AAS/RDF Interoperability Approaches for DPP

A White Paper by the AAS/RDF Volunteer Cross-Project Work Group

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Abstract	The goal of this document is to support technological convergence between two data modelling frameworks, namely the AAS and the RDF frameworks, often cited in the context of European DPP implementation. The document explains the motivations behind this work and describes a number of initiatives working towards this goal, in support of innovation. The document ends with a number of recommendations. This document is the result of a large-scale collaboration between 17 projects and 32 researchers.
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Contents

1 Introduction

The Asset Administration Shell (AAS) is an international standard (IEC 63278) which can be used to define the characteristics and behavior of a digital twin. When complemented by additional specifications (e.g. IDTA Specifications) and references to controlled vocabularies, it is one of the approaches by which semantic interoperability can be achieved for Digital Product Passports (DPP). An alternative approach relies on well-established RDF-based (Resource Description Framework) methodologies for knowledge engineering and the Semantic Web (W3C) standards stack.

The goal of this work is to support technological convergence between these two approaches in a manner that does not lock out any technological options or specific approaches, and without over-burdening adopters of either approach, in order to support innovation. The authors also aim to explore how this complementary work can provide greater value to the DPP data modeling community and ecosystem, in particular through the extension of the formal knowledge engineering capabilities offered by RDF (including knowledge inference, automatic inconsistency detection and vocabulary alignments, etc.) to AAS-based data modeling flows.

Because of the large number of initiatives already addressing this topic, the goal of this paper is to provide an overview of the goals pursued by each team working on the subject, build a greater understanding of the current state of research and implementation, and, finally, provide an organised set of useful resources. For this reason, the resources provided below distinguish between approaches which mean to facilitate and exploit AAS-to-RDF conversion mechanisms and those which mean to facilitate and exploit RDF-to-AAS conversion mechanisms.

An important consideration in the DPP context is that the DPP itself should not be considered to be a fixed (and possibly standardised) block of data. To become an efficient tool for industry, a DPP should be extensible to possibly include regulated mandatory data, regulated optional data, and additional voluntary data. This additional voluntary data could be data that is meant to promote additional product features or data that is useful to industry ecosytem partners. Furthermore, the DPP data structure should quickly adapt to changes to the data elements that must or could be included in a DPP, to absorb changes to regulatory requirements or business needs, with no standardisation process bottleneck.

2 Why interoperability is needed for DPP

To understand why interoperability is such an important topic for the creation of the DPP, it is helpful to look at the ends DPP were conceived for in the first place and at the current situation especially in terms of digital development. Inter alia, the DPP was created to cater for the following purposes: tracing and tracking of products and raw materials, provision of information along value chains, e.g. to simplify reporting obligations through digital and automated access to relevant data sources, enable Circular Economy strategies and business models, support of customs and market surveillance efforts, informing procurement decisions e.g. of private end-consumers and public procurers, and many others.

A look at the current situation, however, exposes some significant challenges to creating such an interoperable DPP System. A non-exhaustive list of reasons is: Actors within the European industrial and digital landscape have varying preferences and in some cases vested interests in promoting one specific technology, the existence of legacy systems employing proprietary, local, IT systems that do not use any form of data sharing standards in companies, sectors or regions, which may also lead to missing data or information in other places, since those cannot be shared due to missing technical standards.

A further motivation for interoperability in the DPP context is remanufacturing, where largely manual and condition-based shopfloor operations involve frequent human interactions and continuously generate new records on product condition, component substitutions, process interventions, and final qualifications that must be reconciled with existing product information across multiple systems. Remanufacturers may also need to update passport information or generate new DPPs when remanufactured products are placed back on the market under applicable ESPR requirements. As EU circular economy policy increasingly promotes remanufacturing across additional product groups, diverse legacy systems and industry data standards will need to exchange data efficiently. Remanufacturing therefore highlights the need for scalable interoperability approaches within future DPP ecosystems.

All of the goals mentioned above rely on easy access to relevant information but the lack thereof or breaks in the chain of data transfer makes their fulfillment either unachievable or very expensive. Hence, they rely on data ecosystems where relevant data can flow interoperably at little or no cost. Furthermore, huge costs will result from lack of interoperability as a result of suppliers having to serve different technological systems in different sectors like providers of raw materials or chemicals. For others, the inability to receive data from or to provide data to non-interoperable targets could result in the inaccessibility of certain markets - a problem that is increased manifold if one considers that DPP are emerging also in other non-European areas of the world each at worst with their own underlying system and technical standards. Interoperability is therefore one of the most important technical features required to make the DPP a success.

The specific topic of interoperability in the DPP context is discussed in the following publications: Hbeich et al. (2025); Bernier and Hbeich (2026); Pourjafarian et al. (2025); Glachs et al. (2026); Ahmeti et al. (2026); Belova et al. (2025); Kebede et al. (2026); Li et al. (2025).

3 Reasons for AAS/RDF complementarity

In this section, we list a number of motivations for building interoperability between AAS and RDF data modeling approaches. This list of motivations builds upon the obvious motivation of reusing resources (e.g. applications and services) developed specifically for AAS or RDF data and the dual motivation of being able to provide data, e.g. in a Data Space, to data consumers in either representation.

In all cases, it is assumed that (explicit) semantic interoperability is fully enabled by references to controlled vocabularies that respect FAIR (Findable, Accessible, Interoperable, Reusable) principles.

3.1 General considerations

- **Ensure compliance to Data Act Article 35 (1)** European Union (2023). This article defines requirements for open interoperability specifications and harmonised standards to ensure the interoperability of data processing services. In the case of the DPP, this would e.g. concern the need to ensure portability of DPPs between different DPP service providers (DPPSP). Article 35 (1)a requires that the harmonised standards achieve, where technically feasible, interoperability between different data processing services that cover the same service type. (1)b requires that the standards enhance portability of digital assets between different data processing services that cover the same service type. (1)c requires that the standards facilitate, where technically feasible, functional equivalence between different data processing services that cover the same service type. And (1)e requires that the standards be designed in such a way so as to allow for technical advances and the inclusion of new functions and innovation in data processing services. The evaluation of these requirements is based on a number of proposed criteria including e.g."The specification shall define mechanisms or interfaces for automating the translation or mapping of data between heterogeneous semantic models to enable interoperability." Kroon et al. (2025) Thus, in order to ensure consistency between EU regulations (ESPR and Data Act), such mechanisms should be included in the standards currently being defined in CEN/CENELEC JTC-24.

3.2 Consume - RDF as input to AAS

- **Enriching AAS-based digital twin models with RDF-based DPP data:** The main goal of the AAS standard is to facilitate the interoperability between digital twins. The capability to consume RDF-modeled DPP data in the AAS digital twin modeling ecosystem would enrich this last.
- **Enrich AAS data with more context and concepts from existing RDF ontologies:** Expressing AAS data in RDF enables enriching it with additional semantic context. When connected to established, industry-standard ontologies and vocabularies (e.g. those listed on the LOV repository, elements are placed within a broader conceptual framework. As a result, semantic coherence is strengthened, and interoperability across domains is easier to achieve.
- **Enrich the AAS ecosystem with extensive domain and use-case specific RDF ontologies and vocabularies:** Domain-specific RDF/OWL ontologies can extend the AAS and DPP ecosystem by standardising entire verticals—such as after-sales service (ASS) — with FAIR, dereferenceable vocabularies. For example, the Verisav initiative provides three open vocabularies: a DPP vocabulary aligned with EU ESPR and UNTP, an RMA (Return Merchandise Authorization) vocabulary for return and service-ticket workflows, and a WTY (Warranty & Contracts) vocabulary for machine-readable warranties and payment automation. These ontologies are published with persistent URIs (W3ID), registered in LOV, and support JSON-LD and Turtle. By offering reusable semantic building blocks for specific use cases, such ontologies enrich the broader AAS/RDF landscape and support interoperability without locking adopters into a single modelling approach. Boutillier (2026),
- **Enable data virtualisation:** AAS data can be virtualised as RDF using declarative mappings to specified ontologies. This approach has the advantage that the data is not duplicated, i.e., the one source of truth is virtualised on demand. The virtualised data is exposed using SPARQL endpoints, where queries are translated back to original sources (e.g. SQL in RDBs), and can be used in conjunction or part of query federation. This concept of virtualisation in literature is often called "OBDA" (Ontology-based Data Access), where the ontology layer is not only used as a vocabulary to define (SPARQL) queries, but also to reason with (ontological) axioms and rules on top. The extension of OBDA with updates called "OBDM" (Ontology-based Data Management) is an approach that can be used to tackle the inverse problem of RDF-2-AAS, where updates orginated from the RDF 'semantic layer' are propagated back to the original sources (e.g. RDBs). The problem is akin to the *view updates* problem in the database theory, and can be employed typically when one-to-one, unambiguous mappings from sources to ontological terms are possible Lenzerini (2011).
- **Facilitate data fusion operations:** Economic Operators typically have multiple data sources for product-related data. These might be from incoming DPPs (modeled according to different standards), supply-chain related data and data from internal IT systems such as PIM, ERP, MES, PLM, etc. Each data source is typically based on different data models and implicit semantics, which contributes to fragmentation. By expressing data

according to a common RDF conceptualisation (thanks to the many available x-to-RDF transforms tools) and using explicit semantics, this data can be combined without creating semantic conflicts, resulting in fewer internal data silos. This helps create better cross-system interoperability for the Economic Operator.

3.3 Produce - RDF as output from AAS

- **Facilitate reuse of AAS submodel data in RDF data ecosystems:** To make it possible to reuse data from AAS submodels (or parts of it) in RDF data ecosystems, a "standardised" way to perform the "Semantic lifting" of data elements in an AAS submodel, assuming these are identified using Semantic IDs, is needed. Semantic lifting is often implemented differently across systems, yet inconsistencies persist even when the same vocabulary is used. Therefore, a more standardized transformation based on Semantic IDs is needed to make the mapping to RDF clearer and more reproducible.
- **Optimise expanded AAS serialisation file-size with JSON-LD:** Expanded AAS JSON serialisation offers users with the possibility to express explicit semantic references using Semantic IDs. However, this generates larger transmission files. Unfortunately, explicit references to vocabularies are lost in the optimised 'values-only' JSON serialization (this is called 'compressed' serialization in prEN 18223). These can be provided with a file size equivalent to compressed serialisations thanks to JSON-LD.
- **RDF packaging:** AAS can be a way to package RDF data together, for example to package several RDF graphs e.g. corresponding to the DPPs of the different components of the product. This could be done using the AAS Bill of Materials (BOM) submodel template which include property references to link to another component. (This assumes that the AAS specification must evolve to support JSON-LD serialisation.)
- **Facilitate AAS-to-UNTP and UNTP-to-AAS data transformations:** Within the DPP context, multiple modeling standards coexist and adhere to distinct modeling principles. As a result, transforming data between these models without automatic alignment mechanisms is both complex and error-prone. Representing both approaches in RDF enables the formal expression of correspondences between them. Consequently, concepts and properties can be aligned at the semantic level, making the automatic transformation more transparent and systematic. This process enhances interoperability between AAS and UNTP DPPs.
- **Leverage Solid Pods for the implementation of DPP data repositories:** Solid is an online file system that provides users with file-level read and edit control for access by people, applications, and AI agents. Users have personal online data stores called Pods. Solid applications can read and write documents directly from Pods under the user's control. All data in a Solid Pod is stored and accessed using standard, open, and interoperable data formats and protocols. As such, Solid can serve as a basis for conveniently sharing AAS-based DPPs, along with other Circular Economy Data. This approach is being pursued in the DACE project.

3.4 Process - RDF for data management within AAS

- **Facilitate the detection of semantic collisions for DPPs:** Some DPPs do not currently use explicit semantics which can lead to meaning and value type conflicts. Semantic lifting helps identify conflicts in DPP data that lack clear semantics. In many systems, data fields might look alike but have different meanings, units, or value types. These differences often go unnoticed when data stays within separate applications. By converting data to RDF and linking it to formal vocabularies, these conflicts become easier to spot. This way, mismatches in meaning and value types can be found and fixed earlier and more systematically.

- **Improve automatic processing capabilities for AAS submodel data:** A JSON-LD representation of AAS data facilitates a number of automatic data processing functions. These are described below (validation, reasoning, aligning, querying):

- **Enable automatic artifact generation and validation with SHACL:** Using RDF with the Shapes Constraint Language SHACL allows for advanced validation of AAS-based data, in particular to ensure compliance with an ESPR delegated act. AAS sets some structural rules, but many validation rules are still built into applications or specific implementations. With data in RDF, SHACL shapes can clearly define structure, value types, and conditional dependencies between properties. Keeping data and validation rules separate also makes it easier to reuse, share, and manage these rules across different systems and organizations. This is the approach taken by the Semantic Aspect Meta Model (SAMM), which provides SHACL shapes for schema validation. This can also help in the validation of DPPs carrying varying combinations of mandatory (defined by regulation) and voluntary data.

- **DPP creation:** Product data expressed in RDF makes it possible to use SHACL to select the desired DPP data from a larger set of product data.

- **Enable reasoning for model consistency verification:** Consistency means that the model does not include or allow for any contradictions. One unique contribution of ontologies (using the Web Ontology Language OWL DL/Description Logic) is their ability to be checked with automated reasoners (e.g., HermiT, Pellet, FaCT++, RacerPro, ...) This ensures the coherence of the conceptual model, by detecting logical contradictions and unsatisfiable classes that would otherwise remain hidden. For example, reasoning can be useful for the verification of part-whole relations, i.e. if x is locatedIn y and y is locatedIn z, then x is locatedIn z however, if x is memberOf y and y is memberOf z, then x is not necessarily memberOf z. Adding such semantic rules on top of these relations will enrich the model and allow both consistency checks (at the level of the model itself) and coherence checks (between the instances and the model).

- **Enable alignment to standardised RDF top-level ontologies:** alignments with industry standard ontologies: e.g. Industrial Data Ontology (IDO) (ISO/PWI 23726-1 Ontology-based Interoperability for Industrial Data which will be published as an ISO standard in 2026.) e.g. BFO ontology e.g. Web of Things e.g. ETSI SAREF ontology When AAS data is represented in RDF and aligned with reference ontologies, automated reasoning can verify that the alignment remains logically valid. This also applies when looking to align with other initiatives such as the work being carried out by the International Organisation for Standardisation (ISO) regarding ontology-based interoperability (e.g., ISO/PWI 23726-1), Basic Formal Ontology upper-level ontology, the World Wide Web Consortium (W3C) Web of Things Semantic Model, or other domain specific (ETSI SAREF) ontologies. Given those conditions, reasoning engines can validate AAS data for semantic integration by identifying classes or relations that are inconsistent or unintended.

- **Enable SPARQL querying capabilities for large-scale or federated AAS data repositories:** Enabling SPARQL queries over AAS data provides more flexible (i.e. API-free) access to distributed DPP repositories. Today, AAS data is primarily accessed through APIs. While useful for certain use cases, this approach makes cross-cutting queries more challenging. When data is exposed as RDF, SPARQL can query both large and multiple data repositories uniformly. This is particularly useful in federated scenarios where DPPs are managed by different actors. As a result, complex, cross-domain queries can be expressed more easily. This is particularly relevant for representing Bills of Materials (BoM), as formalized for example in the Hierarchical Structures submodel, within the AAS of

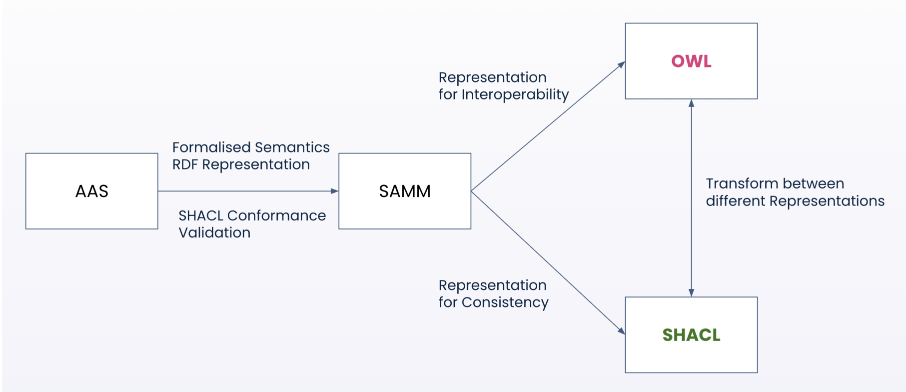

Figure 1: Transformation of AAS Aspect Models: OWL + SHACL

complex assets composed of multiple assets, each with its own AAS. In such cases, the identifiers of underlying assets are referenced in the higher-level AAS, forming hierarchical relationships. When these AAS are represented within a graph structure, the retrieval of AAS instances of underlying assets, which are only referenced via asset identifiers, becomes significantly more efficient.

- **Enable a standardised conversion between the AAS query language and SPARQL** The AAS standard provides a meta querying language (AAS-QL) which can be used to run a server-side query to a high number of Asset Administration Shells at the same time AAS Query language. If the AAS data base is graph-based, then a standardised AAS-QL to SPARQL conversion can be defined.

4 AAS-to-RDF approaches

In this section, we describe a number of initiatives working towards facilitating and exploiting AAS-to-RDF conversion mechanisms.

4.1 A SAMM2OWL+SHACL Transformation

The Semantic Aspect Meta Model (SAMM) took a decision to represent AAS as a lightweight RDF model, staying away from using OWL and providing SHACL shapes for model validation. While SAMM decided to avoid OWL and open world reasoning, there is still benefit from representing SAMM Aspect Models (semantic schema definitions) with OWL for interoperability reasons. By using OWL, Aspect Models can be aligned with other models on the RDF level using unambiguous semantic definitions. For example, we enable the rich, industry-vetted data models of the AAS world to bridge over and be utilized within the decentralized, linked-data architectures of the UNTP.

A transformation from SAMM to OWL can be represented using rule-based approaches for mappings, and can be implemented using standards like SHACL rules (W3C recommendation in the upcoming version 1.2) or SPARQL update.

Furthermore, we can use the same approach to additionally derive SHACL shapes for specific Aspect Models, which can be used to validate instance data for consistency reasons (note that this is not the same as the SAMM-provided meta shapes).

Finally, and to close the circle, the approach can transform OWL to SHACL and vice versa as well. Figure 1 shows how the different model representations and transformations relate to each other. With our transformation approach, we hope to bridge between these frameworks

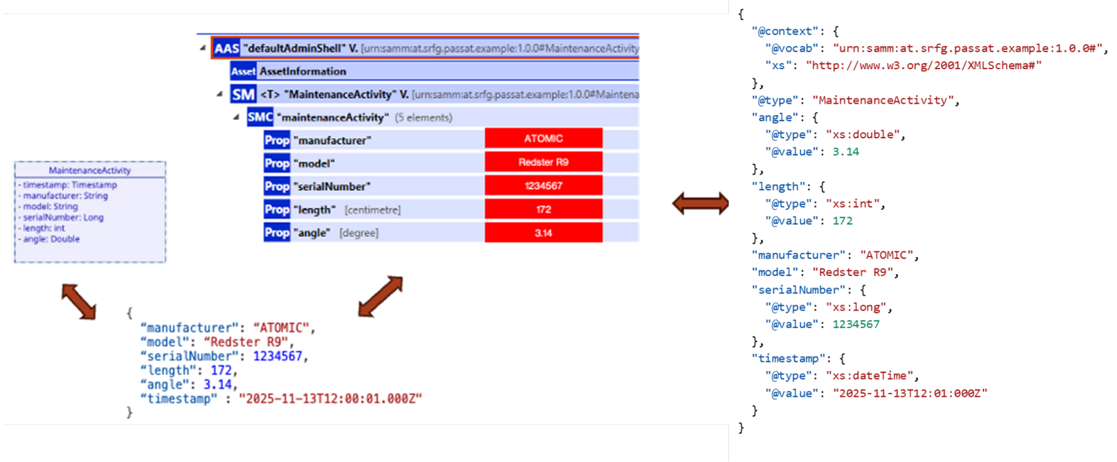

Figure 2: Transformation of AAS Data: Data Objects, JSON and JSON-LD

and facilitate a "best of both worlds" scenario: the structural reliability of AAS for industrial operations, the flexible, verifiable traceability of ontologies for cross-border regulatory compliance and the consistency assurance of SHACL for quality and stability reasons.

4.2 A JSON-LD serialisation methodology (PASSAT)

The Asset Administration Shell (AAS) comes along with a meta-model for representing various assets as digital twins, and also specifies its functional counterpart, the I4.0 component, which provides standardized methods for accessing the data modeled with the AAS meta-model. These methods allow for the retrieval of the data at varying levels of detail, ranging from the complete meta-model details down to a reduced representation of the data in value-only format. While processing the complete AAS information requires knowledge of the AAS meta-model, the value-only formats represent the domain-specific data structures of the modeled assets. For this reason, data exchange with external partners is typically conducted in this format. The drawback, however, is that all semantic information is lost in the value-only format and must be reconstructed by the recipient.

This problem can be solved with JSON-LD (JavaScript Object Notation for Linked Data) as an additional serialization format, which in contrast to the existing RDF serialization of the full metadata, represents the value only data as an RDF graph. While JSON as the default serialization format of the AAS is a lightweight data-interchange format, easy to read and write for humans, and easy to parse and generate for machines, JSON-LD as defined by the W3C extends the default functionality to support Linked Data. Thus, JSON-LD is designed to make JSON data interoperable across systems by embedding semantic information using IRI's and providing a context for interpreting the data.

The simple example shown Figure 2 outlines the difference. The plain JSON lacks the information, that for example the data **"is a"** *MaintenanceActivty*, that the *angle* is a double/float value, or that the *timestamp* follows strict formatting rules. Consequently, the class definition for *MaintenanceActivity* must exactly match the JSON elements produced by the AAS *ValueOnly* serialization in order to properly initialize a *MaintenanceActivity* object. In contrast, with JSON-LD, the AAS serialization contains the semantic information (semantic identifier, data type, object/class type) which allows easy processing of the data for AAS and RDF-based endpoints.

In order to represent AAS submodels (or submodel elements) as an RDF graph, a semantic identifier must be found for each AAS submodel element. Because the submodel element's *idShort* is a local identifier and not usable within RDF graphs, semantic lifting must resolve the element's semantic identifier for each element to be contained in the RDF graph. For this,

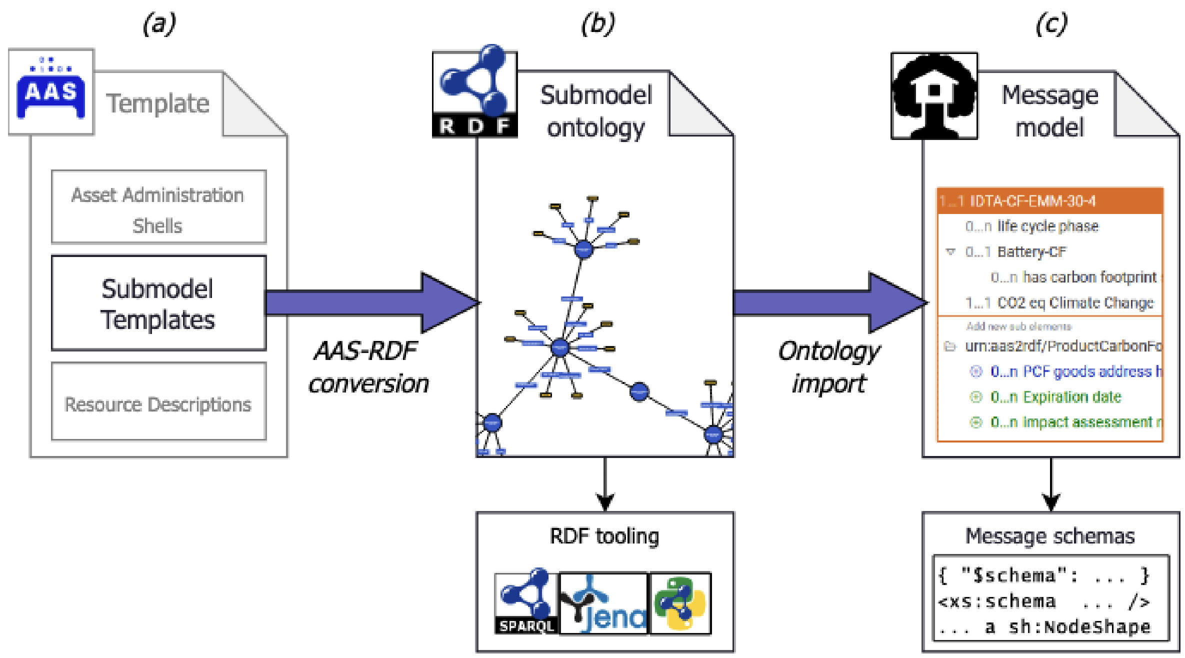

Figure 3: Source: Kuiper et al. (2026)

the element's *semanticId* must finally point to a valid concept description, usually available as ConceptDescription in the AAS Environment. The *ConceptDescription*'s id is then used as predicate in the RDF statement. Furthermore, AAS submodel elements containing children (e.g. *SubmodelElementCollection*, *Entity*) represent complex data objects and should outline their object type with an *isCaseOf* reference. As a result, a RDF graph which follows the AAS structure and more important outlines the values along with the semantic definition is generated. This enables the usage of existing RDF technologies such as SHACL validation, and supports the provision or consumption of RDF graphs.

This solution has been implemented in a prototypic Asset Repository for the PASSAT project.

4.3 An AAS submodel to RDF converter tool (TNO)

This work consists in the design of an open-source tool to convert an AAS template submodel to an OWL-DL ontology in RDF representation with the goal of facilitating semantic interoperability with other RDF vocabularies. Data is lifted from an AAS submodel to create an "ad hoc" OWL ontology that can be loaded to Semantic Treehouse (an open-source platform for designing and publishing data standards). Some of the currently addressed challenges include managing submodel elements that come with or without Semantic IDs and combining submodel data elements with data elements from other vocabulary sources in order to reuse existing vocabularies/ontologies (e.g. SEMIC vocabularies). The Prov-O ontology is used to describe the provenance of the generated ontology: where it was generated from (a specific version of the conversion tool); the generation source (a specific AAS serialisation, using a permalink); and where you can find the source code of the conversion tool.

The workflow is shown in Figure 3. This tool is currently being used actively in various DPP modelling efforts, where e.g. IDTA template submodels and external RDF vocabularies are combined to create a single RDF-based DPP "template". An example for a battery passport can be found in the Semantic Treehouse DPP Vocabulary Hub.

4.4 The DATA4CIRC AAS ontology model

One of the main objectives of the DATA4CIRC project is the implementation of an EU Digital Product Passport (DPP) based on the DPP4.0 concept. The goal is to further mature this concept into a practical and interoperable EU DPP solution that aligns with the upcoming European standards under CEN/CENELEC JTC 24.

Within the semantic modelling task of DATA4CIRC, an AAS OWL ontology is being developed to provide a formal semantic backbone for the DPP framework. Our work builds on and reuses existing resources, including the IDTA RDF ontology and SHACL schemas from the AAS specification repository, the Eclipse BaSyx Python SDK and its experimental RDF adapter, as well as relevant community-driven implementations. We are aware of ongoing discussions and open issues in the community, such as handling of ordered structures, identity stability, and serialization aspects, and these considerations are taken into account in our approach. The ontology is designed to closely follow the AAS metamodel and will be extended where necessary to represent DPP-relevant AAS submodel templates in a consistent and usable way.

Furthermore, the ontology will, where appropriate, be connected with established semantic frameworks such as PLC, IOF, SAREF, SAREF4INMA, and BFO, supporting broader semantic interoperability beyond the AAS ecosystem.

4.5 An AAS to UNTP DPP bridge

Data-driven product configurations play a crucial role in Industry 4.0 architectures. The project ECO-TCO - Optimizing product design and configuration for an ecodesign compliant total cost of ownership approach investigates how data from a Digital Product Passport (DPP) can be utilized for green configuration and sales purposes. The project approaches the topic from the perspective of Total Cost of Ownership (TCO), which enables users to compare and select products based on their cost structure, under special consideration of their environmental performance, as well as their compliance with current regulations in various jurisdictions. In a particular work package, the project addresses semantic interoperability between the Asset Administration Shell DPP4.0 (AAS) and the UN/CEFACT UN Transparency Protocol (UNTP) by “anchoring” an AAS Digital Product Passport (DPP) submodel to UNTP’s global, sector-neutral vocabulary. It proposes an AAS DPP Submodel Template where each submodel element (e.g., Property, Collection) carries a “semanticId" referencing the matching UNTP concept via an IRI (e.g., Product.idValue for GTIN). An illustrative mapping aligns common AAS DPP submodels — product identification, materials provenance, emissions/circularity scorecards, and conformity claims - field-by-field to UNTP DPP specification terms, while AAS remains the technical container and exchange API. Since UNTP is typically represented in JSON-LD (an RDF serialization), these IRIs link AAS elements to RDF semantics: shared identifiers enable consistent interpretation across organizations. This lightweight approach to semantic interoperability deliberately circumvents the need for ontologies and instead provides a simple semantic bridge to reduce fragmentation across different DPP specifications. This approach can be seen as a light-weight approach to improve semantic interoperability between various DPP specifications, without hampering more sophisticated, ontology- or KOS-based approaches that might be applied at a later point in time.

4.6 Onto-DESIDE - The Circular Economy Ontology Network

The Circular Economy (CE) aims to maintain material continuity through the cycle of production, consumption and recycling. The conceptual reality the CE operates within produces, consumes and relies on vast amounts of data. To make sense of this data in an efficient way as to create new, and to scale, CE collaboration data and concepts need formal specifications to be semantically interoperable and to enable the needed information sharing and collaboration.

The Onto-DESIDE project explored the CE perspective on semantically interoperable data in relation to creating CE value networks and how concepts align with DPP data and concepts, providing an overview of alignments where concepts and data are the same. Onto-DESIDE created the Circular Economy Ontology Network, focusing on concepts that enable CE collaboration, aligning with the implementation of the ISO 59000 series of CE standards concepts and definitions. The learning's from Onto-DESIDE surface the need of an interoperability layer that is agnostic to specific industry implementations of how to share data, focusing on enabling collaboration on shared concepts, cross different industries. Although the project did not target AAS interoperability specifically, the general approach and platform would also support mapping and interchange with such systems.

4.7 LinkedFactory: Combine AAS data with RDF-based digital twins

LinkedFactory is a data architecture designed to create digital twins of products and technical systems. It achieves this by integrating RDF-based structural descriptions with high-volume time-series data, enabling uniform querying through SPARQL. By leveraging RDF to model complex, nested, and interrelated structures, the concept is able to represent Digital Product Passport (DPP) data at varying levels of granularity. High-volume time-series data can be linked to any structural element using Linked Data principles and the SPARQL federated query extension. The reference implementation, LinkedFactory Pod, allows to query remote Asset Administration Shell (AAS) HTTP/REST endpoints via SPARQL. This enables the seamless retrieval, transformation, and aggregation of AAS data for integration into triple stores as part of a comprehensive digital twin or DPP representation.

4.8 DACE: Data Competence Center for Circular Economy Data

The DACE project addresses the critical role of data in enabling CE strategies, where the effective use of product-, material-, and lifecycle-related data is essential for minimizing resource extraction and environmental impact. The project adopts a comprehensive approach by combining research on CE data competencies (Space), capacity building and training (Academy), and stakeholder networking (Hub). Within this context, DACE also investigates data modeling and interoperability mechanisms for CE data, which include Digital Product Passports. A key contribution is the development of bidirectional transformation approaches between AASs and RDF representations, enabling CE data to be both integrated into industrial digital twin environments and exposed within RDF-based data spaces for advanced querying and semantic integration. To achieve this, the project uses Solid as an underlying infrastructure. This work supports the broader objective of strengthening CE data competence by bridging heterogeneous data ecosystems while preserving semantic consistency and enabling scalable and data-driven CE applications.

5 RDF-to-AAS approaches

In this section, we describe a number of initiatives working towards facilitating and exploiting RDF-to-AAS conversion mechanisms.

5.1 PSS-PASS: Reusing industry standard RDF ontologies in AAS contexts

One of the goals of the PSS-PASS project is to develop the Digital Product Service System (DPSSP) OWL ontology for DPP and novel DPSSP services. The concept of DPSSP emerges in PSS-Pass to make the connection of Product Service Systems (PSS) (an increasing paradigm of companies offering their Products together with Services to fulfil the customer needs) with DPPs. PSS-Pass integrates PSS principles into both the use and construction of DPP. To enable a range of services that could be offered by exploiting DPPs' potential, it is crucial that DPPs contain information that can expand and improve service offerings.

The DPSSP ontology is composed of the PSS ontology Correia and Stokic (2024) that is part of the Industry Ontology Foundry (IOF) (an initiative that develops industry supporting ontologies that are BFO-based (Basic Formal Ontology)), as well as a BFO aligned version of the EUDPP ontology Tüzün et al. (2025) as well as project relevant concepts. Ongoing work consists in exploring means to connect the DPSSP ontology to the project AAS environment (so called DPSSP Digital Environment) used to model the DPPs and DPSSPs in the context of an AAS based data space enabler. The connector being developed takes the DPSSP structure from the developed ontology and creates an AAS submodel that is the basis for the DPPs and DPSSPs created by the project pilots.

5.2 Combining AASs and Ontologies in the bi0SpaCE Project

The bi0SpaCE project aims to support the digital and circular transition of European bio based industries by developing advanced digital solutions and an open access platform that enables transparent, secure, and interoperable sharing of sustainability data across bio based value chains. In bi0SpaCE, the Asset Administration Shell (AAS) will be used to represent Digital Twins (DTs) for processes and Digital Product Passports (DPPs) for products. Ontologies will be used throughout the project to support multiple semantic tasks.

First, ontologies or existing standards (e.g. eClass) are used to define the structure of AAS Submodel Templates (SMTs). For most SMTs, such as the Nameplate, the structure is fixed. However, for others, like Technical Data submodels required for DPPs, the structure depends on the specific asset type being modeled. Second, during automatic AAS instantiation, ontologies can be combined with Large Language Models (LLMs) to extract relevant information from unstructured data sources (such as product sheets) and implicit knowledge in documents (e.g., maintenance logs, shift books, and technical documentation), using the ontologies to prevent hallucinations and ensure semantic accuracy. Third, ontologies are used to define SemanticIDs for non standardized AAS SMTs, ensuring consistent semantic interpretation and interoperability across systems.

To support the tasks mentioned above, the bi0SpaCE project has already developed a materials-based ontology for bio-based materials that captures the full bio-based material hierarchy, from primary feedstocks through intermediates, final products, by-products, waste, and recovered secondary materials.

6 AAS-RDF bidirectional approaches

In this section, we describe a number of initiatives working towards facilitating and exploiting bidirectional conversion between AAS and RDF.

6.1 AAS is a Graph: Representing AAS with RDF

The Asset Administration Shell (AAS) officially defines three serialization formats. While JSON is the most widely adopted format and XML is primarily used within the AASX package format for offline data exchange, an official RDF serialization also exists (e.g., Turtle or JSON-LD). This one-to-one RDF representation is formalized through an OWL ontology[1] and is accompanied by SHACL shapes to validate metamodel-related constraints, such as ensuring that a property

[1] https://github.com/admin-shell-io/aas-specs-metamodel/blob/master/schemas/rdf/rdf-ontology.ttl

contains only one value. Since this RDF representation is part of the AAS specification, it enables the use of SPARQLRimaz et al., SHACLRimaz et al. (2023), and rule-based reasoning in an interoperable way based on a fixed graph structure.

Currently, the py-aas-rdf tool addresses the lack of native support in official SDKs by providing a bridge for the RDF serialization proposed in the AAS standard. This tool allows for lossless, round-trip transformations between JSON/XML and RDF. However, certain elements of the official representation are still being refined; for instance, known issues with SHACL shapes are currently being tracked in the specification's repository. Simultaneously, industry experts within the IDTA are working to enhance this one-to-one representation to make it more natural and better aligned with common industry practices. The goal is to improve the toolset to facilitate direct AAS creation within an RDF environment, allowing for full utilization of the Semantic Web technology stack.

Technical challenges remain, particularly regarding array-type referencing and the fact that specific AAS types are sometimes mapped only as generic "properties," which results in a loss of granular information. Resolving these issues will allow AAS data to be stored as an RDF graph alongside other semantic artifacts, such as SAMM Aspect Models and ECLASS, both of which now provide RDF representations. Finally, it should be noted that this one-to-one mapping is often viewed as a structural representation rather than a "natural" semantic knowledge graph, as it retains the artificial data structures of the AAS. This distinction motivates further work to layer domain-specific modeling on top of this foundational representation.

6.2 A Bidirectional Conversion Approach between DPPs Represented in AAS and the DPP4Fun ontology (Cir4Fun)

The conversion approach (Nguyen et al., 2026) proposed by the CEA List team in the context of the Cir4Fun project relies on (1) an ontology called Product Digital Twin Ontology (PDTO), and (2) mapping rules that enable the bidirectional conversion between AAS-based and ontology-based DPPs. The conversion not only involves a syntactic or format-level transformation between AAS and RDF but also ensures semantic interoperability between the source and target models.

The core idea is to build an ontology whose schema (1) is aligned with the DPP information model as modeled using the AAS metamodel, and (2) supports bidirectional mapping, that is, every AAS element required to model an AAS-based DPP can be mapped to one or more elements of the ontology schema and vice versa. In this sense, we first developed PDTO as a general-purpose ontology to represent Product Digital Twin (PDT). A DPP, which in some cases can be regarded as a specific type of PDT (Nguyen et al., 2025), then can also be modeled by PDTO. Furthermore, we developed DPP4Fun, a sector-specific ontology dedicated to the furniture domain. DPP4Fun reuses the vocabulary and structure of PDTO and extends them with additional concepts from the Furniture Sector Ontology (FSO). Second, we developed a Python program that implements the mapping rules and enables conversion between AAS-based DPPs in JSON, XML, and YAML, and ontology-based DPPs in RDF/XML, TTL, N-Triples, and JSON-LD. Figure 4 illustrates the main idea of our approach. Note that the semantic IDs of an AAS-based DPP can reference concepts from the DPP4Fun ontology; thus, both representations share the same semantics.

The results of the conversion solution were partially evaluated using an AAS-based DPP viewer developed in the RAASCEMAN project. In detail, DPP4Fun-based DPPs were converted into AAS-based DPPs, then could be manually inspected and evaluated using the tool. Conversely, for the transformation from AAS-based to DPP4Fun-based representations, we validated the resulting ontology-based DPPs using a SHACL-based validation tool.

At the current state, the solution is 90% completed and has been tested with DPP samples defined in the Cir4Fun project. We are now in the maintenance phase and plan to release the

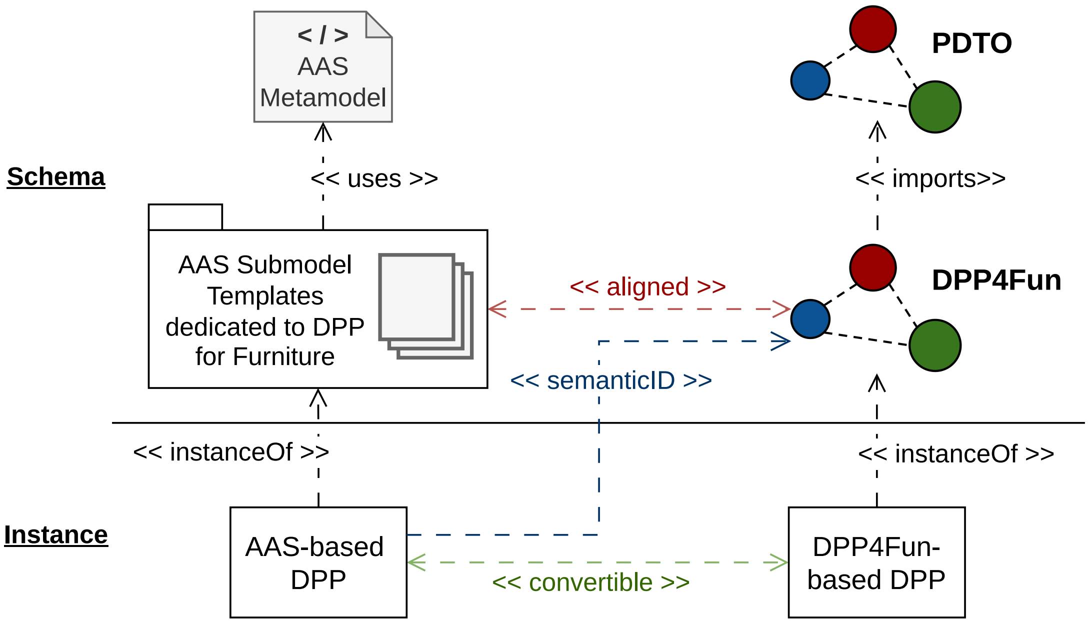

Figure 4: Overview of the relationship between AAS-based and DPP4Fun-based DPPs

final version at the end of this task / work package.

6.3 AAS-for-Everything: A Semantic Layer for Data Mesh Architectures

Within Semiconductor-X, the concept termed AAS-for-Everything is proposed as a semantic integration layer representing an evolution from traditional data lake architectures towards a data mesh/data fabric paradigm, in which heterogeneous data sources are semantically lifted and uniformly represented using digital twins in form of the Asset Administration Shell (AAS). The objective is to provide a universal representation in which all entities of business and operations are modeled as AAS instances (with the existing metamodel). In this context, the AAS is generalized to cover arbitrary entities—not only assets, but also documents, processes, and transactional data such as notifications, quality reports, purchase orders, and test series (e.g., wafer tests)—as digital twins. This semantic lifting is enabled through JSON-LD as a performant serialization format that preserves value-oriented data representations while maintaining their semantic interpretability within an RDF context, while simultaneously enabling efficient storage and high-performance processing of AAS data. The approach further supports the integration of existing semantic models and vocabularies by enabling an RDF-to-AAS bridging concept, allowing RDF-based representations to be mapped into AAS structures and incorporated into the unified semantic layer. As a result, heterogeneous data sources and pre-existing knowledge graphs can be seamlessly integrated into a unified semantic layer, where entities and their relationships can be consistently interpreted, queried, and combined across systems.

7 Recommendations

- AAS and RDF can be combined to leverage the strengths of both approaches. AAS provides a structured, modular, and use-case-driven framework for organising data through submodels that can be defined and maintained by domain experts. These submodels are application-friendly and well-suited for data space interactions, as they are designed around specific use cases and business contexts. RDF and JSON-LD complement this through the efficient expression of explicit semantics, flexible data linking, and access to a mature ecosystem of tools for validation, querying, reasoning and integration. RDF/JSON-LD can be used to enhance AAS-based interoperability with additional cross-system and cross-domain capabilities.

- The possibility to use dereferenceable identifiers such as HTTP URIs as semantic references rather than IRDIs to refer to vocabularies from the Common Data Dictionary would allow automatic retrieval of these controlled vocabularies. IRDIs do not easily enable machines to automatically retrieve definitions or semantic relations. In contrast, HTTP URIs can be resolved on the Web and possibly also return RDF descriptions that include hierarchies and constraints. As a result, the controlled vocabulary can be accessed and processed directly. This approach would support semantic lifting of many AAS submodels and would enable embedding their semantics more naturally within the Linked Data ecosystem.

- The addition of an additional JSON-LD serialisation to the AAS specification would make it easier to integrate AAS data into linked data environments. This proposal has already been the topic of discussion in the following Github issue.

- In view of the expected large numbers of future DPPs and DPP repositories, it would be useful to consider standardising an AAS-QL to SPARQL conversion to facilitate large repository queries for graph-based databases.

- Enable scalable access to distributed DPP data: As the number of DPPs grows, approaches for efficient access to distributed data should be further explored, including mechanisms for querying across multiple systems and repositories. This may include decentralised data storage and access approaches, such as Solid Pods, where data remains under the control of data owners while being accessible in an interoperable manner.

- Share good practices for semantic lifting from AAS to RDF: Several approaches described in this paper rely on semantic lifting of AAS submodel elements using semanticIds and ConceptDescriptions. Collecting and sharing good practices for representing AAS values, collections, entities, semanticIds, units, qualifiers, and references in RDF would support reuse and help different implementations become more easily comparable.

- Clarify transformation profiles and expected round-trip behaviour: AAS-to-RDF, RDF-to-AAS, and bidirectional transformations serve different purposes. Future work could clarify whether a given transformation is intended to be lossless, structurally faithful to the AAS metamodel, semantically enriched, or use-case specific. This would make the available tools easier to compare and reuse.

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