A Design Study for Interoperable Digital Product Passports: Embedding UNTP Semantics in AAS Submodels*

Giray Havur[1,2,*], Tassilo Pellegrini[1], Gottfried Schenner[2] and Francesco Fusco[2]

[1]Fachhochschule St. Pölten, Campus-Platz 1, 3100 St. Pölten, Austria
[2]Siemens AG Österreich, Siemensstraße 90, 1210 Wien, Austria

Abstract

The proliferation of Digital Product Passports (DPP), driven by regulatory demands for sustainability, faces significant challenges from semantic fragmentation. This paper proposes a novel approach to achieve global semantic interoperability by embedding UN/CEFACT Transparency Protocol (UNTP) semantics as a submodel within the Asset Administration Shell (AAS). The AAS provides a robust technical vehicle, while UNTP offers a sector-agnostic, internationally recognized semantic base. We formalize how UNTP DPP semantics can be structured as an AAS submodel, illustrate its potential for cross-sector interoperability, and contextualize sector-specific ecosystems as downstream applications. This alignment aims to create a scalable and coherent foundation for DPPs, with the aim of mitigating duplicate efforts. The paper explores architectural implications, integration with data spaces, and synergies with existing standards.

Keywords

Digital Product Passport, Asset Administration Shell, UN/CEFACT, UNTP, Semantic Interoperability, Industry 4.0, Digital Twin, Circular Economy, Sustainability, Standardization

1. Introduction

The global shift towards sustainability has made Digital Product Passports (DPP) a crucial component of industrial policy and regulation, such as the EU's Ecodesign for Sustainable Products Regulation (ESPR) [1]. DPPs are structured digital records that capture essential product data throughout its lifecycle, intended to provide machine-readable, transparent, and verifiable information [2]. However, the rapid emergence of competing DPP frameworks (e.g. UNTP [3], EU DPP, Catena-X [4], DPP4.0 [5]) is causing semantic fragmentation, which threatens to silo product data and weaken the global utility of DPPs [6].

To address this, we propose a framework for global semantic interoperability by embedding the semantics of the UN Transparency Protocol (UNTP) [3] as a submodel within the Asset Administration Shell (AAS) [7]. The UN/CEFACT Core Component Library (CCL) provides a rich, harmonized, and internationally vetted vocabulary, making its UNTP specification an ideal semantic backbone for DPPs. The AAS, standardized as IEC 63278, offers a modular and extensible digital twin framework that is well suited to manage product lifecycle data. This approach avoids data duplication, promotes regulatory alignment, and establishes a sector-neutral backbone for DPP adoption. We formalize this integration, explore its architectural implications and present an illustrative use case from the ECO-TCO project [8] to demonstrate its practical benefits.

The remainder of this paper reviews the relevant background on DPPs and related standards (Section 2), details the proposed UNTP-AAS integration (Section 3), illustrates its application with a use case (Section 4), discusses key challenges (Section 5), and summarizes our findings and outlines future directions (Section 6).

Posters, Demos, Workshops, and Tutorials of the 21st International Conference on Semantic Systems (SEMANTiCS 2025)„ co-located with SEMANTiCS'25: International Conference on Semantic Systems, September 3–5, 2025, Vienna, Austria

*This work has been partially funded by the Austrian Research Promotion Agency (FFG) under the project grants FO999915294 (ECO-TCO).

*Corresponding author.

giray.havur@fhstp.ac.at (G. Havur); tassilo.pellegrini@fhstp.ac.at (T. Pellegrini); gottfried.schenner@siemens.com (G. Schenner); francesco.fusco@siemens.com (F. Fusco)

0000-0002-6898-6166 (G. Havur); 0000-0002-0795-0661 (T. Pellegrini); 0000-0003-0096-6780 (G. Schenner)

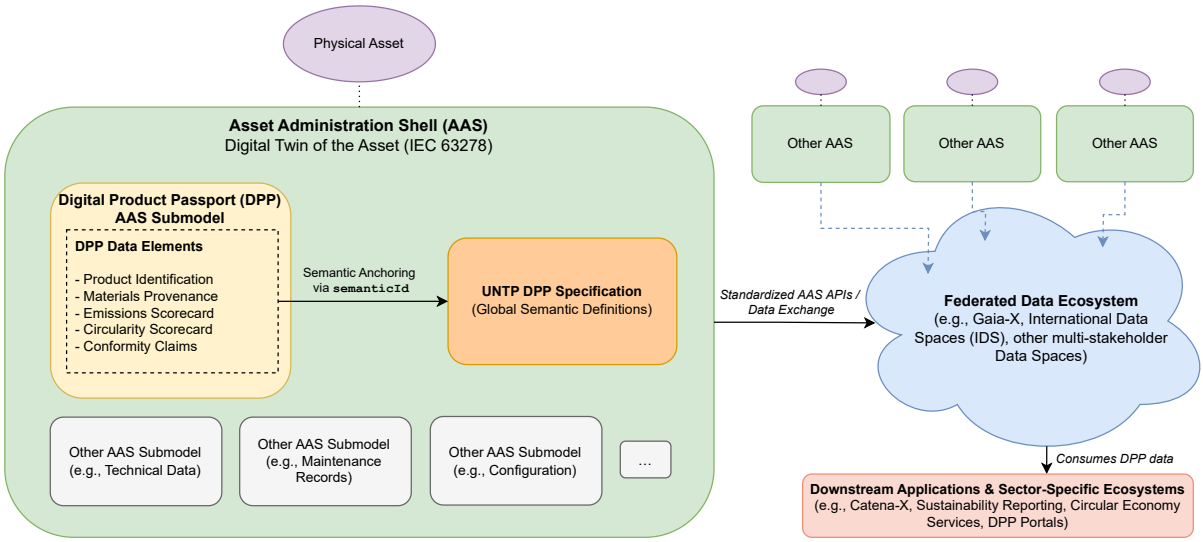

Figure 1: Conceptual Integration of a UNTP-Anchored Digital Product Passport (DPP) within the Asset Administration Shell (AAS) and a Federated Data Ecosystem.

2. Background and Related Work

DPPs are evolving into regulatory requirements under policies like the ESPR, which mandate them for products such as batteries, electronics, and textiles. DPPs must support unique product identification, standardized data structures, lifecycle data management, and robust access control [3]. The key challenge remains the heterogeneity of emerging initiatives, which risks creating "semantic silos"[6].

Several architectures exist for product information. *GS1 EPCIS 2.0* focuses on event-based traceability, while the EU's *EPREL* database supports energy labeling but lacks an open ontology. The *Asset Administration Shell (AAS)*, a de facto standard in Industrie 4.0, provides a modular framework for the representation of digital assets. A crucial feature of AAS is its ability to link every element of the data to an external semantic definition via a globally unique `semanticId`, ensuring data can be correctly interpreted between systems [6]. This mechanism is central to our proposal.

Large-scale data space initiatives like the sector-agnostic *Gaia-X* [9] and the automotive-focused *Catena-X* [10] leverage AAS but often rely on domain-specific semantic models, which can create interoperability barriers. Similarly, the *DPP4.0* initiative [5] uses AAS, but has not yet detailed a comprehensive open semantic layer beyond existing standards like ECLASS.

This highlights the need for a neutral and globally harmonized semantic foundation. The *UN/CEFACT Transparency Protocol (UNTP)* is designed to fill this gap. Based on the UN/CEFACT CCL, the UNTP DPP specification defines a lightweight structured model for B2B data exchange, focusing on product identification, provenance, emissions, circularity, and conformity claims [3]. Positioned as an upstream B2B data source, the UNTP model can provide a consistent and verifiable data foundation for diverse downstream applications and regional DPP systems [2].

3. Embedding UNTP Semantics into AAS Submodels for DPPs

We propose operationalizing the UNTP-AAS integration through a dedicated AAS Submodel Template for DPPs in Figure 1. The UNTP DPP specification [3] provides the harmonized semantic foundation, its elements serving as the definitive meaning of data points within an AAS. This is achieved by linking each AAS submodel element to its corresponding UNTP concept via the `semanticId` field, ensuring the data remain technically consistent and semantically interpretable between organizations and jurisdictions.

Table 1 illustrates how representative UNTP DPP data fields (i.e. product identification, materials provenance, and emissions data) can be mapped to AAS `Property` and

Table 1
Illustrative mapping of representative UNTP DPP elements to AAS submodel elements.

DPP Data Field	UNTP Concept (Source Element and URI)	AAS Element
Product Identification		
Product GTIN	From `Product.idValue` where scheme is "GTIN". URI: `<untp_vocab>/Product#idValue`	`Property`; `idShort`: "ProductGTIN"
Product Name	From `Product.name` URI: `<untp_vocab>/Product#name`	`Property`; `idShort`: "ProductName"
Materials Provenance		
Material Name	From `MaterialsProvenance.Material.name` URI: `<untp_vocab>/Material#name`	In `SMC` ("Materials"), `Property`; `idShort`: "MaterialName"
Mass Fraction	From `MaterialsProvenance.Material.massFraction` URI: `<untp_vocab>/Material#massFraction`	`Property`; `idShort`: "MassFraction"; Unit: %
Emissions Scorecard		
Carbon Footprint	From `EmissionsScorecard.carbonFootprint` URI: `<untp_vocab>/...#carbonFootprint`	`Property`; `idShort`: "CarbonFootprintValue"
PCF Standard	From `EmissionsScorecard.reportingStandard.name` URI: `<untp_vocab>/Standard#name`	`Property`; `idShort`: "PCFReportingStandard"

`SubmodelElementCollection` types from the AAS Metamodel v3.0.2 [7]. This creates a modular submodel that accurately represents complex DPP content with full semantic clarity. For true interoperability, the entire DPP submodel itself would also be anchored by a dedicated `semanticId` pointing to a standardized definition (e.g., a future IEC or IDTA specification), allowing systems to unambiguously identify the data structure as a UNTP-compliant passport.

This integration yields significant architectural advantages. By embedding DPP data natively within the digital twin, the information becomes an integral part of the asset's comprehensive digital representation, accessible via standardized AAS APIs. This approach complements emerging federated data space architectures such as Gaia-X, where the data space provides the identity and exchange infrastructure, while the AAS-based DPP supplies the standardized, semantically rich data payload. Furthermore, the framework is highly synergistic with other industrial standards. In joint architectures [11], OPC UA can serve as the connectivity layer for real-time operational data, ECLASS can provide detailed product classification, and AAS can act as the core structure for lifecycle data. Within this ecosystem, UNTP provides the globally neutral semantic layer that harmonizes these diverse information models for B2B trade and sustainability reporting.

4. Use Case: The ECO-TCO Project

The *ECO-TCO project* [8] aims to leverage DPP data to support sustainable product configuration and reduce environmental impacts for a Siemens "SITOP power supply line." A key challenge is integrating diverse data for Total Cost of Ownership (TCO), Environmental Product Declaration (EPD) and Product Environmental Footprint (PEF) analyses.

The proposed UNTP-AAS framework offers a structured solution to address the project's needs. An AAS serves as the central digital twin for the product, consolidating data from PLM, MES, and ERP systems into dedicated submodels. A specific DPP submodel, structured with UNTP semantics, provides standardized and verifiable sustainability data (e.g., recycled content, carbon footprint). This semantically harmonized data can then be reliably used in TCO calculations and EPD generation, improving data quality, reducing integration effort, and ensuring alignment with regulatory requirements, thus demonstrating that a common semantic layer is not merely a convenience but a prerequisite for automating such complex, cross-domain sustainability analyses. The project serves as a compelling example of how standardized DPPs can deliver tangible business and environmental value.

5. Discussion

The vision of globally interoperable DPPs based on UNTP and AAS is promising, but requires navigating several interconnected challenges. On a *semantic level*, a primary task is to bridge the conceptual differences between UN/CEFACT's origins in static trade data and the dynamic, event-driven nature of digital twins. To avoid being perceived as a *competing standard*, the strategy must emphasize its role as a harmonization layer, providing authoritative mappings or 'crosswalks' to established domain-specific models like GS1 and ECLASS, rather than seeking to replace them. This approach is exemplified by the joint architectures mentioned earlier, where UNTP provides the neutral semantic layer that connects and adds value to established standards like ECLASS and OPC UA. A potential mitigation is to develop collaborative "semantic profiles" and clearly position UNTP as a foundational B2B data layer that feeds more dynamic, consumer-facing DPP applications. On a *technical level*, the lack of large-scale implementations and the perceived complexity of AAS and semantic technologies, especially for SMEs [12], are significant obstacles. Overcoming these requires intensifying pilot projects to demonstrate clear value and scalability, along with developing standardized submodel templates and open-source tooling (converters, validators) to lower the barrier to entry.

Beyond technical and semantic issues, the challenges of *governance and adoption* are paramount. A mismatch often exists between the agile development cycles required by industry and the more deliberate, consensus-driven pace of standards bodies like UN/CEFACT. Establishing formal liaisons and joint working groups can help align these timelines. A more critical challenge lies in ensuring robust data security, privacy, and granular access control for sensitive DPP information. This requires leveraging native AAS security features and aligning with established data space trust frameworks such as the International Data Spaces (IDS) model. Architectural design must explicitly incorporate privacy-by-design principles and mechanisms for intellectual property protection, compliant with legal frameworks like GDPR and the EU Data Act [13]. Finally, overcoming non-technical barriers, such as business reluctance to share data and the lack of clear incentives [6], requires clearly articulating value propositions, such as reduced compliance burdens and new service opportunities, and advocating for supportive policy drivers and financial incentives. Successfully navigating these interconnected challenges is fundamental to realizing the vision of a truly interoperable DPP ecosystem.

6. Conclusion

This paper argued that *the embedding of UNTP semantics within AAS submodels* offers a powerful and globally viable solution to the challenge of DPP interoperability. The result is a framework that is technically robust, semantically consistent, and capable of operating in various systems and jurisdictions.

Realizing this vision requires sustained collaborative action from all stakeholders. Key future steps include:

- **Finalizing Standards:** Accelerate the development and alignment of UNTP and AAS submodel templates through collaboration between UN/CEFACT, IDTA, ISO, and other standards bodies.
- **Developing Open-Source Tools:** Create accessible tools for converting, validating, and deploying UNTP-AAS DPPs to lower adoption barriers for SMEs.
- **Promoting Pilot Projects:** Launch cross-domain pilots based on initiatives like ECO-TCO to validate the architecture and demonstrate tangible benefits.
- **Strengthening Governance:** Develop robust data governance practices to address privacy, IP protection, and fine-grained access control, integrating legal frameworks such as the EU Data Act and the AI Act [14].

The achievement of a globally interoperable DPP ecosystem is a strategic imperative to advance sustainability and innovation. The synergistic approach presented here provides a clear and actionable path toward this goal.

Declaration on Generative AI: The author(s) have not employed any Generative AI tools.

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