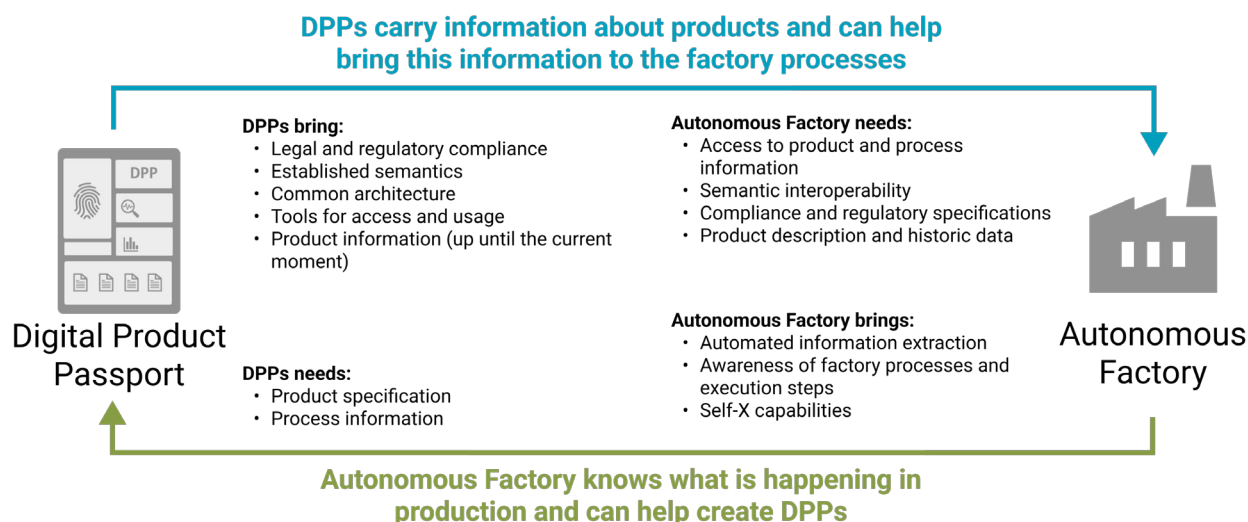


Fig. 3. The bi-directional relationship between DPPs and Autonomous Factories. Each concept provides what the other requires: DPPs contribute standardized, machine-readable product information that Autonomous Factories need for autonomous decision-making, while Autonomous Factories generate reliable, granular operational data that DPPs require to deliver value. This reciprocity creates a reinforcing loop in which DPPs enable autonomy and Autonomous Factories scale the creation and use of DPPs.

On the DPP side, the main contribution is structured, machine-readable, and standardized data. This digital continuity allows autonomous systems to understand what they are working with and to make informed, data-driven decisions. At the same time, DPPs themselves need reliable, timely, and granular product information, data that is difficult to obtain manually at scale. On the Autonomous Factory side, the primary contribution is autonomous data generation. With advanced monitoring, logging, and decision-making capabilities, Autonomous Factories can capture and feed operational data directly into DPPs. This makes compliance more scalable, reduces administrative burden, and improves consistency. Yet Autonomous Factories in turn need trustworthy product and lifecycle data, something DPPs are uniquely designed to provide.

The logic of this autonomy-DPP loop, shown in Figure 3, is straightforward:

- **Autonomy requires context.** Machines can only act intelligently if they know the material, component, or product they are dealing with. DPPs provide that context.
- **DPPs require data.** Information must be generated, updated, and verified at scale. Autonomous Factories provide that data through embedded sensing, processing, and actuation.
- **Integration yields reinforcement.** The more factories operate autonomously, the more complete and accurate DPPs become. The richer the DPPs, the more effectively factories can operate with minimal human intervention.

An example for how this loop can work is re-X. When a product returns to the factory, it carries a DPP containing information about its usage and condition. The Autonomous Factory can then inspect the product and decide on the appropriate next step. Any processes executed (e.g. repair, reuse, refurbish, or remanufacture) are recorded back into the DPP of the product or its resulting sub-products. In this way, the DPP provides the reliable data needed for autonomous decision-making, while the factory in turn updates the DPP with accurate, up-to-date information.

Beyond the production floor, this loop extends into administrative domains. As Autonomous Factories blur the line between shop floor and back office, DPPs can act as living records across customer, legal, and internal processes. In doing so, they not only enable compliance but also strengthen integration, interoperability, and business value.

Together, these dynamics show that DPPs and Autonomous Factories are not parallel developments but complementary ones. Each supplies what the other lacks: DPPs bring standardized information to autonomy, while Autonomous Factories bring scalable information generation to DPPs.

5. Emerging Trends and Developments

The concepts of DPPs and Autonomous Factories are evolving rapidly, shaped by technological, regulatory, and organizational developments. While originating from different domains, both are converging toward shared goals through interoperable technologies. Their potential contribution to sustainable manufacturing—economic, social, and environmental—echoes the challenges outlined in the Draghi report [1]. Yet, both remain in early stages of maturity. This section outlines the main open challenges and the steps being taken to address them.

5.1. Open Issues and Challenges

Despite current momentum, several gaps remain. As described in Section 2.2 and 2.4, existing efforts are largely isolated. This risks creating point solutions that solve short-term needs, but are difficult to scale or integrate once convergence becomes necessary.

Most Autonomous Factory innovation is disconnected from DPP development. While factories focus on IT–OT integration, the DPP push introduces a third layer, the supply chain environment, which is seldom considered. Unless addressed early, this added layer will intensify interoperability challenges.

Another issue is the standardization gap. Systems are being designed against incomplete, shifting, or conflicting requirements. Without common reference points, responsibilities blur, and solutions risk obsolescence. Because both DPPs and Autonomous Factories demand collaboration across multiple stakeholders, piecemeal developments built in isolation are unlikely to connect smoothly to future standardized infrastructures.

Finally, security concerns are critical. DPPs, especially beyond minimal compliance, may contain sensitive or business-critical information. Autonomous Factories could benefit from such data internally, but external sharing raises IP and cybersecurity risks. The key challenge is striking the balance: determining what information should be shared, with whom, and under which safeguards.

5.2. Immediate Business Impacts and Business validation

Given the lack of established solutions, evolving requirements, and the absence of complete regulatory frameworks, an important first step is to identify suitable entry points for DPPs. Rather than developing isolated tools in a vacuum, a more promising strategy is to start from business needs and processes, ideally in collaboration with key value-chain partners or sectoral initiatives. This is the approach currently being explored in the Dutch national program NextGenHighTech (<https://nxtgenhightech.nl/en/>), where DPPs are explicitly considered in relation to the autonomous factory, with the aim of examining and validating their potential interconnection.

Manufacturers are beginning to assess how their operations might be influenced by the broader transition toward a circular and environmentally sustainable economy. For instance in the Rob4Green project (<https://rob4green-project.eu/>) it will be explored how DPPs can help enable performing certain tasks and decisions autonomously. Similarly, companies are starting to investigate how upcoming regulations could affect their activities and what role DPPs might play in supporting or transforming internal processes, not only for compliance, but also for creating added value. Early experimentation, such as those taking place in TNO's Remanufacturing Lab (<https://www.tno.nl/en/technology-science/facilities/remanufacturing-lab-test-experimentation/>), seeks to provide first insights into how DPPs might contribute to circular practices, while supporting manufacturing innovation.

It is equally important to begin exploring where, across the value chain, DPPs could provide shared benefits, particularly in connection with other ongoing innovations. Organizations can also identify existing gaps or inefficiencies that DPPs might address and consider which functionalities could be most relevant to enhance performance, compliance, or integration with emerging autonomous production capabilities.

By following such a pragmatic, partnership-driven approach (focused on early exploration and validation of real business cases) organizations can reduce risk, ensure relevance, and incrementally build readiness for the eventual convergence of DPPs and Autonomous Factories.

While current initiatives provide only partial insights and remain exploratory in nature, they represent important first steps toward understanding how DPPs and autonomous manufacturing might reinforce one another. Our contribution lies in formalizing these early explorations into a structured research pathway. By mapping where projects are beginning to address the overlap, and by identifying where critical gaps remain, we provide a foundation for systematic investigation. This creates a starting point for reflecting on the broader industrial, regulatory, and strategic implications of aligning these two trajectories.

6. Discussion

This work explored the intersection of two major development trends: DPPs and Autonomous Factories. Although they arise from different domains, both fundamentally depend on accessible, reliable, and interoperable information.

They are also driven by common external pressures—regulatory requirements, sustainability goals, and competitiveness. As policymakers mandate DPP infrastructures and manufacturers pursue smart and autonomous production, aligning these efforts becomes both logical and economically prudent. At the same time, manufacturers are under increasing pressure to stay competitive, seeking efficiency, flexibility, and future-readiness through investments in smart and autonomous production capabilities. Given that both DPP implementation and autonomous system development demand substantial resources, it is in the best interest of industry to explore how these initiatives can intersect and reinforce each other.

Therefore DPPs should not be seen merely as compliance tools, but as enablers of autonomy. They introduce organizations to the standards and architectures that Autonomous Factories will require, while also supporting lifecycle intelligence across production, remanufacturing, and recycling. Conversely, autonomous systems can leverage DPPs to improve efficiency and circularity. Early studies, such as that by Szaller et al. [10], already point to such benefits in remanufacturing.

The convergence of these trajectories has wider implications. Policymakers should target sectors with the greatest potential for joint adoption, aligning DPP legislation with digitalization and sustainability strategies. For industry, investments in DPPs should be framed not as overhead but as a pathway to competitiveness, innovation, and resilience.

With coordinated action, DPPs can catalyze more than compliance. They can accelerate the digital evolution of industrial ecosystems and lay the foundation for the broader realization of Autonomous Factories. In short, DPPs and Autonomous Factories—though emerging from different domains—share a reliance on interoperable, trustworthy digital information and are driven by the same regulatory and competitive pressures. DPPs should be seen as enablers of autonomy, while autonomy can amplify the value of DPPs. Aligning regulation and industrial strategy can transform compliance into innovation, positioning both technologies as mutually reinforcing pathways toward sustainable and resilient manufacturing.

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