# A Design Study on Embedding UNTP Semantics into AAS Submodels for Interoperable Digital Product Passports

Giray Havur*†, Tassilo Pellegrini*, Gottfried Schenner†, and Francesco Fusco†
*Fachhochschule St. Pölten, Campus-Platz 1, 3100 St. Pölten, Austria
†Siemens AG Österreich, Siemensstraße 90, 1210 Wien, Austria
Email: {giray.havur, tassilo.pellegrini}@fhstp.ac.at, {gottfried.schenner, francesco.fusco}@siemens.com

***Abstract*—The proliferation of Digital Product Passports (DPP), driven by regulatory demands for sustainability, faces significant challenges from semantic fragmentation. This position 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 offers a robust technical vehicle and UNTP a sector-agnostic, global semantic base. We formalize how UNTP DPP semantics can be structured as an AAS submodel and illustrate its potential for cross-sector interoperability. This alignment creates a scalable and coherent foundation for DPPs, mitigating duplicate efforts and exploring architectural implications, data space integration, and synergies with existing standards.**

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

## I. Introduction

The global shift towards sustainability has elevated Digital Product Passports (DPPs) to a crucial technical component in industrial policy and regulatory frameworks, such as the EU's Ecodesign for Sustainable Products Regulation (ESPR) [1]. DPPs function as structured digital records that accompany a product throughout its lifecycle, capturing essential information about its origin, composition, and environmental impact. Conceptually, they are both a dynamic data record and a standardized data infrastructure built to facilitate interoperability [2]. The goal is to equip stakeholders with machine-readable, transparent, and verifiable data, thereby driving sustainable business practices.

However, the rapidly expanding landscape of DPP initiatives is becoming increasingly fragmented at the semantic level [3]. A growing number of competing frameworks, including UNTP [4], the EU DPP, Gaia-X [5], Catena-X [6], and the "Digital Product Passport for Industry 4.0" (DPP4.0) [7], risk siloing valuable product information. This fragmentation could undermine the global utility of DPPs by obstructing cross-border trade, circularity, and regulatory coherence.

To address this, we propose a framework for global semantic interoperability by embedding the semantics of the UN Transparency Protocol (UNTP) [4] as a submodel within the Asset Administration Shell (AAS) [8]. 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. Our core contribution is a novel architectural pattern that combines the global, sector-neutral semantics of UNTP with the robust digital twin technology of the AAS. This approach promotes regulatory alignment and establishes a truly interoperable backbone for DPP adoption.

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## II. Background and Related Work

DPPs are evolving from concepts to regulatory mandates, driven by policies like the ESPR [1] and the EU Battery Regulation. These regulations require DPPs for a growing list of products, including batteries, electronics, textiles, and construction materials. According to ESPR, several key requirements must be met: unique product identification, standardized machine-readable data structures, comprehensive lifecycle data management, material provenance, environmental impact metrics, circularity information, and robust access control [4]. The heterogeneity of emerging initiatives remains a primary challenge, risking the creation of "semantic silos" [3].

Several related architectures for documenting product information exist, each with distinct trade-offs. *GS1 EPCIS 2.0* is a mature standard for supply chain visibility but is fundamentally event-centric, designed to answer "what, where, when, and why" for traceability events. While valuable, it is less suited for representing the holistic, state-based digital twin of a product that an AAS provides. In contrast, our approach uses the AAS to model the product's current state and historical properties, not just its logistics trail. The EU's *EPREL* database, while important for regulatory compliance in energy labeling, is a centralized system with a fixed schema and lacks an open, machine-interpretable ontology, limiting its extensibility and interoperability for broader DPP use cases.

The *Asset Administration Shell (AAS)*, a de facto standard in Industrie 4.0, provides a modular framework for creating digital representations of assets. Each AAS consists of a shell header and one or more modular submodels, which group specific aspects of the asset (e.g., technical data, sustainability

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metrics). Within submodels, data are represented through elements such as 'Properties', 'Files', and 'Collections'. Crucially, each AAS, submodel, and element can be linked to a globally unique semantic identifier (`semanticId`), typically an IRI referring to an external dictionary or ontology. This mechanism ensures data can be correctly interpreted across different systems [3] and is central to our proposal.

Large-scale data space initiatives like the sector-agnostic *Gaia-X* [5] and the automotive-focused *Catena-X* [6] leverage the AAS as a technical component. However, they primarily develop and rely on domain-specific semantic models (e.g., the Catena-X for the automotive sector). While highly effective within their respective domains, these models can create semantic silos, posing challenges for cross-sectoral interoperability, for instance, when an automotive component is repurposed in a different industry. Our proposal addresses this gap by positioning the sector-neutral UNTP as a foundational semantic layer, which can bridge these domain-specific models, rather than replacing them.

The *UN/CEFACT Transparency Protocol (UNTP)* is designed to fill this gap. While the UNTP specification is recent, its credibility and strength stem from its foundation in the UN/CEFACT Core Component Library (CCL), a globally recognized standard (ISO 15000-5) that has been developed over two decades and is widely used in international trade and e-business for harmonizing B2B data exchange. The UNTP DPP specification leverages this mature semantic library to define a lightweight, structured set of classes and properties for product data, typically represented in JSON-LD [4]. The UNTP model focuses on essential attributes such as product identification, issuer information, material provenance, production details, emissions and circularity scorecards, and conformity claims. Positioned as an upstream B2B data source, the UNTP model can provide a consistent and verifiable data foundation for downstream applications and regional DPP systems [2].

## III. Embedding UNTP Semantics into AAS Submodels for DPPs

We propose operationalizing the UNTP-AAS integration through a dedicated AAS Submodel Template for DPPs, as depicted conceptually in Fig. 1. The UNTP DPP specification [4] 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 that the data remain consistent and interpretable between organizations and jurisdictions. Table I illustrates how representative UNTP DPP data fields can be mapped to AAS element types from the AAS Metamodel v3.0.2 [8].

Listing 1 presents a simplified JSON example of an AAS property acting as a DPP data point. The 'semanticId' explicitly links the 'ProductGTIN' property to its definition in the UNTP vocabulary. This ensures any system capable of parsing an AAS can understand the precise meaning of this data element, regardless of its internal data model.

```
{
  "modelType": "Property",
  "idShort": "ProductGTIN",
  "value": "01234567890123",
  "semanticId": {
    "type": "ExternalReference",
    "keys": [{
        "type": "Property",
        "value": "https://uneca.org/untp-vocab/
    Product#idValue"
    }]
  }
}
```

Listing 1. Simplified JSON Snippet of an AAS-DPP Submodel Element with UNTP Semantics.

This integration offers several important benefits [3]. It enables global semantic interoperability, as UN/CEFACT's identifiers facilitate seamless data exchange. The architecture remains modular and extensible; the AAS framework supports dynamic updates, allowing the DPP to evolve as a *living document* throughout the product lifecycle. The framework also improves trust and verifiability through its alignment with technologies like W3C Verifiable Credentials and Digital Conformity Credentials (DCC) [4].

## IV. Architectural Integration and Synergies

This approach complements emerging federated data space architectures like Gaia-X and those built on the International Data Spaces (IDS) model. In this paradigm, the data space provides the federated identity, trust, and data exchange infrastructure, while the AAS-based DPP supplies the standardized, semantically rich data payload. A global DPP ecosystem will likely adopt a federated architecture where manufacturers host their own DPP data, while trusted registries support discovery and interoperability. The neutrality and global mandate of UN/CEFACT provide a trusted foundation for governance across different data spaces and regulatory jurisdictions.

The framework is highly synergistic with other industrial standards. In joint architectures, such as that proposed by CESMII, IDTA, the OPC Foundation, and ECLASS [9], each standard plays a distinct role. OPC UA can serve as the connectivity layer for streaming real-time operational technology (OT) data into AAS submodels, thus populating the DPP with up-to-date manufacturing information. ECLASS can provide deep, hierarchical product classification within the AAS structure. Within this ecosystem, UNTP provides the globally neutral semantic layer that harmonizes these diverse information models for B2B trade and sustainability reporting, acting as a bridge between different domains.

## V. Use Case: The ECO-TCO Project

The *ECO-TCO project* [10] is a nationally funded research initiative aiming to leverage DPP data to support circular production and sustainable product configuration. Focusing on a Siemens "SITOP power supply line," its key targets include improvements in eco-friendly product design, more accurate Environmental Product Declaration (EPD) metrics, comprehensive Total Cost of Ownership (TCO) analysis, and optimized pricing models informed by Product Environmental

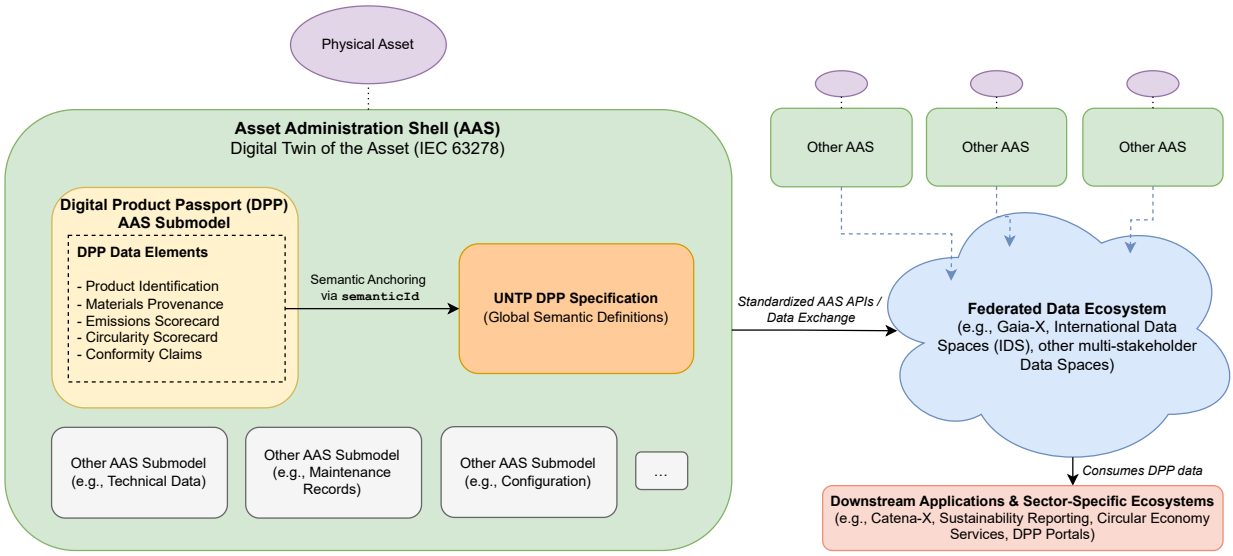


Fig. 1. Conceptual Integration of a UNTP-Anchored Digital Product Passport (DPP) within the Asset Administration Shell (AAS) and a Federated Data Ecosystem.

TABLE I
ILLUSTRATIVE MAPPING OF REPRESENTATIVE UNTP DPP ELEMENTS TO AAS SUBMODEL ELEMENTS

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

Footprint (PEF) data. A central challenge is integrating the diverse datasets required for these analyses.

The proposed UNTP-AAS framework offers a structured solution. 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. This semantically harmonized data can then be reliably used in TCO calculations and EPD generation. The framework's use of a common data model and standardized semantics directly improves data quality while lowering integration effort, thereby reducing ambiguity. This foundation of reliable data enables enhanced traceability of environmental impacts, which is essential for making informed "design for circularity" decisions. The project thus serves as a compelling example of how standardized DPPs can deliver tangible business and environmental value.

## VI. DISCUSSION

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. 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. To address gaps in the still-evolving UNTP specification, fallback vocabularies such as schema.org or relevant ISO standards can be used. Another semantic challenge is the perceived redundancy with established domain-specific models like ECLASS or GS1. The proposed approach does not aim to replace these but to use UNTP as a "lingua franca" for inter-

domain communication, focusing on mapping and alignment rather than substitution.

On a *technical level*, the lack of large-scale implementations and the perceived complexity of AAS and semantic technologies, especially for SMEs [11], 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 for businesses with limited technical resources.

Beyond technical and semantic issues, the challenges of *governance and adoption* are paramount. A mismatch often exists between the development cycles required by industry and the more deliberate, consensus-driven pace of standards bodies like UN/CEFACT. Establishing formal liaisons and working groups, such as the *ISO and UNECE Joint Initiative on Digital Product Passports*, can help align these timelines and ensure standards evolve to meet urgent industry needs.

Adoption is further hindered by non-technical barriers, such as business reluctance to share data, perceived costs, and the lack of clear incentives [3]. To mitigate this, it is crucial to clearly articulate value propositions, e.g., reduced compliance burdens and new circular economy service opportunities and to advocate for supportive policy drivers and financial incentives.

Finally, ensuring robust *data security, privacy, and granular access control* for sensitive DPP information is a critical challenge. Given the commercially sensitive nature of lifecycle data, a successful DPP ecosystem must be built on a foundation of trust. 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, mechanisms for intellectual property protection (e.g., using W3C Verifiable Credentials for selective disclosure), and fine-grained access control policies. This ensures compliance with legal frameworks like GDPR, the EU Data Act, and the EU Data Governance Act, allowing businesses to share necessary data within a trusted and regulated environment without compromising competitive advantages.

## VII. 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 across diverse systems, industries, and jurisdictions. By combining the strengths of an internationally recognized semantic standard (UNTP) with a mature digital twin technology (AAS), this approach provides a clear path to overcoming semantic fragmentation.

Realizing this vision requires sustained, collaborative action. Key future steps must include *finalizing standards* by accelerating the development and alignment of UNTP and AAS submodel templates through collaboration between UN/CEFACT, IDTA, ISO, and other standards bodies. Concurrently, the community must focus on *developing open-source tools* to create accessible converters, validators, and SDKs that lower adoption barriers, especially for SMEs. It is also vital to *promote pilot projects*, building on initiatives like ECO-TCO, to validate the architecture at scale and provide empirical evidence of its benefits. Finally, these technical efforts must be supported by *strengthening governance*, which involves developing robust data governance practices to address privacy, IP protection, and fine-grained access control, while integrating legal frameworks, e.g., the EU Data Act and the AI Act [12].

Achieving a globally interoperable DPP ecosystem is a strategic imperative to advance sustainability and innovation. The synergistic architectural pattern presented in this paper provides a promising and structured foundation toward this goal. While the proposal remains conceptual, it offers an actionable path for pilot projects and standardization efforts to build upon.

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