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Deliverable D3.1
Major industrial data models

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Abstract

This document constitutes deliverable D3.1 of the Arrowhead fPVN project.

Work package 3 is responsible for defining and selecting data model languages, providing guidelines and tools for the Use Cases. The deliverable D3.1 contains an assessment report on major industrial data models and their foundations, similarities and dissimilarities.

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Abstract	This document constitutes deliverable D3.1 of the Arrowhead fPVN project. Work package 3 is responsible for defining and selecting data model languages, providing guidelines and tools for the Use Cases. The deliverable D3.1 contains an assessment report on major industrial data models and their foundations, similarities and dissimilarities.

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1. Introduction

WP3 will select and analyse relevant standards and their data models. The partners will search for commonalities and synergies between the selected data models and their languages. The work will be finalized in a report describing the key properties of the predominantly applied data models and the similarities and dissimilarities between selected, use case related data models.

2. WP3 Objectives

WP3 will collect the relevant standards and their data models. The partners will search for commonalities and synergies between the selected data models and their language.

The main objectives of WP3 are:

- Select major standardised data models relevant to the use cases.
- Identify the foundational properties of the selected data models.
- Identify similarities and dissimilarities between the standardised data models.
- In cooperation with WP4 propose updates to the selected standard which will improve data model translation accuracy.

2.1 Objectives

This table shows which objectives that are addressed by this part of the deliverable and how these are supported.

Objective	Contribution
Select major standardised data models relevant to the use cases.	This document contains a survey about the major standardised data models regarding the Automotive fPVNs, the Aerospace fPVNS, the Green Energy fPVNs and the Process Industry fPVNs.
Identify the foundational properties of the selected data models.	This document summarizes the key properties, limitations and use cases of the major standardised data models. The selection of the standards is based on the T3.1 survey results.
Identify similarities and dissimilarities between the standardised data models.	This document contains comparison analysis regarding selected data model pairs.
In cooperation with WP4 propose updates to the selected standard which will improve data model translation accuracy.	Not applicable in this document. This will be the objective of the D3.2 report.

3. Requirements

WP3 has collected input from the WP3 partners and from the use case partners to define, collect and analyse the predominantly applied industrial data models.
WP3 has provided a list of the major standards, next to the analysis results. The survey will be evaluated by WP1 and WP4.
The results of D3.1 will be further processed in D3.2 and in D4.2 in cooperation with T3.2 and WP4.

4. Artefacts

The following subchapters summarize briefly the major project events and their results regarding the deliverable.

4.1 Initial kick off meeting, Helsinki, Finland

The initial kick off meeting has been conducted together with all WPs in Helsinki, Finland. WP3 also had a unique session, where the partners discussed the objectives and predefined the working steps. The WP3 partners also created an initial list about the major standardised data models, which could be used as a starting point in the first questionnaire of T3.1 [1].

4.2 Survey on major standardized data models

During the online meetings, T3.1 defined an initial survey in cooperation with WP1 and WP4. The questionnaire has been divided into two parts:

1. Part 1 – Major standardized data models
2. Part 2 – Data and analysis-related questions.

The goals of the first part were the following:

- Collect the currently used data model standards.
- Identify, which partner could help with the analysis.
- Associate the use cases with standards.

The goals of the second part were the following:

- Identify the representation of the process-related data.
- Discover, which partner could share data sets with the project partners.
- Collect previous analysis results, which has already been done before.

The survey is attached in reference [1]. This survey has been refined into Appendix [1]. The major results of the survey are summarized in chapter 5 “Results of the first T3.1 survey”.

4.3 First workshop, St. Polten, Austria

The first fPVN workshop was held in Austria, St. Polten. AITIA presented the survey results and the initial draft of the D3.1 report. The partners discussed the current state of the report, including the subchapters, and clarified the next steps. The survey results were also shared with WP4.

4.4 Contribution to D3.1

After the workshop, several reminders and private mails were sent to ask further information from the partners. The collected contributions were merged into this report.

5. Results of the first T3.1 survey

The first questionnaire of T3.1 is aimed to collect the major industrial standards related information from the WP3 partners and from the use case leaders [1]. The survey contained 16 questions, differentiated into the following two major parts:

- Part1 – Major standardized data models.
- Part2 – Data- and analysis-related questions.

The following subchapters highlight the main information from the survey results related to D3.1 and WP4.

The questions and the answers are listed in **Appendix 1** (AH_fPVN_WP3_T3.1_Survey.docx)

5.1 Participant's contribution to WP3 and to D3.1

Regarding the partners, the following three categories could be differentiated:

1. Almost the **half** of the participants **know several data model standards** and **could help** in the analysis.
2. A **third** of the participants would like to **find a currently standardized data model** to represent their data.
3. **15%** of the respondents **have problems** with a currently applied standard and would like to find a solution.

5.2 Connection to use cases

Figure 5.2.1 represents the relation between the respondents and the use cases. It can be seen that the major of the respondents are interested in **Process industry**.

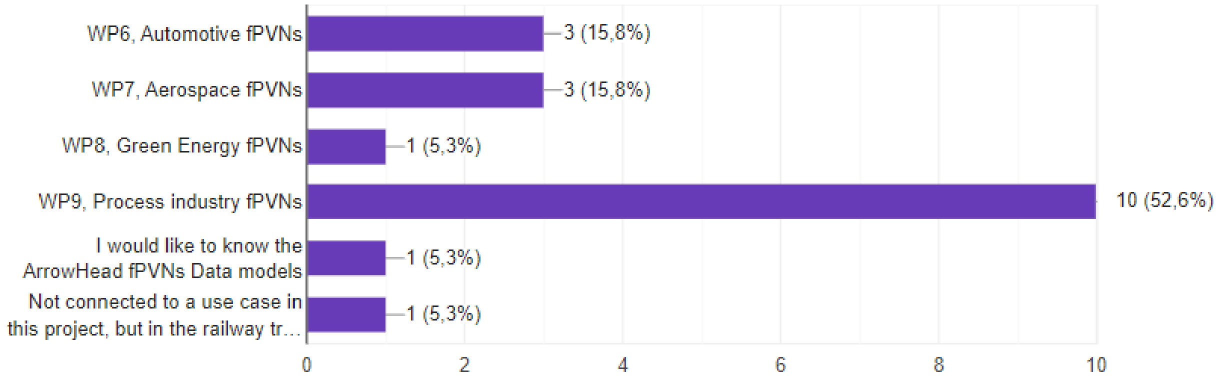

Figure 5.2.1 – Respondents' connection to the use cases

5.3 Relevant standards and their data models

The first survey of T3.1 [1] collects the predominantly used industrial standards, which is a significant information for WP1, WP3 and WP4. Figure 5.3.1 represents the 6 major standards based on the answers. Regarding the standard-related questions, each participant could select more options.

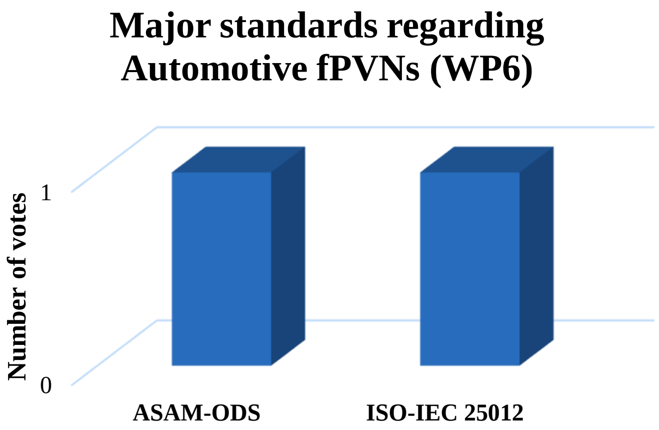

Figure 5.3.1 – Major standards and their distribution

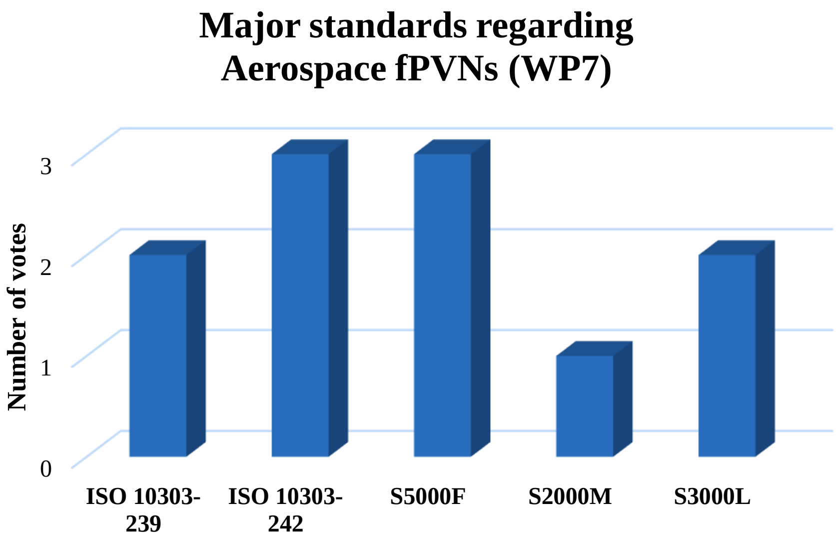

Figure 5.3.1 – Major standards and their distribution

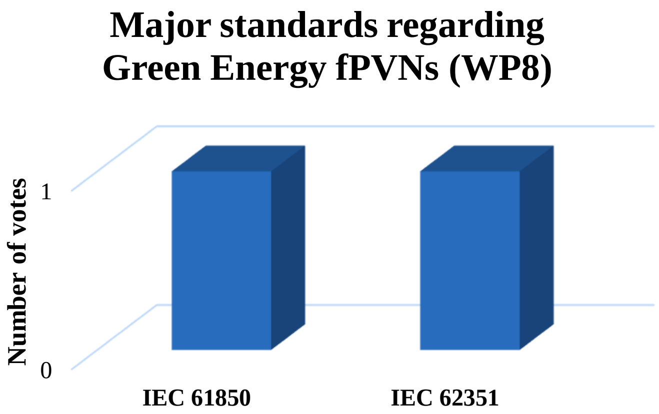

Figure 5.3.1 – Major standards and their distribution

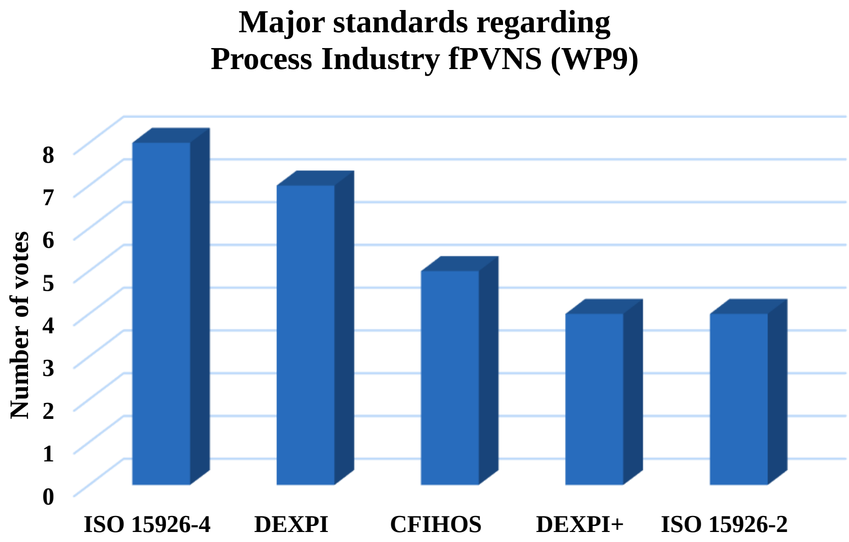

Figure 5.3.1 – Major standards regarding Process Industry fPVNs

40% of the survey participants apply the ISO 15926-4 standard, and the DEXPI data model in their industrial domain. A third of the respondents selected the ISO 81346-1 standard, and the quarter answered the CFIHOS standard. 20% of the survey participants answered the DEXPI+ and the ISO 15926-2 standards.

Figure 5.3.2 represents the all answers regarding the applied standards in the industrial domains.

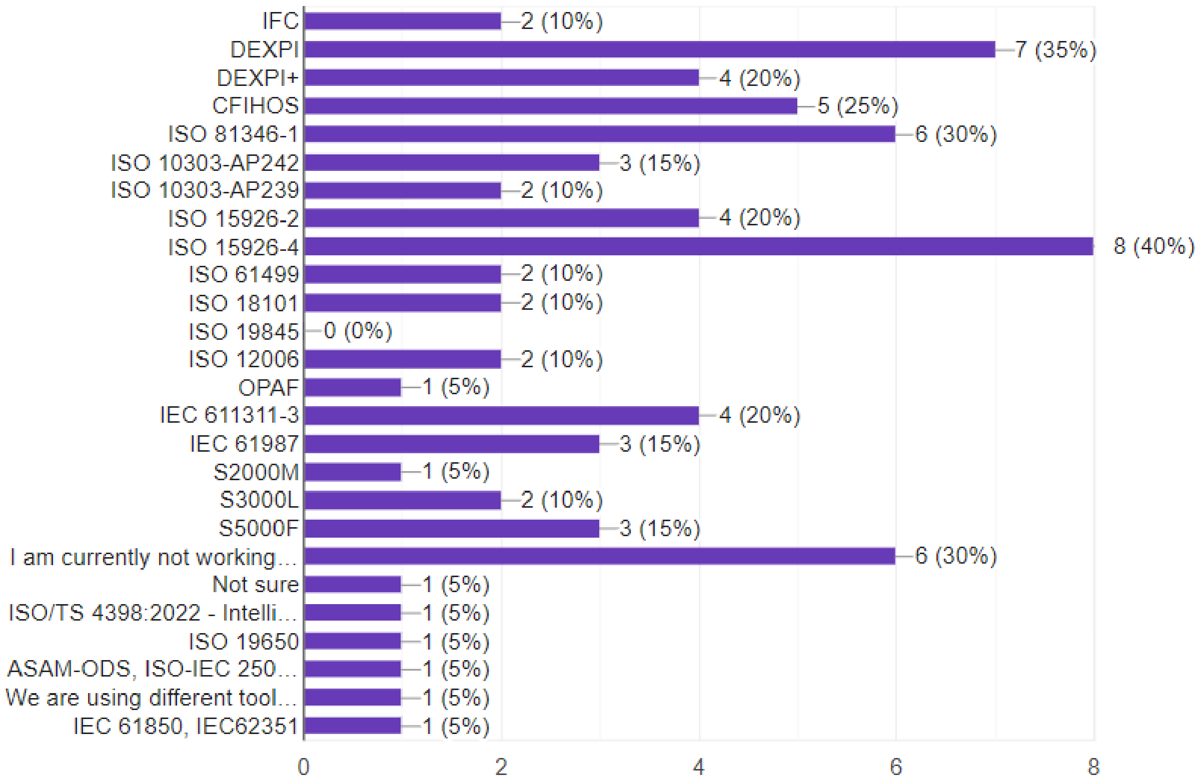

Figure 5.3.2 – Distribution of the standards and data models

The following list represents the applied standards based on the use case categories.

Automotive fPVNs (WP6):

- ASAM-ODS, ISO-IEC 25012

Aerospace fPVNs (WP7):
- ISO 10303-239 and 242, S5000F, S2000M, S3000L

Green Energy fPVNs (WP8):
- IEC 61850, IEC 62351

Process industry fPVNs (WP9):
- DEXPI, DEXPI+, CFIHOS, ISO 15926-2 and 4, ISO 18101, IEC 61987, IEC 611311-3, ISO 81346-1, ISO 10303-239 and 242, ISO 12006, ISO 19650, ISO 61499, OPAF

5.4 Representation of the data

To collaborate with WP4 and help the selection of the AI models' objectives, the survey collected the relevant format of the data. Each participant could select more options regarding the data formats. Based on the answers, the following major formats could be highlighted:
- XML
- JSON
- SysML

Evaluating the above categories, an XML – XML (different schemas), an XML – JSON, or a JSON – JSON (different schemas) translation could solve interoperability problems. WP4 should investigate the AI-based models regarding XML and JSON translation possibilities.
SysML, PDF and HTML are the other top categories. Partners should collect data sets for further evaluation.
Figure 5.4.1 represents all answers and their distribution. It should be noted, that each respondent could select more options.

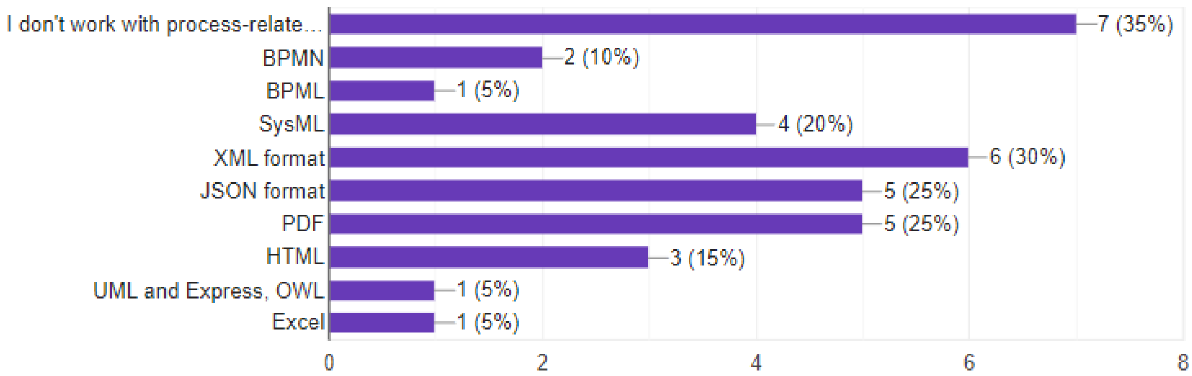

Figure 5.4.1 – Distribution of the answers from the participants

The following list represents the applied data formats based on the use case categories.

Automotive fPVNs (WP6):
- XML, JSON, PDF, HTML, SysML

Aerospace fPVNs (WP7):
- BPML, SysML, XML, JSON, Excel

Green Energy fPVNs (WP8):
- JSON

Process industry fPVNs (WP9):
- BPMN, SysML, UML, OWL, XML, JSON, PDF

5.5 Data sets

To analyse the data representation needs, the interoperability needs, or to update a specific standard, the data sets should be shared with the designated partners. As a first step, the survey determined that **40% of the participants have data**, and **20%** of the respondents **can share** this data set **for further analysis**. Another third of the partners probably also have data sets, but it needs to be collected in the next steps.

Some partners already have analysis results regarding their own data set, which could be shared with designated partners.

5.6 Possible standard pairs to solve interoperability problems

Based on the answers, **the half** of the respondents **need data model translation** to solve interoperability problems.
Table 1. summarizes possible data model pairs based on the survey results.

No.	#1 Standard (From)	#2 Standard (To)
1	P&D ISO 10628 (PDF)	DEXPI
2	ISO 23726/ISO 15926-4	ISO 10303-239/242
3	ISO 81346	ISO 23726/ISO 15926-4
4	DEXPI and DEXPI+	ISO 23726/ISO 15926-4
5	CFIHOS	ISO 23726/ISO 15926-4
6	ISO 10303-239	S2000M/S5000F/S3000L

Table 1. – Possible standard pairs for the translation steps

6. Data model foundations

This chapter briefly summarizes the foundational properties of the data models.

6.1 ISO 15926

The purpose of ISO 15926 is to facilitate exchange and integration of data to support the life-cycle activities processes of process plants. To do this it specifies a data model that defines the meaning of the life-cycle information in a single context supporting all the views that process engineers, equipment engineers, operators, maintenance engineers and other specialists may have of the plant.

Traditionally, data associated with a process plant have been concentrated on some individual view of the plant at a point in time. Such data are usually defined and maintained independently of other groups of users, resulting in duplicated and conflicting data that cannot be shared either within an enterprise or with business partners of an enterprise.

ISO 15926 representations are specified by a generic, conceptual data model that is suitable as the basis for implementation in a shared database or data warehouse. The data model is designed to be used in conjunction with reference data, i.e. standard instances that represent information common to a number of users, process plants, or both. The support for a specific life-cycle activity depends on the use of appropriate reference data in conjunction with the data model.

ISO 15926 is organized as a comprehensive series of parts, each published separately. For fPVN the relevant parts are:

- ISO 15926-2: Data model
- ISO/TS 15926-4: Core reference data

Another part that could have been relevant for fPVN is ISO/DTR 15926-14: Data model adapted for OWL 2 Direct Semantics. This draft Technical Report has been withdrawn and replaced by ISO 23726: Industrial Data Ontology (IDO).

A detailed analysis of ISO 15926 is available in **Appendix 2** (Understanding ISO 15926-4: An In-Depth Overview).

6.2 ISO 15926-2: Data model

ISO 15926-2 is a generic, conceptual data model written in EXPRESS. It has not been updated since edition 1 was published in 2003. ISO 15926-2 is mainly used as a reference model.

6.3 ISO/TS 15926-4: Core reference data

ISO 15926 is designed with a data model to be used in conjunction with reference data, i.e. standard instances that represent information common to a number of users, production facilities, or both. The support for a specific life-cycle activity depends on the use of appropriate reference data in conjunction with the data model.

The ISO 15926- reference data have been developed since 1990 from experience of operators, contractors and equipment suppliers operating in the plant engineering supply chain. The reference data therefore largely cover process plants installed in the oil, gas, process and power industry.

The reference data can be extended though Change Requests (CR) with data that have not yet been covered such as specific nuclear data and specific pulp and paper equipment data. Such CR's will be processed in an ISO verification procedure using agreed rules from ISO 15926-6: Rules for the development and validation of reference data of ISO/TS 15926-4.

ISO/TS 15926-4: Initial reference data edition 1 was published in 2007. Edition 2 was published in 2018. Edition 3 is under development, and it has been renamed to Core reference data. The final draft has been approved and publication is expected early 2024.

Edition 3 is a major improvement and enhancement of the standard. It has also been aligned with reference data in DEXPI and CFIHOS. It is therefore recommended to use this edition. DEXPI and CFIHOS has to a great extent been based on ISO/TS 15926-4 and keeping the reference data aligned make it possible to exchange data conforming to these standards.

6.4 DEXPI

The Data Exchange in Process Industry (DEXPI) Initiative has been working towards the development of a general data exchange standard for the process industry. The DEXPI specification is the result of this initiative. It is an extension of the ISO 15926 standard, which was originally intended for information exchange between P&ID and 3D modeling tools. The main objective of the DEXPI Initiative is to develop and promote a general data exchange standard, covering all phases of the lifecycle of a process plant, ranging from specification of functional requirements to assets in operation. However, the DEXPI specification is currently focused only on P&ID information exchange. [2]

Figure 6.2.1 – List of organizations involved in the DEXPI initiative (updated in 2020) [3]

The DEXPI Initiative is supported by a group of O/Os, major CAE and software vendors, research organizations as well as by a group of international standardization organizations.

Data interoperability of P&IDs and their information is important as it enables exchange of data that can be used for different applications over the plant lifecycle.

The DEXPI Information Model is a class model in terms of the Unified Modeling Language (UML). The exchange format for DEXPI 1.3 is Proteus Schema 4.1. To this end, there is a mapping from each type and attribute in the DEXPI Information Model to an XML pattern. Even if there are special cases due to certain design decisions in Proteus Schema, some general guidelines for the DEXPI-Proteus mapping apply. [3]

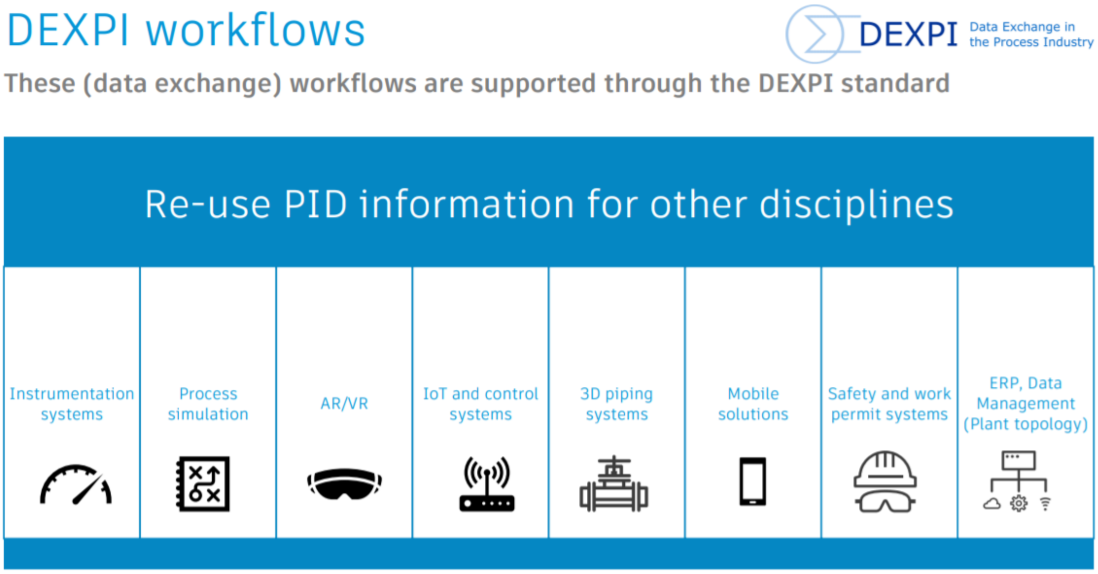

Figure 6.2.2 – Workflows supported by DEXPI

DEXPI has been under development during the last 8 years. It is currently under further improvement, and it is constantly tested. However, the first industrial pilots have just started, mainly in the oil and gas and pulp and paper sector. In these pilots, data exchange between different project stakeholders is carried out using DEXPI and this data is used for different applications. However, additional testing in real industrial cases is required to further refine this format and more success stories are needed to prove its applicability.

6.5 DEXPI+

The DEXPI+ specification is still under preparation. A release candidate has been published for DEXPI+ specification version 1.0 [4]. The aim of DEXPI+ specification is to define an information model for representing the information in Process Flow Diagrams (PFD) and Block Flow Diagrams (BFD) [4]. The DEXPI+ information model is included in the DEXPI data model [5] (model for piping and instrumentation diagrams) as an additional package.

As in the DEXPI specification also in DEXPI+ the information model is independent of the presentation layer, i.e., the graphical presentation of BFD and PFD [4]. The information model form in conjunction with the presentation layer a standard format to exchange BFDs and PFDs.

The DEXPI+ information model describes a process of a facility [4]. The process is modelled as interconnected process steps. Each process step is a system performing a process activity. The semantic description of a process step is depicted by a process activity. A process step includes port and parameter objects. A port defines the interface between two systems through which the systems can interact. The interaction between process systems is represented by a process connection object linking an inlet port and an outlet port. Between the ports either stream (flow of material), energy flow (thermal, electrical or mechanical), or information flow (e.g., measurements or control signals) is exchanged. Information about the process step itself is included in the parameter objects.

A hierarchy of process steps (see Fig. 6.6.1) is used to represent the conceptual design of a processing facility [4]. A top-down approach is used. At the highest level, a single process is defined to model the whole production system. The single process is divided into smaller sub-processes that are illustrated in BFDs. The sub-processes are further divided into unit operations that are depicted in the PFDs.

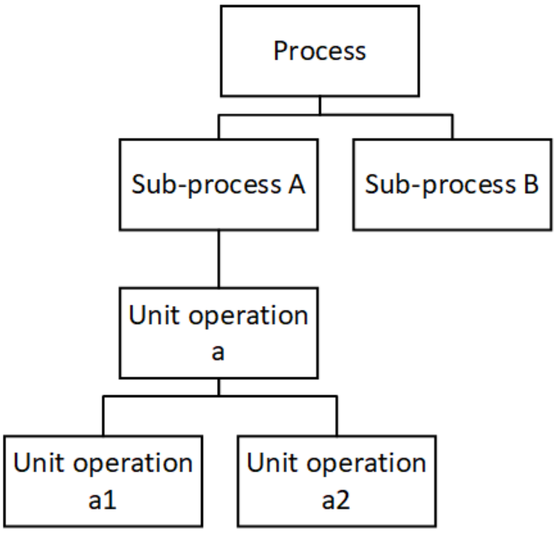

Figure 6.6.1. Hierarchy of process steps (modified from [4]).

The subsystems of a process step are represented with details on process steps [4]. The details on process steps are further divided into subclasses to represent, e.g., stirring or agitating functions, separation stages in a column-based separation process, or burner components.

Four reference diagrams have been used for developing and validating the DEXPI+ information model. The diagrams have been implemented as an experimental XML schema [4]. The common ISO 10303 schema has been used to develop the experimental schema. The Proteus schema [6] (the exchange format of DEXPI) is not utilized.

In addition to the experimental XML schema, DEXPI+ proposes to use AutomationML [7] for the serialization of the models. The benefit for using AutomationML include that there would not be a need to develop a new non-standard XML (like the Proteus schema) or JSON schema. However, the use of a standard format can also entail overhead into the data exchange.

The DEXPI+ specification is still under development. The release candidate version identifies that further work is needed specially related to defining the presentation layer and its relation to the information model [4]. Since DEXPI 1.3 the graphics package has complemented the DEXPI information model to include also conceptual and graphics information in a single model (the graphics package in DEXPI 1.3 is still informative) [5].

6.6 ISO/IEC 81346-1

IEC 81346 is a key standard in the field of industrial automation, specifically focused on the structuring and referencing of technical information within this domain. It provides a comprehensive framework for organizing and labeling industrial systems, which is essential for design, documentation, and communication in the automation industry.

ISO/IEC 81346, formally known as "Industrial systems, installations, and equipment and industrial products - Structuring principles and reference designations," offers a structured and consistent approach to naming and classifying industrial systems and their components. This consistency is vital for clarity and understanding in industrial automation.
ISO/IEC 81346 consists of more parts (e.g., IEC 81346-1, IEC 81346-2, IEC 81346-10, IEC 81346-12). These parts work together to establish a logical system for assigning reference designations to equipment and their functions. Part 1 (IEC 81346-1) provides the overarching framework for the classification and referencing of objects in industrial systems. It introduces the concept of a 'Functional Breakdown Structure (FBS)' to organize functions and sub-functions within a system. The FBS comprises a

hierarchical arrangement that starts with the highest-level function and breaks it down into more detailed sub-functions.

Key properties:

- Unambiguous Identification: One of the main goals of IEC 81346 is to ensure that every component in an industrial system has a unique and unambiguous reference designation. This enables engineers, technicians, and other stakeholders to easily locate and identify components, enhancing efficiency and safety in the workplace.
- Improved Collaboration: IEC 81346 fosters better collaboration within and across industries by providing a common language for all involved in industrial automation. Engineers, manufacturers, operators, and maintenance personnel can communicate more effectively when using standardized reference designations.
- Lifecycle Management: IEC 81346 supports the entire lifecycle of industrial systems, from design and construction to operation, maintenance, and eventual decommissioning. This systematic approach ensures that information remains consistent and useful throughout the life of the system.
- International Applicability: IEC 81346 is an international standard, making it suitable for use worldwide. It helps to eliminate confusion resulting from language and regional differences, promoting global consistency in industrial automation practices.
- Integration with Other Standards: IEC 81346 can be used in conjunction with other standards related to industrial automation, such as IEC 61131 for programmable logic controllers and IEC 61499 for function blocks. This compatibility enhances the overall effectiveness of industrial automation systems.

In summary, IEC 81346 is a fundamental standard in the field of industrial automation, providing a structured and universally applicable framework for the classification and referencing of industrial systems, equipment, and components. It promotes clarity, consistency, and efficiency in design, documentation, and communication within the industry, ultimately contributing to safer and more effective industrial automation practices.

6.7 CFIHOS

The Capital Facilities Information Handover Specification (CFIHOS) is an industry standard developed to improve how information is exchanged between the companies who own, operate, and construct equipment for the process and energy sectors. Starting with a common equipment naming taxonomy and supporting specifications, its goal is to become a common language for the exchange of information in these sectors.

The initial focus is on information, both structured data and traditional document formats, which must be handed over when a project moves from its development to operations phase. Ultimately, the aim is for CFIHOS to become the de-facto standard for information exchange throughout the physical asset lifecycle, from vendor information through to decommissioning.

The CFIHOS RDL (Reference Data Library) provides a standard and unified naming convention for equipment classification, its properties, disciplines and documents. It is a set of information requirement specifications for documents and tagged items. The CFIHOS RDL includes:

- A list of classes for Tag and Equipment (what the equipment does and what it is)
- A list of properties (attributes, measures, characteristics etc.)
- Lists of requirements by class (data and document requirements)
- Standard unique coding of data to facilitate digital design and other workflows

- A list of document types
- A list of disciplines.

CFIHOS covers only the exchange of structured data and documents - not graphical, geometry, and model data.

6.8 IEC 61131-3

PLCopen is an independent worldwide organization aiming to improve efficiency in industrial automation. PLCopen and its members have focused on defining technical specifications around the IEC 61131-3 standard to reduce costs in industrial engineering. This resulted for example in standardized libraries for different application fields, harmonized language conformity levels, engineering interfaces for exchange, and transparent communication. [11]
In 2014, PLCopen organization published the PLCopen XML to enable exchange of 61131-3 programs, libraries and projects between software tools like development environments. This standard, defined as IEC 61131-10, provides an open interface between different software tools. It enables exchange of information displayed on a screen of one system to other platforms. This information is not limited to textual information, but also graphical information, including the position and size of the function blocks, and how they are connected. The transferred program remains the same after the exchange.

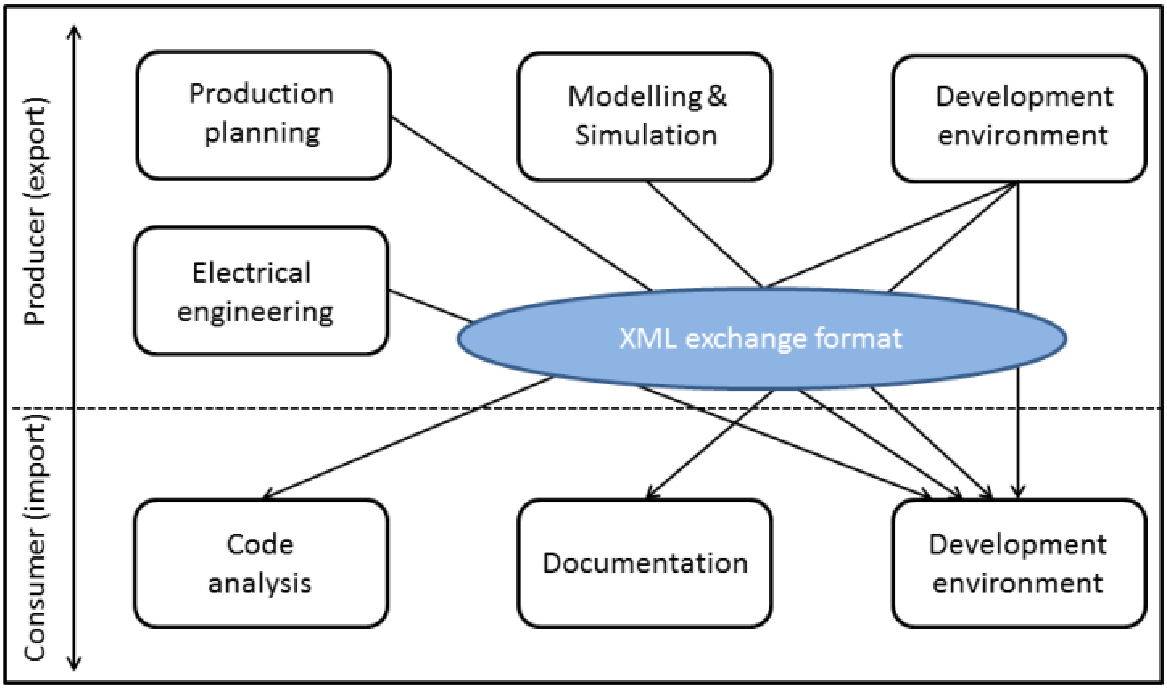

Figure 6.7.1 – PLCopen XML exchange

The goal is to seamlessly transfer a control project from one development environment to another without loosing information even when it is incomplete, e.g., not compatible without errors. This is also valid for the POUs, and especially for the User Derived Function Block libraries. The XML exchange format provides for life cycle management of automation systems, e.g., in case of redesign, maintenance or device replacement. If an IEC 61131-3 project is stored in this standard's XML exchange format, it could be reused independent of a special development environment. And thus, it could be modified and maintained by any other development environment supporting this standard's XML exchange format. [12]

The PLCopen XML standard allows the representation of a complete project within the IEC 61131-3 environment, including the common elements with Sequential Function Chart (SFC), the two textual languages Structured Text (ST) and Instruction List (IL), and the two graphical languages Function Block Diagram (FBD), and Ladder Diagram (LD). The formats are specified through corresponding XML schema. An independent file, also part of this specification. The described formats are for the import and export of IEC 61131-3 Projects and Program Organization Units (POUs). The exchange of graphical language constructs between different Programming Systems is focused on logical information with optional explicit graphics. [13]

There are many possible uses for the PLCopen XML standard:

- The exchange or POU(s) or complete projects.
- (One time) migration to another system.
- Parallel use of multiple systems.

The PLCopen standard has also been adopted by the AutomationML organization [5]. This cooperation closes the gaps between production design (virtual factory) and the shop floor resulting in reduced time to market and lower costs for manufacturers. Several PLCopen member companies are supporting the XML. [14]

6.9 S5000F

S5000F is an international specification for in-service data feedback.

With the introduction of new and complex technical products, a proper support system must be made available in a timely manner. This requires a proper product surveillance in order to fulfil the product liability regulations and to ensure a proper and optimal exploitation of product capabilities. A process for information feedback thus becomes necessary so as to ensure cost-efficient and optimised operation of the product. Over the life cycle of a complex technical system or product, support costs are much higher than the acquisition costs. Therefore, this specification is a prerequisite for cost saving and optimized product exploitation. It describes the relevant data flow for the involved parties and information feedback when the data is analysed and turned into recommendations.

The specification S5000F [36] [37] has been designed to cover the information that is required to be feedback for both Integrated Product Support (IPS) and other domains. It should be kept in mind that in-service data feedback is one of the most important functions of in-service support. It enables fleet and support managers and technical system manufacturers to perform a thorough analysis of operational and maintenance performance, as well to use real data for analytics and simulations.

A detailed overview is available in **Appendix 3** (S5000F_Overview.docx).

6.10 S3000L

S3000L [38] is an international procedure specification for Logistic Support Analysis (LSA).
S3000L describes the LSA process and the corresponding analysis activities to be considered for the definition and ongoing maintenance of a suitable support environment to operate technical complex and long-living products. Complementary to the procedural chapters of the specification, the corresponding data model is described by a detailed UML model based on ISO Standard 10303, AP239, PLCS. A schema has been derived from the UML model to enable the exchange of data.

The specification S3000L is designed to cover the activities and requirements for the establishment of the LSA process:

- to create an Integrated Product Support solution;
- to identify required resources to support a system;
- to reduce costs;
- to increase availability;
- to exchange information between different parties;
- and to store data and results for future reference;
- in a structured and methodological way.

To ensure the maximum availability against the minimum costs of technically complex and long-living products, it is essential to identify the required resources and create a proper product support environment from the beginning of the product usage phase. An extensive analysis process must be established to cover the support requirements for the complete life cycle. This process ensures the consideration of all product support requirements during the design and development phase, the in-service phase and finally during the disposal phase.

LSA activities cover a wide range of technical and logistic analyses and the documentation of the results. The outcome forms the basis for the subsequent disciplines within the ILS (Integrated Logistic Support) process like technical documentation or materiel support.

Scope of S3000L

The specification S3000L is designed to provide guidance for analysis activities during the LSA process.

A schema derived from of the S3000L UML model and a detailed data element list enables the storage and exchange of information using XML files. A set of ‘valid values’ schemas are provided to support the tailoring of the data set and adaptation to the program requirements. The following aspects are included:

- S3000L supports the design of an LSA process in the initial project phases including the performance of an LSA Guidance Conference
- S3000L provides rules for the creation of a suitable product breakdown and for the selection of LSA candidate items
- S3000L describes type and methodology for specified analysis activities
- S3000L provides guidelines on how to process the results of the different analysis activities and on how to achieve a cost-efficient support concept
- S3000L describes the interface to the customer within the LSA process
- S3000L covers the interface between the LSA process and the analysis activities of the support engineering areas like Reliability, Maintainability and Testability analysis (RM&T)
- S3000L describes the interface between the LSA process and the ILS disciplines, which provide the ILS products like:
- Personnel and training requirements
- Spare parts and consumables support
- Technical documentation
- Special support and test equipment
- Facilities/infrastructure requirements
- Software support requirements

- S3000L describes the identification of maintenance tasks and the Maintenance Task Analysis

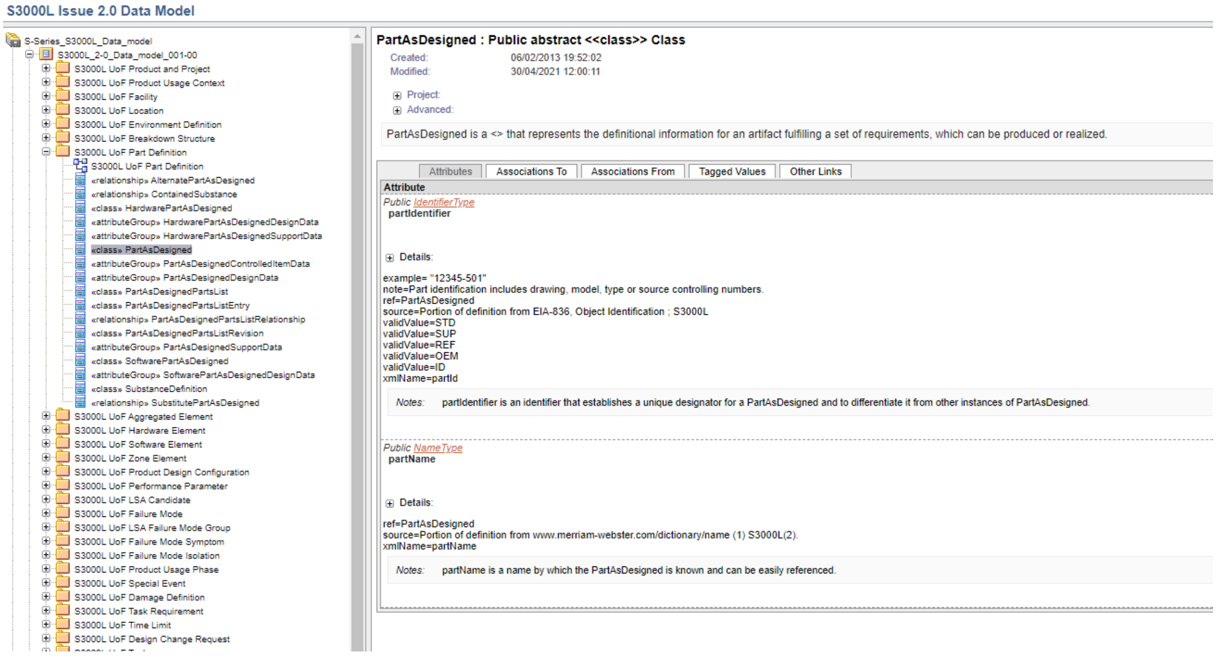

Figure 6.14.1 – A screenshot from the Data Model browser

6.11 S2000M International Specification for Material Management

S2000M is an international standard that specifies the information exchange requirements for most materiel management functions commonly performed in supporting international projects. It was developed by the Aerospace and Defence Industries Association of Europe (ASD) and the Aerospace Industries Association of America (AIA) to facilitate the material management processes and procedures to be applied in support of military and non-military products. It forms part of a common, interoperable, international ASD Suite of Integrated Product Support (IPS) specifications.

Class of standard

S2000M is a data model standard, which means it defines the structure, semantics, and constraints of the data that describe the material management activities in support of a product and its engineering process. It is based on the ISO 10303 series of standards, which are also known as STEP (Standard for the Exchange of Product model data).

Scope of standard

The scope of S2000M covers the following aspects of material management:
Some of the key concepts of S2000M are:

- covers all material management activities in support of military and non-military products throughout the lifecycle of an asset or project.
- describes the business relationship between contractor and customer by providing the process flow, the relevant transactions and data elements used for the information exchange.
- is organized into chapters, which are designed to stand alone for ease of understanding as well as ease of implementation.
  Some of the chapters are:
  Provisioning,
  Pricing,
  Order Administration,
  Invoicing.

- is part of a common, interoperable, international ASD Suite of Integrated Logistics Support (ILS) specifications.

Relation to ISO 10303-239 PLCS

The relation between ASD ILS Suite and ISO 10303-239 is that they are both standards for information management in the aerospace and defence industry.
However, they have different scopes and objectives:

- ASD ILS Suite is a set of specifications that cover different aspects of integrated logistics support (ILS), such as technical publications, material management, logistics support analysis, preventive maintenance, in-service data feedback, and training analysis and design1. The ASD ILS Suite is developed and maintained by the Aerospace and Defence Industries Association of Europe (ASD) and the Aerospace Industries Association (AIA), and it aims to improve the efficiency, interoperability, and quality of the ILS processes and data.
- ISO 10303-239, also known as PLCS (Product Life Cycle Support), is an international standard that provides a framework for the effective and efficient management of information throughout the whole lifecycle of a built asset or project, using BIM processes and technologies2. ISO 10303-239 is developed and maintained by the International Organization for Standardization (ISO), and it aims to support the exchange and sharing of information between different systems and organizations.

The ASD ILS Suite and ISO 10303-239 are related in the following ways:

- They are both based on a common data model, which is defined in SX002D - Common data model for the S-Series IPS specifications. This data model is aligned with the ISO 10303-239 data model, and it supports the implementation of the ASD ILS Suite specifications using XML schemas.
- They are both involved in the development of the new ISO 10303-239 Edition 3 project, which intends to update the current ISO 10303-239 Edition 2 standard to support the latest business requirements and specifications from the aerospace and defence industry, and to ensure interoperability with other related ISO 10303 standards, such as ISO 10303-242 (AP242) for engineering and manufacturing. The ASD ILS Suite specifications are one of the main sources of input for the ISO 10303-239 Edition 3 project, and they will benefit from the improved capabilities and features of the new standard.

Data model language

S2000M uses the XML schema to define the data model.

Data exchange format

S2000M uses the XML data exchange format.

Industry applying the standard

S2000M is mainly applied in Aerospace&Defence industries that deal with complex products that have a long-life cycle and require extensive support, such as aerospace, defense, automotive, marine, and energy. The largest implementation base is in the military industry. Some examples of products that can benefit from S2000M are aircraft, ships, vehicles and telecommunication systems.

Relevance for the future

S2000M is relevant for the future because it enables the efficient and effective management of material information throughout the product life cycle, which can lead to improved product quality, reduced costs, increased safety, and enhanced customer satisfaction.

6.12 ISO 10303-239 Product Life Cycle Support

ISO 10303-239, also known as Product Lifecycle Support (PLCS), is a data model standard that specifies how to represent and exchange information about a complex product and its support solution throughout its life cycle. It was developed by a joint industry and government initiative to facilitate the maintenance, upgrade, and modification of products such as aircraft, ships, vehicles, and industrial plants.

Class of standard
ISO 10303-239 is a data model standard, which means it defines the structure, semantics, and constraints of the data that describe a product and its support. It is part of the ISO 10303 series of standards, which are also known as STEP (Standard for the Exchange of Product model data).

Scope of standard
The scope of ISO 10303-239 covers the following aspects of product life cycle support:

- information for defining a complex product and its support solution;
- information required to maintain a complex product;
- information required for through life configuration change management of a product and its support solution;
- the representation of product structures, assemblies, and breakdowns, including the identification and representation of parts, their versions, definitions, documentation, and management information;
- the representation of multiple product structure views, such as functional, physical, system, and zonal breakdowns;
- the representation of the shape of an assembly as the composition of the shape representation of its components;
- the identification of positions within an assembly of parts to which component parts may be attached;
- the association of valued properties to a part or to an assembly;
- the representation of interfaces between products;
- the classification of parts, documents, and assemblies;
- the representation of a product through life, including the representation of product requirements and their fulfilment, the representation of existing or potential future products, the identification of the configuration of a product for a given role, the specification of effectivity constraints applied to the configuration of a product, and the representation of predicted and observed states of products;
- the specification and planning of activities for a product, including the specification of tasks to be performed on a product, the representation of conditions for performing the tasks, the representation of the type of person and skills required for performing a task, the representation of planning and scheduling of the tasks, and the management and authorization of the subsequent work;
- the representation of the activity history of a product, including the recording of the usage of a product and the resource usage, and the recording of the activities performed on a product and the resource usage;
- the representation of the product history, including a historical record of the states of a product, a historical record of the configuration status of the product, the location of product data, and the observation of product data.

Data model language
ISO 10303-239 uses the EXPRESS data modeling language as well as SysML to define the schema of the data model. EXPRESS is a formal language that supports the specification of data types, entities, attributes, relationships, constraints, and rules. It is also part of the ISO 10303 series of standards.

Data exchange format

ISO 10303-239 uses the STEP-XML data exchange format to encode the data model in XML. STEP-XML is a standard that defines how to represent EXPRESS data models in XML. It is also part of the ISO 10303 series of standards.

Industry applying the standard

ISO 10303-239 is mainly applied in industries that deal with complex products that have a long-life cycle and require extensive support, such as aerospace, defense, automotive, marine, and energy. Some examples of products that can benefit from ISO 10303-239 are aircraft, ships, vehicles, telecommunication systems, power plants, oil platforms, mining equipment, elevators, and process plants.

Relevance for the future

ISO 10303-239 is relevant for the future because it enables the efficient and effective management of product information throughout the product life cycle, which can lead to improved product quality, reduced costs, increased safety, and enhanced customer satisfaction. It also facilitates the interoperability and integration of different systems and tools that support the product life cycle, such as product lifecycle management (PLM), computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), enterprise resource planning (ERP), and maintenance, repair, and overhaul (MRO) systems.

6.13 ISO 18101

ISO 18101, titled "Oil and gas industries — Integrated operations — Information management", focuses on the management of information in the oil and gas industry, specifically in the context of integrated operations.

The scope of ISO 18101 includes:

- Standardization of Information Management: ISO 18101 aims to standardize the way information is managed across various operations in the oil and gas sector, including exploration, production, and transportation.
- Facilitation of Integrated Operations: The standard provides guidelines to facilitate integrated operations, aiming to enhance efficiency and safety. It focuses on ensuring that relevant information is accessible, accurate, and timely.
- Interoperability and Data Exchange: It emphasizes interoperability among different systems and stakeholders, ensuring that data exchange is seamless and consistent.
- Application in Digital Transformation: The standard is particularly relevant in the context of digital transformation in the oil and gas industry, as it supports the effective use of digital technologies and data analytics.

6.14 OPAF

OPAF, the Open Process Automation Forum is a consensus-based group of end users, suppliers, system integrators, standards organizations, and academia. It addresses both technical and business issues for process automation. OPAF is a part of The Open Group, a global consortium that enables the achievement of business objectives through technology standards with more than 800 participating organizations including users, systems and solutions suppliers, tool vendors, integrators, academics and consultants across multiple industries.

A "Standard of standards"		
O-PAS part	**Subject matter**	**Referenced standards**
Part 1	Technical architecture	IEC 62264 (ISA 95)
Part 2	Security	IEC 62443 (ISA 99)
Part 3	Profiles	n.a.
Part 4	Connectivity framework	IEC 62541 (OPC UA)
Part 5	System management	DMTF (Redfish)
Part 6	Information and exchange models	IEC 62714 (AutomationML IEC 62682 (ISA 18) IEC 61131 IEC 61499
Part 7	Physical platform	"whitespace"

Figure 6.14.1 – The scope of OPAF [42]

OPAF, formally launched in November of 2016, develops and maintains the Open Process Automation Standards (O-PAS, figure 1). To ensure interoperability, the parts of O-PAS follow accepted reference standards including ISA 95, ISA 99, ISA 18, OPC UA, and others. The O-PAS Standard, Version 2.1 Preliminary was published in May 2021 and is available now.

6.15 ISO 10303-242

ISO 10303-242, also known as Managed Model-Based 3D Engineering (MIMB3DE), is a data model standard that specifies how to represent and exchange information about a complex product and its engineering process throughout its life cycle. It was developed by the International Organization for Standardization (ISO) to facilitate the integration and interoperability of different systems and tools that support the product life cycle, such as product lifecycle management (PLM), computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), and enterprise resource planning (ERP) systems.

Class of standard
ISO 10303-242 is a data model standard, which means it defines the structure, semantics, and constraints of the data that describe a product and its engineering process. It is part of the ISO 10303 series of standards, which are also known as STEP (Standard for the Exchange of Product model data).

Scope of standard
The scope of ISO 10303-242 covers the following aspects of product life cycle engineering:

- information for defining a complex product and its engineering process, including parts, assemblies of parts, tools, assemblies of tools, and raw materials;
- engineering and product data for the purpose of long-term archiving and retrieval;
- product data management data and configuration control data for managing large numbers of variants of products during the design phase;
- data describing the changes that have occurred during the design phase, including tracking of the versions of a product and of the data related to the documentation of the change process;
- identification of standard parts, based on international, national, or industrial standards;
- release and approval data for product data;
- data that identify the supplier of a product and related contract information;
- properties of parts or of tools;
- references to product documentation represented in a format other than those specified by ISO 10303;
- product manufacturing information, covering the design and manufacturing planning phase;
- identification of physically realized parts or of tools, including assembly of physically realized products and recording of test results;
- process planning information describing the relationships between parts and the tools used to manufacture them and to manage the relationships between intermediate stages of part or tool development;
- mechanical design data, including different types of geometry models, such as 2D- and 3D-wireframe, geometrically bounded surface, topologically bounded surface, faceted-boundary, boundary, compound shape, constructive solid, parametric and constrained, 2D-sketch, 3D tessellated, and 3D scan models;
- representation of the shape of parts or tools that is a combination of two or more of different types of geometry models;
- data that pertains to the presentation of the shape of the product;
- representation of portions of the shape of a part or a tool by manufacturing features;
- data defining surface conditions;
- dimensional and geometrical tolerance data;
- quality criteria and inspection results of given three-dimensional product shape data;
- product documentation as annotated 3D models and as drawings;
- kinematics simulation data for the description of kinematic structures and motion;

- composite design data for the definition of composite structural parts and the association of the constituents of composite and metallic parts with the constituent shape model.

Data model language
ISO 10303-242 uses the EXPRESS data modeling as well as SysML language to define the schema of the data model. EXPRESS is a formal language that supports the specification of data types, entities, attributes, relationships, constraints, and rules. It is also part of the ISO 10303 series of standards.

Data exchange format
ISO 10303-242 uses the STEP-XML data exchange format to encode the data model in XML. STEP-XML is a standard that defines how to represent EXPRESS data models in XML.

Industry applying the standard
ISO 10303-242 is mainly applied in industries that deal with complex products that have a long-life cycle and require extensive engineering, such as aerospace, defense, automotive, marine, and energy. Some examples of products that can benefit from ISO 10303-242 are aircraft, ships, vehicles, telecommunication systems, mining equipment, and elevators.

Relevance for the future
ISO 10303-242 is relevant for the future because it enables the efficient and effective management of product information throughout the product life cycle, which can lead to improved product quality, reduced costs, increased safety, and enhanced customer satisfaction. It also facilitates the interoperability and integration of different systems and tools that support the product life cycle, such as product lifecycle management (PLM), computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), and enterprise resource planning (ERP) systems.

6.16 IFC – Industry Foundation Classes

Industry Foundation Classes (IFC) is a data model standard that specifies how to represent and exchange information about building and/or infrastructures design. It is an open, international standard (ISO 16739-1:2018) that promotes vendor-neutral, or agnostic, and usable capabilities across a wide range of hardware devices, software platforms, and interfaces for many different use cases. The IFC schema specification is the primary technical deliverable of buildingSMART International to fulfill its goal to promote openBIM.

Class of standard
IFC is a data model standard, which means it defines the structure, semantics, and constraints of the data that describe a product and its engineering process. It is closely related to the ISO 10303 STEP standard and utilizes many of the concepts of STEP like the geometry models, the data modeling languages as well as the data exchange formats.

Scope of standard
The scope of IFC covers the following aspects of product life cycle engineering:

- information for defining a complex building or infrastructure and its engineering process, including parts, assemblies of parts, tools, assemblies of tools, and raw materials;
- engineering and product data for the purpose of long-term archiving and retrieval;
- identification of standard parts, based on international, national, or industrial standards;
- release and approval data for product data;
- data that identify the supplier of a product and related contract information;
- properties of parts or of tools;
- ~~references to product documentation represented in a format other than those specified~~ by IFC;

- design data, including different types of geometry models, such as 2D- and 3D-wireframe, 3D tessellated, and 3D scan models;
- representation of the shape of parts or tools that is a combination of two or more of different types of geometry models;
- data that pertains to the presentation of the shape of the product;
- data defining surface conditions;
- composite design data for the definition of composite structural parts and the association of the constituents of composite and metallic parts with the constituent shape model.

Data model language
IFC uses the EXPRESS data modeling language to define the schema of the data model. EXPRESS is a formal language that supports the specification of data types, entities, attributes, relationships, constraints, and rules. Express is a part of the ISO 10303 series of standards.

Data exchange format
IFC uses the STEP-XML data exchange format to encode the data model in XML. STEP-XML is a standard that defines how to represent EXPRESS data models in XML. It is also part of the ISO 10303 series of standards.

Industry applying the standard
IFC is the main data modeling standard of the world-wide building and infrastructure industry.

Relevance for the future
IFC is relevant for the future because it enables the efficient and effective management of product information throughout the product life cycle, which can lead to improved product quality, reduced costs, increased safety, and enhanced customer satisfaction.

6.17 IEC 61499

The IEC 61499 standard defines a generic model for distributed control systems and builds on the IEC 61131 standard, which defines a generic architecture and presents guidelines for the use of function blocks in distributed Industrial-Process Measurement and Control Systems (IPMCSs).

The Eclipse Foundation 4diac project is focused on creating open-source software for distributed industrial control and automation based on the IEC 61499 standard. The components of Eclipse 4diac are provided under Eclipse Public License, Version 2.0.

The part of the standard:

- IEC 61499-1: Architecture. Part 1 defines a generic architecture and presents guidelines for the use of function blocks in distributed industrial-process measurement and control systems (IPMCSs). This architecture is presented in terms of implementable reference models, textual syntax and graphical representations. The models given in this standard are intended to be generic, domain independent and extensible to the definition and use of function blocks in other standards or for particular applications or application domains. It is intended that specifications written according to the rules given in this standard be concise, implementable, complete, unambiguous, and consistent.
- IEC 61499-2: Software tool requirements. Part 2 defines requirements for software tools to support the specification of function block types, the functional specification of resource types

and device types, configuration, implementation, operation and maintenance of distributed IPMCSs.
- IEC 61499-4: Rules for compliance profiles. Part 4 defines rules for the development of compliance profiles. It specifies the features of Part 1 and Part 2, including interoperability, portability and configurability.

Control and automation application portability across industrial automation vendor systems is a major goal of the Open Process Automation Forum and many users. Currently IEC 61449-2 defines rules for engineering tools as well as XML interchange format. In addition, IEC 61131-10 specifies an XML-based exchange format for the export and import of IEC 61131-3 projects. The big issue is these are not meaningfully supported and there is no certification to the standards.

6.18 ISO 12006 – Building construction

ISO 12006 is an international standard that deals with the organization of information about construction works. It is within the discipline of architecture for building construction. It aims to enable the exchange and integration of information among different systems and tools that support the design, construction, operation, and maintenance of buildings and civil engineering works.

Class of standard
ISO 12006 is a data model standard, which means it defines the structure, semantics, and constraints of the data that describe construction works and their engineering processes. It does not carry any detailed data model, only an overview model. The classes, relations and constraints are defined in natural language.
It consists of three parts:

- Part 1: Principles and requirements;
- Part 2: Framework for classification;
- Part 3: Framework for object-oriented information.

Scope of standard
The scope of ISO 12006 covers the following aspects of construction works:

- information for defining building complex, buildings and building elements and the relations between them.
- references to product documentation represented in a format other than those specified by ISO 12006;
- product manufacturing information, covering the design and manufacturing planning phase;
- process planning information describing the relationships between parts and the tools used to manufacture them and to manage the relationships between intermediate stages of part or tool development.

Data model language
ISO 12006 uses the EXPRESS data modeling language to define the overview schema of the data model. EXPRESS is a formal language that supports the specification of data types, entities, attributes, relationships, constraints, and rules.

Data exchange format
ISO 12006 does not specify a data exchange format.

Industry applying the standard
ISO 12006 is mainly applied in industries that deal with complex products that have a long-life cycle and require extensive engineering, such as building and civil engineering. Some examples of products that can benefit from ISO 12006 are buildings, bridges, tunnels, roads, dams, and pipelines.

Relevance for the future
ISO 12006 is relevant for the future because it enables the efficient and effective management of information about construction works throughout their life cycle, which can lead to improved product quality, reduced costs, increased safety, and enhanced customer satisfaction.
It is the foundation for classification standards like IEC 81346.

6.19 IEC 61987

IEC 61987 is a series of standards concerning Industrial-Process Measurement and Control. These standards provide guidelines and structures for various aspects of industrial process measuring equipment.

The key properties of the different parts are the following:

- IEC 61987-1:2006: This section defines a generic structure for the product features of industrial-process measurement and control equipment, whether they have analogue or digital output. The purpose is to aid in the understanding and transfer of product descriptions between different parties.
- IEC 61987-10:2009: This standard establishes a method for standardizing descriptions of process control devices, instrumentation, and auxiliary equipment, as well as their operating environments and requirements, such as measuring point specification data.
- IEC 61987-11:2016: This part offers a characterization of industrial process measuring equipment, facilitating its integration into the Common Data Dictionary (CDD). It includes generic structures for the operating lists of properties (OLOP) and device lists of properties (DLOP) for measuring equipment, conforming to IEC 61987-10.
- IEC 61987-12:2016: This part focuses on flow measuring equipment. It provides an operating list of properties (OLOP) for describing the operating parameters and requirements of flow measuring equipment, as well as device lists of properties (DLOP) for various types of flow measuring equipment.
- IEC 61987-24-3:2017: This part provides OLOP for the description of operating parameters and requirements for flow modification accessories for automated valves. It also includes DLOPs for these accessories, detailing them in Annex B.

In summary, the IEC 61987 series serves as a comprehensive guide for standardizing and characterizing industrial process measurement and control equipment, ensuring clarity and consistency in the description and communication of product features and specifications across the industry.

6.20 ISO/TS 4398:2022

ISO/TS 4398:2022 is a standard for Intelligent transport systems (Guided transportation service planning data exchange).

The main goal of the standard is to allow interoperability between heterogeneous subsystems operating on railway transportation systems by a unified data model that allows efficient and unambiguous description of assets and operations. The standard specifies a data format called RailDAX (Railway Data Exchange) that describes infrastructure and rolling stock from an operational perspective, allowing static processes (timetable planning, history logging) as well as dynamic decision making (real-time traffic monitoring and control) and simulation.

RailDAX is based upon the RailML description language version 2.4 [25]. This is an XML-based description language, open-sourced under a Creative Commons [26] licence. RailDax will typically be used by railway authorities, train operators, infrastructure managers and suppliers to the railway industry. The language defines sub-schemas for different entities including infrastructure, timetable, rolling stock, and interlocking. In particular:

- The Timetable sub-schema describes Operating Periods, Train Parts, Trains (a set of train parts) and Rostering (rolling stock schedules).
- The Rolling stock sub-schema describes Vehicles (in many technical aspects) and Formations (homogeneous groups of vehicles).

- The Infrastructure sub-schema describes Topology (the track as a graph), Coordinates (geolocation), Geometry, a variety of infrastructure elements, and Further located elements closely linked with the railway infrastructure.
- The Interlocking sub-schema describes the information needed for interlocking planning and management, reusing many concepts defined by the Infrastructure sub-schema.

6.21 ISO 19650 Common Data Environment CDE

The ISO 19650 CDE standard is an international standard for managing information over the whole life cycle of a built asset using building information modelling (BIM). It defines the concept, principles, and requirements of a common data environment (CDE), which is a single platform or group of integrated IT solutions that provide a centralised repository for the collection, management, and dissemination of project and asset information through a managed process. The ISO 19650 CDE standard aims to facilitate the integration and interoperability of different systems and tools that support the design, construction, operation, and maintenance of buildings and civil engineering works.

Class of standard
The ISO 19650 CDE standard is both a management standard and a data model standard, which means it defines both principles as well as the structure, semantics, and constraints of the data that describe a product and its engineering process.

Scope of standard
The scope of the ISO 19650 CDE standard covers the following aspects of product life cycle engineering:

- The CDE is a **single source of truth** for all information related to a built asset or project, and it supports the **collaboration** and **coordination** among all stakeholders.
- The CDE is divided into four areas: **work-in-progress (WIP)**, **shared**, **published**, and **archive**. Each area has its own **rules** and **responsibilities** for information production, exchange, verification, and use.
- The CDE follows the **information delivery cycle (IDC)**, which is a series of activities and tasks that define how information is **produced**, **exchanged**, **verified**, and **used** throughout the lifecycle of a built asset or project.
- The CDE can be implemented using a **single platform** or a **group of integrated IT solutions**, depending on the needs and preferences of the project or asset participants.
- The CDE is aligned with the **ISO 19650 information management process**, which provides a framework for the effective and efficient management of information using **BIM processes** and **technologies**.

Data model language
The ISO 19650 CDE is a management standard but it utilizes the EXPRESS data modeling language to define the schema of the data models when needed. EXPRESS is a formal language that supports the specification of data types, entities, attributes, relationships, constraints, and rules.

Data exchange format
The ISO 19650 CDE standard does not specify a data exchange format.

Industry applying the standard
The main industry of applicability for ISO 19650 is the built environment, which includes the creation, design, construction, operation, management, and maintenance of buildings and civil engineering works, ~~such as houses, offices, schools, hospitals, bridges, tunnels, roads, dams, and pipelines. The standard is~~

relevant for any organization involved in the use of information management and technologies for the delivery and operation of built assets or products, as well as the provision of services, within the built environment.

Relevance for the future
The ISO 19650 CDE standard is relevant for the future because it enables the efficient and effective management of information about construction works throughout their life cycle, which can lead to improved product quality, reduced costs, increased safety, and enhanced customer satisfaction.

6.22 ASAM-ODS

ODS (Open Data Services) [24] focuses on the persistent storage and retrieval of testing data. The standard is primarily used to set up a test data management system on top of test systems that produce measured or calculated data from testing activities. Tool components of a complex testing system can store data or retrieve data as needed for proper operation of tests or for test data post-processing and evaluation. A typical scenario for ODS in the automotive industry is the use of a central ODS server, which handles all testing data produced by vehicle test beds. The major strength of ODS as compared to non-standardized data storage solutions is that data access is independent of the IT architecture and that the data model of the database is highly adaptable yet still well-defined for different application scenarios. Despite this flexibility, clients can query the data from the database and still correctly interpret the meaning of the data. This is achieved by various means through the standard.

Base model: The base model is used as a parent for deriving specific application models. The base model provides a rough classification of the data in application models by adding semantics to them. This enables client tools from different vendors to correctly interpret the data.

Application models: Application models cover the data storage needs for specific application areas. The standard provides pre-defined application models for test object geometry, NVH testing, test stand calibration, bus data and testing workflows.

Format for physical storage: This part of the standard specifies how a relational database should initially be constructed to store data in a compliant way.

API: Clients have access to data on the ODS-server via a web-service API using the Hypertext Transfer Protocol (short: HTTP-API). Data is serialized and transferred in the Google Protocol Buffers format. For legacy reasons, the standard still contains an object-oriented API based upon the CORBA architecture (short: OO-API) and a remote procedure call API (short: RPC-API).

File description format: The description formats allow file-based data exchange between tools. One non-XML format (for legacy purposes) and a modern XML-format is provided.

External Data API (EXD-API): A programming interface which allows to access mass data stored in external files of any type as long as an EXD-API implementation for such file type is available.

6.23 ISO-IEC 25012

ISO/IEC 25012:2008 [23] defines a general data quality model for data retained in a structured format within a computer system. ISO/IEC 25012:2008 can be used to establish data quality requirements, define data quality measures, or plan and perform data quality evaluations.

It could be used:

- to define and evaluate data quality requirements in data production, acquisition and integration processes,
- to identify data quality assurance criteria, also useful for re-engineering, assessment and improvement of data,
- to evaluate the compliance of data with legislation and/or requirements.

ISO/IEC 25012:2008 categorizes quality attributes into fifteen characteristics considered by two points of view: inherent and system dependent. Data quality characteristics will be of varying importance and priority to different stakeholders. ISO/IEC 25012:2008 is intended to be used in conjunction with the other parts of the SQuaRE series of International Standards, and with ISO/IEC 9126-1 until superseded by ISO/IEC 25010.

6.24 IEEE 1451

The IEEE 1451 list of standards focuses on sensor descriptions in the form of electronic data-sheets, which are stored in a compressed Type Length Value (TLV) format on the devices themselves. The devices need to implement logic to allow for manipulation and retrieval of the stored information. The data is organized in multiple blocks called Transducer Electronic Data-Sheet (TEDS) specified in IEEE 1451.0 [8], where each block contains data matching the name of the block, e.g., Meta TEDS, Channel TEDS, Calibration TEDS, etc. The counterpart interacting with the devices to manipulate the electronic data-sheet is called Network Capable Application Processor (NCAP) and the communication protocol used and its specific IEEE 1451 implementation is specified in sub-standards (IEEE 1451.2, 1451.3). An analysis of the protocol family is given in [9]. Limitations of the IEEE 1451 standard family would be the need to have a processor supporting standard specific operations and, depending on the bulk of information, up to multiple Megabytes of memory on the devices themselves. Another limitation of the standard family is the static number of semantic keywords, which could be extended by using reserved fields, but the extensions have to be implemented on the NCAP device, parsing the information as well as in the electronic data-sheet itself. An example use case in which the standard is used in a wireless sensor network can be seen in [10].

A detailed overview is available in **Appendix 4** (IEEE_1451_Overview.docx).

6.25 IEC 61850

IEC 61850 is an international standard developed by WG10 of IEC TC57, a technical committee of the International Electrotechnical Commission (IEC) that deals with power systems management and associated information exchange. [15]
The objective of IEC 61850 is to provide interoperability and integration of intelligent electronic devices (IEDs) from different vendors in substation automation and power distribution systems. The standard defines a common data model, a common communication service interface, and specific communication service mappings for various protocols.
The standard consists of 14 parts, each addressing a specific aspect of communication and system architecture.

The parts are:
Part 1: Introduction and overview
Part 2: Glossary
Part 3: General requirements
Part 4: System and project management
Part 5: Communication requirements for functions and device models
~~Part 6: Configuration language for communication in electrical substations related to IEDs~~

Part 7: Basic communication structure for substation and feeder equipment
Part 8: Specific communication service mapping (SCSM)
Part 9: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3
Part 10: Conformance testing
Part 90: Use of IEC 61850 for the communication between substations
Part 91: Use of IEC 61850 for the communication between substations and control centres
Part 92: Mapping to Extensible Messaging Presence Protocol (XMPP)
Part 93: Communication networks and systems in substations – Cybersecurity

Key properties of IEC 61850:

- It uses abstract data models to represent the functions and data of substation devices, such as logical nodes, data objects, data attributes, services, and service parameters.
- It supports multiple communication protocols, such as Manufacturing Message Specification (MMS), Generic Object Oriented Substation Event (GOOSE), Sampled Values (SV), Precision Time Protocol (PTP), and Extensible Messaging Presence Protocol (XMPP).
- It defines a configuration language (SCL) based on XML to describe the system configuration, device configuration, and communication configuration.
- It enables plug-and-play functionality for IEDs by using self-description files that contain the device capabilities and configuration information.
- It provides cybersecurity mechanisms, such as authentication, encryption, access control, audit trail, and intrusion detection.

Limitations of IEC 61850:

- It has a complex data model and configuration language that require high-level expertise and tools to implement and maintain.
- It has a high bandwidth requirement for some applications, such as SV and GOOSE, that may cause network congestion or delay.
- It has a lack of backward compatibility with legacy protocols, such as DNP3 or Modbus, that may require additional gateways or converters.

Example use cases of IEC 61850:

- Integrating protection relays, circuit breakers, transformers, meters, and other substation devices from different vendors using MMS and GOOSE communications.
- Transmitting high-resolution measurements from current and voltage transformers to protection and control devices using SV communications.
- Synchronizing the time of substation devices using PTP communications.

Previous analysis on IEC 61850:

- A study by Gungor et al. [16] reviewed the state-of-the-art applications of IEC 61850 in smart grid systems. The study highlighted the benefits and challenges of using IEC 61850 for smart grid communications.
- A study by Zhang et al. [17] proposed a novel method to test the interoperability of IEDs based on IEC 61850. The method used a model-based testing approach that generated test cases from the SCL files and verified the test results using an ontology-based reasoning engine.
- A recent review by Ayello et. al [18] proposed interoperability based on IEC 61850. They proposed a new method for performing interoperability in a multi-vendor environment and carried out a teleprotection case study that successfully certified end-to-end interoperability.

6.26 IEC 62351

IEC 62351 is a series of standards developed by WG15 of IEC TC57, a technical committee of the International Electrotechnical Commission (IEC) that deals with power systems management and associated information exchange. [19]
The objective of IEC 62351 is to provide end-to-end security for power system communication, including data authentication, access control, encryption, and key management. The standard covers various communication protocols used in power systems, such as IEC 60870-5, IEC 60870-6, IEC 61850, IEC 61970, IEC 61968, and DNP3.

The standard consists of 11 parts, each addressing a specific aspect of security. The parts are as follows:
Part 1: Introduction to the standard
Part 2: Glossary of terms
Part 3: Security for any profiles including TCP/IP
Part 4: Security for any profiles including MMS (e.g., IEC 60870-6, IEC 61850, etc.)
Part 5: Security for any profiles including IEC 60870-5 (e.g., DNP3 derivative)
Part 6: Security for IEC 61850 profiles
Part 7: Security through network and system management
Part 8: Role-based access control
Part 9: Key management
Part 10: Security architecture
Part 11: Security for XML files

Key properties of IEC 62351:

- It uses Transport Layer Security (TLS) to provide encryption and authentication for TCP/IP-based profiles.
- It uses X.509 certificates to verify the identity of communication nodes and digital signatures to authenticate data transfer.
- It defines Management Information Base (MIB) that are specific for the power industry, to handle network and system management through Simple Network Management Protocol (SNMP) based methods.
- It covers the access control of users and automated agents to data objects in power systems by means of role-based access control (RBAC).
- It describes the correct and safe usage of cryptographic information, such as passwords, encryption keys, certificates, and revocation lists.
- It explains the security architectures for the entire IT infrastructure of power systems, identifying critical points and appropriate mechanisms.
- It embeds the original XML content into an XML container, providing date of issue and access control for XML data.

Limitations of IEC 62351:

- It does not cover the physical security of intelligent electronic devices (IEDs), the operating system or firmware of IEDs, or the manufacturer-specific functions of IEDs.
- It does not specify how to implement the security mechanisms in different devices or platforms, leaving room for interpretation and inconsistency.
- It does not address some emerging security challenges, such as advanced persistent threats (APTs), denial-of-service (DoS) attacks, or insider attacks.

Example use cases of IEC 62351:

- Securing the communication between substation automation systems and control centers using TLS and X.509 certificates.

- Protecting the data exchange between protection relays and circuit breakers using digital signatures and encryption.
- Controlling the access rights of operators and engineers to substation data objects using RBAC.

Previous analysis on IEC 62351:

- A study by Zhang et al. [20] evaluated the performance of IEC 62351-3 and IEC 62351-4 in terms of latency, throughput, and CPU utilization. The results showed that the security overhead was acceptable for most applications.
- A study by Moghadam et al. [21] proposed a lightweight authentication scheme based on IEC 62351-9 for smart grid communication. The scheme used elliptic curve cryptography and hash-based message authentication code to reduce the computation and communication costs.
- A study by Hussain et al. [22] analyzed the security threats and vulnerabilities of IEC 61850 based on IEC 62351. The study proposed a security assessment framework and a security enhancement scheme to improve the security level of IEC 61850.

6.27 ISO 23726-3 Industrial Data Ontology (IDO)

The Industrial Data Ontology (IDO) is an OWL 2 ontology [43]. IDO is designed to support machine automated reasoning over information used in the design and through-life operation of complex, long-life, engineering assets.

IDO is suitable for industrial use cases, to create vocabularies and asset models, and exploit OWL DL reasoning for quality assurance and inference of implicit knowledge.

IDO provides "usable" guidance for creating ontology patterns and examples of patterns commonly used to capture important data and relations in the engineering design process. The use, and reuse, of approved patterns reduces risks that modelling mistakes will be made and increases the speed of the model development and quality checking processes.

The intended users of IDO are involved in the design, construction, manufacturing, operation, maintenance, and disposal of assets and discrete or continuous processing systems in the engineering sector.

IDO was developed in response to demand from the industrial engineering community for ontology-based solutions to the problem of semantic interoperability across information systems associated with the multiple stakeholders involved in complex systems engineering projects and through life asset management.

IDO has a track-record of use in the oil and gas sector under the title of ISO/DTR 15926-14. It has been used for OWL DL reasoning over material master data in the design phase as well as for representing as-built process plants with millions of parts.

IDO is supported and applied in several industries (e.g., SIEMENS, Eurostep, GRUNDFS, Aibel, Equinor, AkerBP, DNV, AkerSolutions, SEIIA, POSC CAesar Association etc.) and in several domains (e.g., mining, manufacturing, energy, aerospace, automotive, maritime).

A detailed overview is available in **Appendix 5** (About_IDO.docx).

7. Data representation formats

Data representation formats are crucial in information technology for structuring, storing, and transmitting data. Key formats include XML, JSON and YAML, each serving specific purposes.

XML (Extensible Markup Language) is a flexible, self-descriptive language used for representing complex data structures. It's widely used in web services, document configurations, and data interchange between various systems. XML's structure involves tags (similar to HTML) to define data, making it both human-readable and machine-readable. However, its verbosity can lead to larger file sizes compared to other formats. XML is also a widely used solution to store P&ID (Piping and Instrumentation Diagram) data or schematic information. XSD (XML Schema Definition) is applied to define the structure and constraints for XML data. It specifies what elements and attributes are allowed in an XML document and the types of data they can contain. This makes it essential for validating XML files, ensuring they adhere to a predefined structure and rules.

JSON (JavaScript Object Notation) is a lightweight data-interchange format, often used for client-server communication. It's easy for humans to read and write, and simple for machines to parse and generate. JSON uses key-value pairs and is more efficient and compact than XML, making it suitable for applications where bandwidth and performance are considerations. To ensure the data integrity and consistency in a JSON-based system, JSON schemas could be used for automated validation.

YAML (YAML Ain't Markup Language) is a human-readable data serialization format. It is often used for configuration files, data exchange between languages, and in applications where data is stored and transmitted. YAML is designed to be easily readable by humans, whit a clear and intuitive structure that resembles natural language. It can represent scalar types (e.g., strings, integers), and collections (e.g., lists, maps). Compared to XML, YAML is less verbose, making it more concise for representing data.

SenML (Sensor Markup Language, RFC 8428) is specifically designed for representing simple sensor measurements in Internet of Things (IoT) environments. It enables the efficient communication of sensor data between devices and servers, supporting various data formats including XML, JSON, and CBOR (Concise Binary Object Representation). SenML structures typically include information like sensor values, units, and timestamps.

Each of these formats has its unique strengths and applications. XML and XSD are often used in enterprise environments and for complex data structures. JSON, due to its simplicity and efficiency, is widely used in communication and data exchange. SenML, on the other hand, is tailored for IoT applications, focusing on sensor data representation.

8. Communication protocols

8.1 CoAP

The Constrained Application Protocol (CoAP) [39] is a lightweight communication protocol specifically designed for resource-constrained devices and networks, making it a popular choice for the Internet of Things (IoT) and machine-to-machine (M2M) applications. CoAP exhibits several key properties that set it apart from other protocols. This subsection discusses the key properties and the use cases.

CoAP is designed to be extremely lightweight and efficient, making it suitable for devices with limited resources, such as sensors, actuators, and small microcontrollers. It operates over UDP. This minimizes latency and resource consumption. CoAP embraces the Representational State Transfer (REST) architectural style, making it easy to model resources as URLs and use standard HTTP methods like GET, POST, PUT, and DELETE. CoAP supports asynchronous communication, allowing devices to initiate and respond to requests without blocking operations, which is essential for real-time applications. It also supports unicast or multicast operation modes.

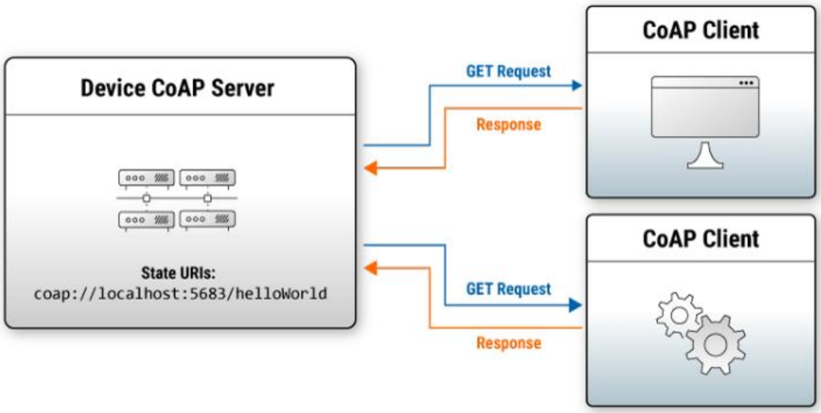

Figure 8.1.1 – CoAP Client – Server model

CoAP is well-suited for a variety of use cases, including:

- IoT Applications: CoAP is a natural fit for IoT, enabling efficient communication between IoT devices and gateways. Its lightweight nature ensures minimal energy consumption, making it ideal for battery-operated devices.
- Home Automation: CoAP can be used in smart home applications to control and monitor various devices, such as lights, thermostats, and security systems.
- Industrial Automation: CoAP is employed in industrial settings for machine control, monitoring, and maintenance, as it offers low latency and robust communication.
- Environmental Monitoring: CoAP is used in environmental monitoring systems, allowing sensors to report data efficiently in remote and resource-constrained environments.

CoAP's adoption is not as widespread as other IoT protocols like MQTT or HTTP, which can lead to limited tooling and community support.

8.2 MQTT

MQTT (Message Queuing Telemetry Transport) is a lightweight, open-source messaging protocol designed for efficient communication between devices in constrained environments [40]. It has a client/server model, where every device is a client and connects to a server, known as a broker. The protocol uses TCP/IP as the transport layer. MQTT is message oriented. Every message is published to an address, known as a topic. Clients may subscribe to multiple topics. Every client subscribed to a topic receives every message published to the topic.

MQTT uses a publish/subscribe paradigm, allowing devices to subscribe to topics and receive messages published on those topics.

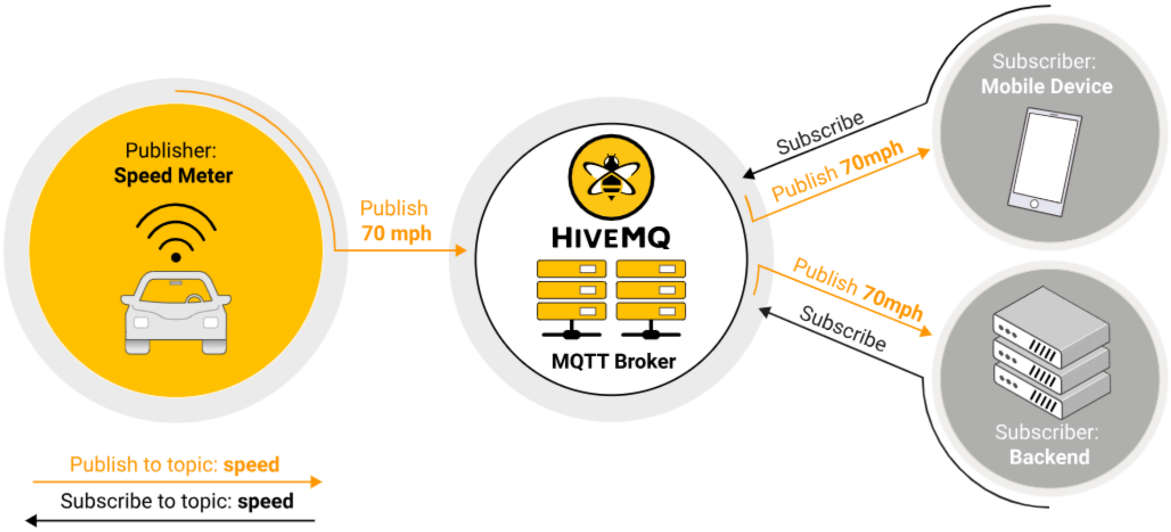

Figure 8.2.1 – MQTT Publish/Subscribe architecture [41]

It offers three Quality of Service (QoS), providing flexibility in message delivery guarantees:

- levels-0: At most once. Messages arrive at most once, hence can be lost when connection problems occur.
- level-1: At least once. Messages are assured to arrive but duplicates can occur.
- level-2: Exactly once. Messages are assured to arrive exactly once.

MQTT requires connection initiation with the MQTT broker. For this purpose, the client uses two messages: PUBLISH, PUBACK. After the MQTT connection has been established, the client can publish data by sending PUBLISH messages to the server.
The most applied is QoS 1 (at least one delivery) to make the transmission reliable, the PUBACK MQTT control package confirms the data publication each time. If data sending is infrequent and requires TCP and MQTT to reestablish connections each time, then the relative overhead becomes huge for small data payload. This is not an optimal solution when the devices are kept in the power saving mode most of the time, only waking up to send a small payload and returning to the power saving mode after that.

MQTT enables the broker to store the last message sent on a topic, ensuring new subscribers receive the last-known state upon subscription. It supports a keep-alive mechanism to maintain the connection between the client and broker, enhancing reliability. MQTT minimizes bandwidth and power consumption, making it suitable for IoT (Internet of Things) applications.

Figure 8.2.2 – Example for IoT communication over MQTT

Example use cases:

- IoT communication: MQTT is widely used in IoT scenarios, facilitating communication between devices such as sensors, actuators, and smart appliances.
- Home automation: MQTT is employed in smart homes for efficient communication between devices like smart thermostats, lights, and security systems.

Limitations:

- MQTT is a stateless protocol, does not inherently track the state of connected clients, which may require additional mechanism for certain applications.

8.3 Diameter

Diameter is an extensible messaging protocol in IP networks, which applies a Request – Answer communication mechanism. It is a general protocol that contains variable, interface-specific parameters (called AVPs, Attribute-Value Pairs). Message types are distinguished by Command Codes, with different Command Codes interpreted on each interface. The Application-ID parameter in the header determines the interface type. Message types may include optional and mandatory AVPs, and may also include vendor-specific parameters (e.g., 3GPP, Huawei, Cisco). Within an AVP, there can be one or more nested AVPs (Grouped AVP).

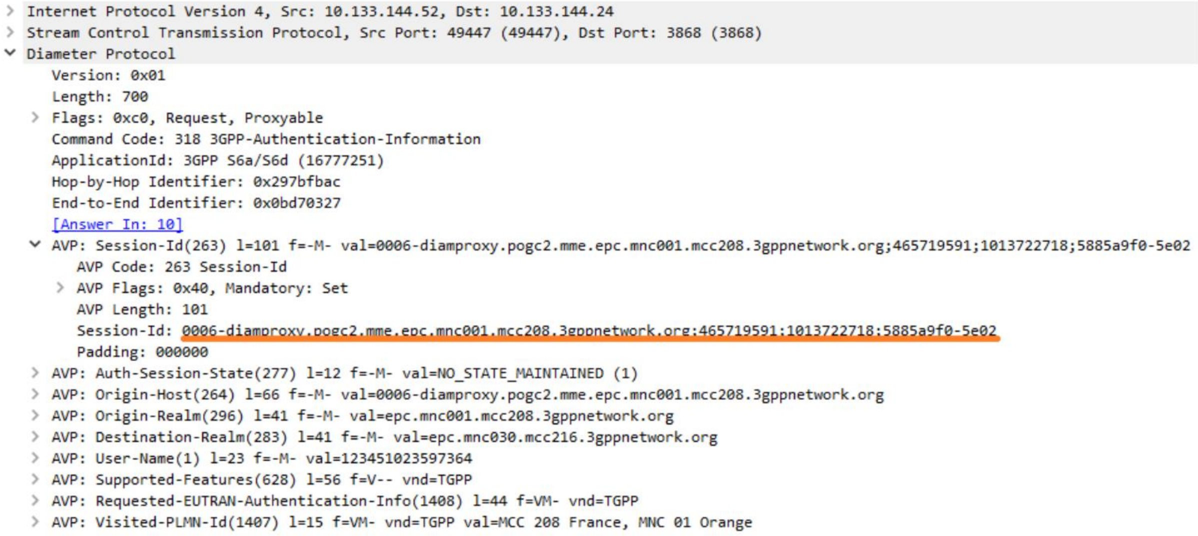

Figure 8.3.1 – Example Diameter message – presented by Wireshark

The format of a parameter is the following:

AVP Code | AVP Flags | AVP Length | Vendor-ID (optional) | Data…

The Diameter protocol carries an AVP (Attribute Value Pair) list. The content of an AVP could be predefined in several IEEE standards, but could be also vendor-specific. It is a descriptive protocol, often containing values as text (UTF-8 string). On some interfaces, message sizes of up to 5000 bytes are not uncommon. It typically travels over the SCTP or TCP protocol.

The Request - Answer messages can be paired based on the Session-ID parameter, which is identical for a related message sequence. The equipment may interpret a long-term session in a communication, where the Session-ID remains the same across multiple consecutive transactions. In this case, the opening and closing events of the session are defined by the standard associated with that interface. A session is a logical connection that exists at the application layer.

8.4 HTTP

HTTP (Hypertext Transfer Protocol) is a popular, widely used, document-centric protocol. The communication is based on a Request – Response model, where clients send HTTP requests, and servers response with HTTP status codes and the requested content. It uses URIs (Uniform Resource Identifier) to identify resources, specifying the location of resources.

HTTP defines various HTTP method to specify the action to be performed on a resource:

- GET: requests a representation of the specified resource. Requests using GET method should only retrieve data.
- HEAD: asks for a response identical to GET, but without the response body.
- POST: submits an entity to the specified resource, often causing a change in state or side effects on the server.
- PUT: replaces all current representations of the target resource with the request payload.
- DELETE: deletes the specified resource.
- CONNECT: establishes a tunnel to the server identified by the target resource.
- OPTIONS: describes the communication options for the target resource.
- TRACE: performs a message loop-back test along the path to the target resource.
- PATCH: applies partial modification to a resource.

HTTP operates in a stateless manner, meaning each request from a client to a server is independent, and the server does not retain information about previous requests.

8.5 HTTP2

HTTP2 (RFC 7540) is designed to improve the performance and efficiency of web communication, but it also applied in data exchange in other domains (e.g., control-plane communication in 5G core networks). It introduces multiplexing, allowing multiple requests and responses to be sent concurrently over a single TCP connection. This reduces latency and improves performance.

HTTP2 uses header compression to minimize the overhead of transmitting redundant information in each request and response. Unlike HTTP/1.1, it is a binary protocol, which simplifies parsing and processing (see Fig. 8.5.1).

It allows servers to proactively push resources to clients before they are explicitly requested, optimizing page load times by reducing the need for additional round-trip requests. It also introduces stream prioritization, enabling the assignment of priority levels to different streams, ensuring more critical resources are delivered first.

```
HTTP2 DECODER (RFC 7540)

 Frame: #1
 ***24b**  Length = 314
 00000000  Type   = 0  DATA

 Data:
   0000----  Spare             = 0
   ----0---  Padded            = 0  false
   -----00-  Spare             = 0
   -------1  End stream        = 1  true
   0-------  Reserved          = 0
   ***31b**  Stream Identifier = 3

 JSON DECODER (RFC 4627)
   01111011  {
   **176b**   "authType": "5G_AKA",
   **128b**   "5gAuthData": {
   **360b**    "rand": "6d96eb71d5bc201872ce6ce635fe9e04",
   **400b**    "hxresStar": "ce9ef8f6c3ab4f44478d1afe7bc14855",
   **352b**    "autn": "3803ef98146f8000ca57cf8b77296674"
   ***24b**   },
   ***96b**   "_links": {
   **104b**    "5g-aka": {
   **720b**     "href": "http://127.0.0.11:7777/nausf-auth/v1/ue-authentications/1/5g-aka-confirmation"
   ***24b**    }
   ***16b**   }
   01111101  }
 END OF JSON DECODER

END OF HTTP2 DECODER
```

Figure 8.5.1 – Example HTTP2 message

8.6 Conclusion on communication protocols

Protocol	Transport Protocol	Security	Binary header	Communication model	Notes
CoAP	UDP	DTLS	Yes	Request – Response	Client – Server communication model, but also supports subscription.
MQTT	TCP	TLS	Yes	Publish – Subscribe	Lightweight protocol to publish IoT measurement data to a common topic.
Diameter	TCP, SCTP	DTLS	Yes	Request – Response	General AVP (Attribute Value Pair) list. The parameters could be a vendor-specific, binary or text-based data. Could create a stateful session.
HTTP	TCP	TLS	No	Request – Response	General solution for requesting/transporting information in JSON or XML format.
HTTP2	TCP	TLS	Mixed	Request – Response	A long TCP connection with several HTTP2 transactions. The key-value pairs in the JSON payload and the URIs could be predefined in standards (e.g., 5G SBI).

9. Modeling and knowledge representation languages

Beyond standardized industrial data structures and their technical representations, the landscape considered in WP3 also contains a different kind of approach to engineering data representation: that of modeling and knowledge representation. The use of such an approach is typically of a mediating nature, being confined neither to pure architectural meta-modeling nor to structured, attribute-based data conveyment.
In the project, we consider two established, complementary approaches along with their arguably most established languages: systems modeling (SysML) and ontological modeling (OWL), respectively.

9.1 SysML

Work Package 3 should not only take care of identifying and analysing the singular data standards and models for their contents and context, but also of offering a conceptual and even practical framework for dealing with interoperability and exchange of engineering and modelling data, providing a desired level of flexibility and adaptability w.r.t. the thinkable and relevant formats in which data can be represented, handed over and transformed.

SysML lends itself as a by-design canonical and adequate choice to become a centrepiece for such activities in an fPVN context.

SysML, or Systems Modeling Language, is a well-established language and standard for systems modeling, maintained by the Object Management Group (OMG). While being mainly diagrammatic in its notation and user interaction facets, SysML also offers standard exchange formats for flexible engineering ecosystem integration, effectively facilitating the analysis, design, and verification of complex systems. SysML emerged as an offshoot of the Unified Modeling Language (UML), the standard for software systems design, tailored specifically to meet the needs of system engineers tackling hardware, software, processes, personnel, and facility interactions in their projects.

As a modeling language, SysML offers a suite of diagrams and constructs that extends beyond software development to support a broader spectrum of engineering disciplines. This framework represents the interactions within a system's components as well as with external systems, thereby allowing engineers to explore and document system characteristics thoroughly before actual implementation. This conceptual tendency appears as a fit basis for comprehensive SoS design activities, however, the adaptation of the original focus on closed-system principles to current trends of open, autonomous, layered SoS interworking still makes the engineering community face research and development challenges.

Using the same UML profiling mechanism which enabled the derivation of the SysML language from the more general modeling principles embodied by UML (being, at the same time, a reduction of certain aspects of the UML scope, but also an extension of it along conceptually relevant aspects of a general systems engineering methodology), a working group within the consortium of an earlier Arrowhead project, Arrowhead Tools (2019-2022) has successfully established an Arrowhead SysML profile. While the profile, in its current form, focuses on the possibilities of statically describing a service-based Arrowhead SoS via a SysML-centric interpretation of the main Arrowhead architectural concepts, the profile remains open to extensions to, e.g., data model descriptions and platform interaction specifications, to which purpose we intend to revisit and further develop it within Arrowhead fPVN.

Another important direction of future considerations within the project is the current emergence of the new version of the standard, called SysML v2. With the advent of SysML v2, the emphasis has been on improving the language to better meet the evolving needs of the digital engineering community. One of the key features of SysML v2 is the introduction of a new textual notation. This textual representation complements the graphical notation and aims to provide a more precise, compact, and human-readable form for expressing SysML models. The new textual notation is not meant to replace the graphical notation but to serve as an alternative for scenarios where textual notation is more efficient or preferable. The textual notation in SysML v2 offers several potential advantages, addressing current expectations towards tooling support in holistic engineering, like advanced version control, automation and interoperability, in particular throught a standardized API and modern, integration-ready model exchange facilities.

9.2 OWL

The Web Ontology Language (OWL) serves as a language for representing and sharing ontologies across the World Wide Web. It is designed to render information on the web machine-readable and interpretable, thereby advancing the realization of the Semantic Web vision.

At its core, OWL's primary purpose is to facilitate the representation of knowledge in a machine-readable format, fostering automated reasoning and inference. It achieves this through the creation of ontologies, structured frameworks defining concepts, relationships, and constraints within specific domains. These ontologies play a critical role in describing the meaning of terms and relationships in data, ultimately empowering the development of more intelligent and context-aware applications.

Built on a foundation of formal logic, specifically rooted in Description Logic, OWL employs a rich set of constructs to articulate classes, individuals, properties, and logical axioms. This allows for the nuanced representation of complex relationships and constraints. The logical underpinning of OWL enables automated reasoning and inference, empowering machines to draw conclusions from both explicit and implicit information encoded in OWL ontologies.

Developed and maintained by the World Wide Web Consortium (W3C), an international organization establishing web standards, OWL stands as a widely accepted and supported language across diverse platforms and applications. The evolution from OWL 1, comprising sub-languages like OWL Lite, OWL DL, and OWL Full standardized in 2004, to the current major version, OWL 2 (published in 2009), introduces additional features and improvements. Notably, OWL 2 encompasses several profiles, including OWL 2 EL, OWL 2 QL, and OWL 2 RL, tailored to specific use cases and balancing expressiveness with computational complexity.

In the context of the Semantic Web stack, OWL and the Resource Description Framework (RDF) are intricately connected. RDF acts as the fundamental data model, serving to represent information on the web and emphasizing the articulation of relationships among resources in a graph-like structure. OWL builds upon RDF by offering a mechanism to express ontologies within RDF graphs. OWL supports various serialization formats, allowing ontologies to be represented in different ways. Two primary serialization formats are commonly used: RDF/XML and Turtle. RDF/XML is an XML-based format that provides a structured representation suitable for both machines and humans. Turtle, on the other hand, is a more compact and human-friendly syntax for RDF data. These serialization formats are interchangeable and represent the same ontological information. The choice between them often depends on preferences, application requirements, and specific interoperability considerations.

In practical terms, OWL finds extensive application in creating ontologies across various domains such as biomedical and healthcare, e-commerce and product data, manufacturing and engineering, agriculture, information integration and data governance, Semantic Web and linked data, geospatial and environmental sciences. Its versatility positions OWL as a fundamental tool for enhancing knowledge representation, data interoperability, and the development of intelligent systems in a multitude of fields.

OWL is instrumental in modeling, offering a standardized approach to representing complex relationships and constraints within particular domains. It facilitates automated reasoning, enabling the automated inference and deduction of implicit knowledge. In the realm of data integration, OWL formalizes ontologies, facilitating seamless integration of disparate data sources. Additionally, it promotes interoperability by establishing a shared understanding of data structures and semantics among different systems, ensuring consistency in how information is interpreted and exchanged.

10. Commonalities

The fPVN uses-case partners often work parallel on the same problems and have several standards to solve similar situations and issues. The following tables highlight the common points regarding the applied standards.

Automotive fPVNs (WP6)

Name of the standard	Data representation format	Ways to utilize
ASAM-ODS	XML (ATFX)	Data modelling and exchange
ISO-IEC 25012	Not defined, could be XML or JSON	Define and evaluate data quality requirements

Aerospace fPVNs (WP7)

Name of the standard	Data representation format	Ways to utilize
ISO 10303-239 and 242	EXPRESS language, SysML	Data modelling and exchange
S5000F	XML	Data exchange
S2000M	XML	Data representation and exchange
S3000L	XML	Data representation and exchange

Green Energy fPVNs (WP8)

Name of the standard	Data representation format	Ways to utilize
IEC 61850	Protocols over Ethernet, IP, UDP/TCP	Communication protocols
IEC 62351	-	Security of data exchange, Security for XML files or for TCP/IP communication

Process industry fPVNs (WP9)

Name of the standard	Data representation format	Ways to utilize
DEXPI, DEXPI+	XML, UML	Data representation
CFIHOS	XML	Data representation and exchange
ISO 15926-2	EXPRESS language	Data representation, integration and exchange
ISO/TS 15926-4	Excel spreadsheets	Data representation, integration and exchange
ISO 18101	XML or JSON	Data exchange
IEC 61987	XML	Data representation
IEC 61131-3	-	Programming languages for PLCs
ISO 81346-1	-	Principles and rules for reference designation
ISO 10303-239 and 242	EXPRESS language	Product lifecycle representation
ISO 12006	-	Building Information Modelling
ISO 19650	Can be encoded in XML or JSON.	Building Information Modelling
ISO 61499	Function blocks	Structure and interconnect components in industrial systems

11. Comparison analysis

11.1 ISO 10628 vs. DEXPI

Category	ISO 10628	DEXPI
Use cases	ISO 10628 is a standard that defines a set of graphical symbols for process diagrams, which are used to represent and document processes in industries like chemical, petrochemical, and manufacturing. It provides a common language for engineers and professionals to create process flow diagrams (PFDs) and piping and instrumentation diagrams (P&IDs). ISO 10628 helps in the visualization of processes, making it easier to understand and communicate complex systems.	DEXPI is a data exchange standard developed to address the limitations of ISO 10628 and enable more comprehensive and standardized data exchange in the process industry. DEXPI is used to represent and exchange process engineering data, including P&IDs, equipment data, and other related information, in a consistent and machine-readable format. Its use cases include data integration, collaboration, and data consistency in the design, operation, and maintenance of industrial plants.
Data format	ISO 10628 primarily deals with graphical symbols and their usage in process diagrams. It doesn't specify a particular data format or data exchange standard. Instead, it focuses on providing a standardized set of symbols for creating diagrams, which can be incorporated into various documentation and design tools.	DEXPI defines a structured data format based on industry standards such as ISO 15926 and EXPRESS. It uses a semantic data model to represent information about equipment, connections, and other elements in a plant. This structured format allows for better data exchange and integration with various software tools and systems.
Limitations	ISO 10628 does not provide a standardized data exchange format for transferring process data between different software applications. This makes it challenging to integrate with other digital tools and systems used in modern engineering and design processes.	DEXPI's structured data format and the use of industry standards like ISO 15926 can be complex and may require specialized expertise to implement and utilize effectively. This complexity can be a limitation for smaller organizations with limited resources.

DEXPI is not as widely adopted as ISO 10628, which means that it may not be as readily available or recognized in all industrial settings. Adoption can be slow due to existing practices and the need for software and tools to support the standard.

In summary, ISO 10628 is primarily focused on providing a set of symbols for process diagrams and lacks a standardized data exchange format, making it less suitable for modern digital workflows. DEXPI, on the other hand, addresses these limitations by providing a structured data format for comprehensive data exchange but may face adoption challenges and complexity. The choice between these standards depends on the specific needs and goals of the organization and its willingness to invest in data integration and exchange capabilities.

11.2 ISO 15926 vs. ISO 10303

Category	ISO 15926	ISO 10303
Use cases	ISO 15926, also known as "Industrial automation systems and integration - Integration of life-cycle data for process plants including oil and gas production facilities," is primarily used for the integration and exchange of data throughout the entire lifecycle of process plants, including design, construction, operation, and maintenance. It provides a common framework for representing and exchanging data related to equipment, processes, and systems in industries such as oil and gas, chemical, and manufacturing.	ISO 10303, often referred to as STEP (Standard for the Exchange of Product Model Data), is a comprehensive standard used in various industries, including manufacturing, aerospace, automotive, and more. It primarily focuses on product data exchange and representation throughout the product lifecycle, encompassing design, manufacturing, and maintenance. ISO 10303 covers a wide range of data, including geometry, materials, assembly structures, and more.
Data format	ISO 15926 is based on an EXPRESS data model and reference data in Excel. This allows for the representation of complex relationships between objects and concepts in a standardized and semantically rich manner. It is a flexible and extensible format suitable for representing a wide range of industrial data.	ISO 10303 uses the EXPRESS data modeling language and provides a structured data format for the exchange of product information. It includes various parts and Application Protocols (APs) tailored to specific industries or domains.
Limitations	ISO 15926 is widely adopted in the process plant, power, and oil&gas industries. ISO 15926's data model can be complex to implement and work with, requiring specialized knowledge and tools.	While ISO 10303 is widely adopted in certain industries like aerospace and automotive, its adoption in other sectors may be limited. This can lead to interoperability challenges when working with partners or suppliers in different domains.

In summary, ISO 15926 and ISO 10303 have different focuses and common use cases. ISO 15926 is tailored for data integration in process industries, while ISO 10303 is designed for product data exchange in various engineering domains. Both standards have complex implementations, limited adoption in certain sectors, and privacy and security considerations. The choice between them depends on the specific requirements and context of the organization or industry in question.

11.3 ISO 15926 vs. ISO 81346

Category	ISO 15926	ISO 81346
Use cases	ISO 15926, also known as "Industrial automation systems and integration - Integration of life-cycle data for process plants including oil and gas production facilities," is primarily used for the integration and exchange of data throughout the entire lifecycle of process plants, including design, construction, operation, and maintenance. It provides a common framework for representing and exchanging data related to equipment, processes, and systems in industries such as oil and gas, chemical, and manufacturing.	ISO 81346, titled "Industrial systems, installations, and equipment and industrial products - Structuring principles and reference designations," provides a framework for the structuring and reference designation of objects and components in industrial systems. It helps standardize how to identify and label equipment and systems in various industries, ensuring clear communication and understanding between stakeholders. Its primary use cases include plant design, construction, maintenance, and operation.
Data format	ISO 15926 is based on an EXPRESS data model and reference data in Excel. This allows for the representation of complex relationships between objects and concepts in a standardized and semantically rich manner. It is a flexible and extensible format suitable for representing a wide range of industrial data.	ISO 81346 is not focused on data format or data exchange like ISO 15926. Instead, it focuses on principles for structuring and labeling objects and components in industrial systems. It provides a logical and consistent system for referencing and identifying equipment.
Limitations	ISO 15926 is widely adopted in the process plant, power, and oil&gas industries. ISO 15926's data model can be complex to implement and work with, requiring specialized knowledge and tools.	ISO 81346 is primarily concerned with the structuring and reference designation of industrial objects. It doesn't cover the broader data exchange, information integration, and semantic modeling aspects of industrial processes and systems.

In summary, ISO 15926 and ISO 81346 serve different purposes and have distinct use cases. ISO 15926 focuses on data integration and semantic modeling in the context of process plants, while ISO 81346 is concerned with structuring and labeling industrial objects and components. ISO 15926 uses a semantic data model, while ISO 81346 is not a data exchange standard.

12. Conclusion

The document provides a report about the major standardised data models, describing the key properties of the predominantly applied, uses case related standards.
The deliverable includes a survey result, key properties, scope and limitations of the collected standards, a summary about communication protocols, and comparisons.
It provides an overview of the currently applied data model standards. As an additional benefit of this document, the use-case participants can identify common issues and solutions based on the comparison results.

The document answers the following objectives of WP3:

- Select major standardised data models relevant to the use cases.
- Identify the foundational properties of the selected data models.
- Identify similarities and dissimilarities between the standardised data models.

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14. Revision history

14.1 Contributing and reviewing partners

Contributions	Reviews	Participants	Representing partner
	v0.1 - v1.1	Nils Sandsmark	POSC Caesar Association
	v0.1	Dirk Walter	DNV
	v0.4	Pal Varga	BME
IEEE 1451		Tobias Mitterer, Vahid Tavakkoli	KLU
DEXPI+		Kim Björkman	VTT
IDO, ISO 23726, S5000F, S3000L, ISO 15926		Erik Molin	SEIIA
ISO 61850, ISO 62351		Alexandru Vulpe	UPB
IEC 81346		Oscar Carlsson	GRA
RailDAX		Stefano Rovetta	UNIGE
DEXPI, IEC 611331-3		Tommi Karhela, Gerardo Santillan	SEMANTUM
ISO 25012, ASAM ODS		Peter Priller	AVL
Communication Protocols, Commonalities		Tamas Tothfalusi	AITIA
SysML		Geza Kulcsar	IQL
	v0.8	Pal Varga	BME
S5000F		Porretti Claudio	LDO
IDO	v0.9	Pål Rylandsholm	POSC Caesar Association
IFC, ISO 10303-239, ISO 10303-242, ISO 12006, ISO 19650, S2000M	v1.0	Torbjörn Holm	EUROSTEP

14.2 Amendments

No.	Date	Version	Subject of Amendments	Author
1	2023-08-28	v0.1	Initial draft based on the first T3.1 questionnaire results	Tamas Tothfalusi
2	2023-09-04	v0.2	Results of the survey, Initial assignment of the partners to the analysis chapters	Tamas Tothfalusi
3	2023-09-19	v0.3	Suggested responsibles for the 2.5.X subchapters	Tamas Tothfalusi

4	2023-09-26	v0.4	Survey results and chapter updates	Tamas Tothfalusi
5	2023-10-05	v0.5	Update based on Green Energy fPVNs' answers	Tamas Tothfalusi
6	2023-10-19	v0.6	Chapter 6 update with DEXPI+ summary from VTT	Tamas Tothfalusi
7	2023-10-25	v0.7	Chapter 6 update with IEEE 1451 summary from KLU	Tamas Tothfalusi
8	2023-11-05	v0.8	Chapter 6, 7 and 10 update from partners contribution	Tamas Tothfalusi
9	2023-11-13	v0.9	Chapter 5,6 and 8 update	Tamas Tothfalusi
10	2023-11-21	v1.0	D3.1 update based on the reviews. Chapter 6 update. Commonalities.	Tamas Tothfalusi
11	2023-11-23	v1.1	Final version	Tamas Tothfalusi

14.3 Quality assurance

No	Date	Version	Approved by
1	2023-11-14	v.09	Nils Sandsmark
2	2023-11-22	v1.0	Nils Sandsmark
3	2023-12-04	V1.1	Jerker Delsign

15. Appendixes

Appendex 1: fPVN WP3 T3.1 Questionnaire

Analysis of commonalities and synergies – Data model standards survey

Questions and Answers

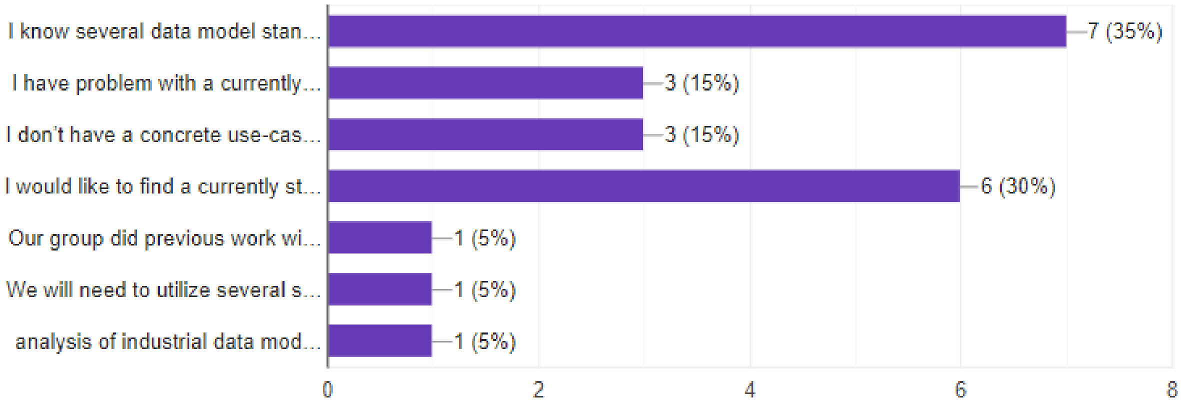
Part 1 – Major standardised data models

Q1.1 What is your contribution to Task 3.1?

Options:

a. I know several data model standards and I could help in the analysis.
b. I have problem with a currently used standard, and I would like to find a solution in the project results.
c. I don't have a concrete use-case in connection with a data model standard yet.
d. I would like to find a currently standardized data model to represent my data.
e. Others:
    i. Our group did previous work with an industry standard data model
    ii. We sill need to utilize several standardized data models in T9.1, and will need to study how to transfer data between data models and similar.
    iii. Analysis of industrial data models and ICT protocol models to facilitate new solutions for the industry that are established and proven in the ICT sector.

Answers:

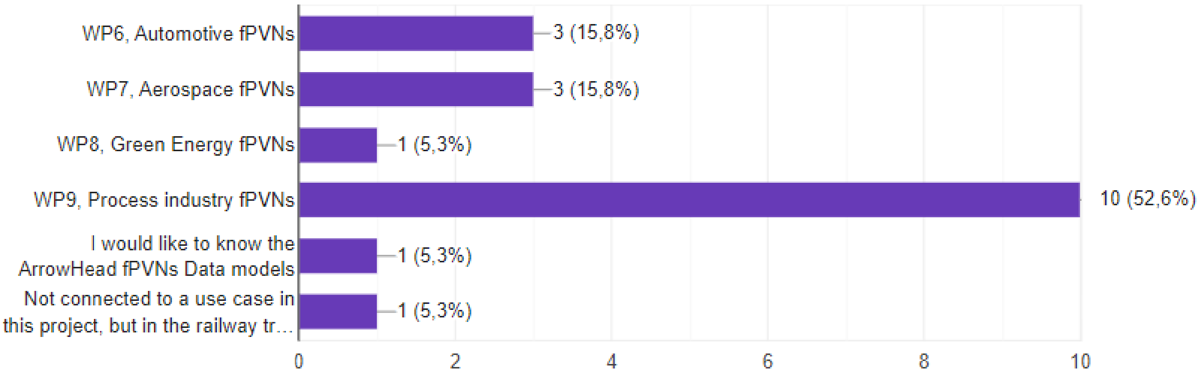


Q1.2 If your contribution is connected to use-cases, which use-case are those? (Please select one or more options)

Options:

a. WP6, Automotive fPVNs
b. WP7, Aerospace fPVNs
c. WP8, Green Energy fPVNs
d. WP9, Process industry fPVNs
e. More detailed:
    a. I would like to know the ArrowHead fPVNs Data models.
    b. Not connected to a use case in this project, but in the railway transportation domain.

Answers:

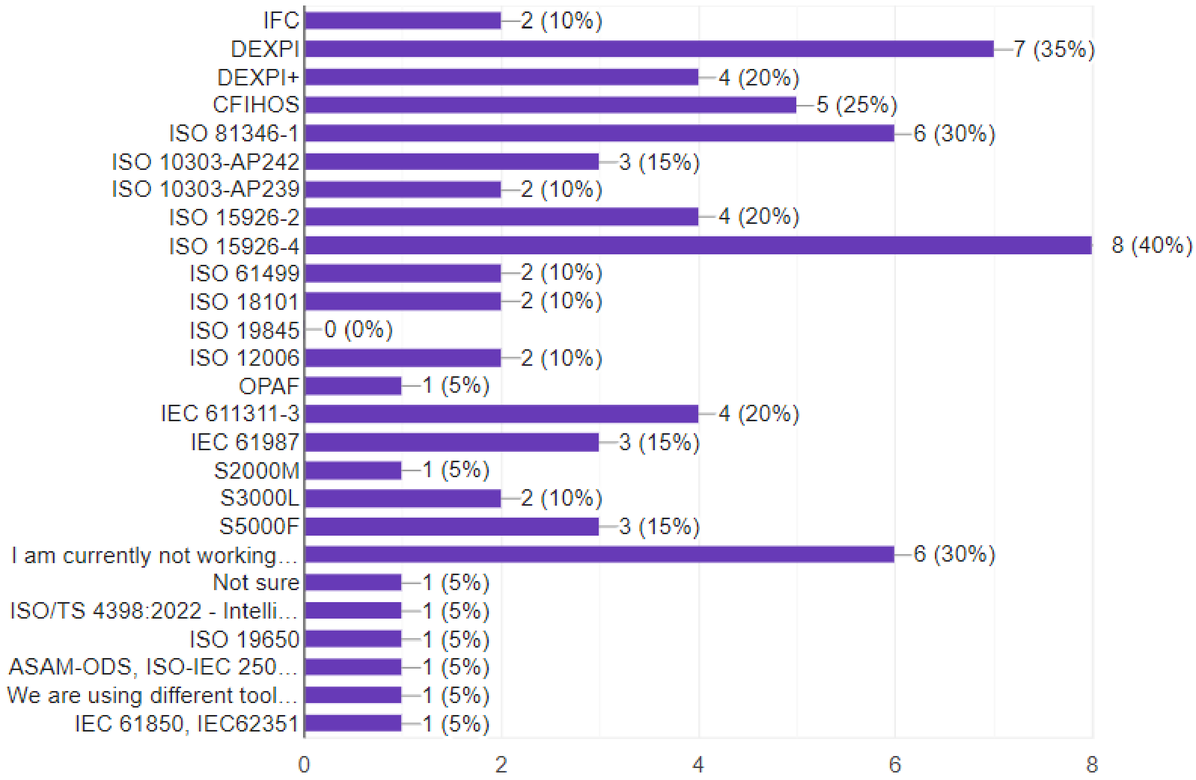


Q1.3 If your company work with data models, which standards are predominantly used in your company? (You can select more options)

Options:

- ISO 81346-1
- DEXPI,
- DEXPI+
- CFIHOS
- IFC
- ISO 10303-AP242
- ISO 10303-AP239
- ISO 15926-2
- ISO 15926-4
- ISO 61499
- OPAF
- IEC 611311-3
- ISO 18101
- ISO 19845 – Unified Business Language
- Building Information Model (BIM)
- IEC 61987 – Common Data Dictionary (CDD)
- ISO 12006
- S5000F
- S2000M
- S3000L
- I am currently not working with specific data standards
- Other: … (please give the name and a reference URL)

Answers:



Q1.4 What tasks do you apply the previously selected standards for? Please write a few sentences

Answers:

- To find proper solution/concept/standards for the use-case pilots in WP9
- We are translating old diagram based Plant Engineering material to intelligent data formats and tools.
- Analyzing how the data model of the IEEE1451 standard for sensors and actuators has commonalities and synergies with data modeling languages for the Arrowhead fPVN project
- Data interchange in the railway domain for (1) Timetables, (2) Infrastructure (tracks and signalling equipment), (3) Rolling stock (vehicles), and (4) Interlocking (signaling routes)
- To share data in different Tools
- Data management, sharing and exhanging in a secure manner
- 11:3 Standard
- Process automation, connectivity interoperability, data exchange standard for the process industry in all phases of the lifecycle of a plant, ranging from specification of functional requirements to assets in operation
- ASAM-ODS is the standard database model in automotive measurement data. ISO-IEC 25012 is the data quality model (accuracy, completeness, consistency, credibility, confidentiality)
- We are transforming our company to start working with standards. Our first implementation is a large waste water treatment plant green field project.
- Integration of legacy flow sheet application to microservices achitecture
- Design, configuration and installation of electrical cabinets and industrial automation systems. Documentation of existing and delivered systems. Customer requirements documentation.
- Send information from one tool to other during the desing and development process for the electro-mechanical parts in the aerospace domain.

- IEC 62351 is used for security (authentication and authorization) in the context of smart grids. IEC 61850 is used for designing communication protocols for intelligent electronic devices at electrical substations

Q1.5 If you could help with the analysis and the comparison of standards in T3.1, what would be your focus?

Options:

a) I work with major industrial data models and I can help with their comparison.
b) We have potential interoperability problems and I would like to find the solution.
c) I would like to extend a standard and propose important updates.
d) Others:

Answers:

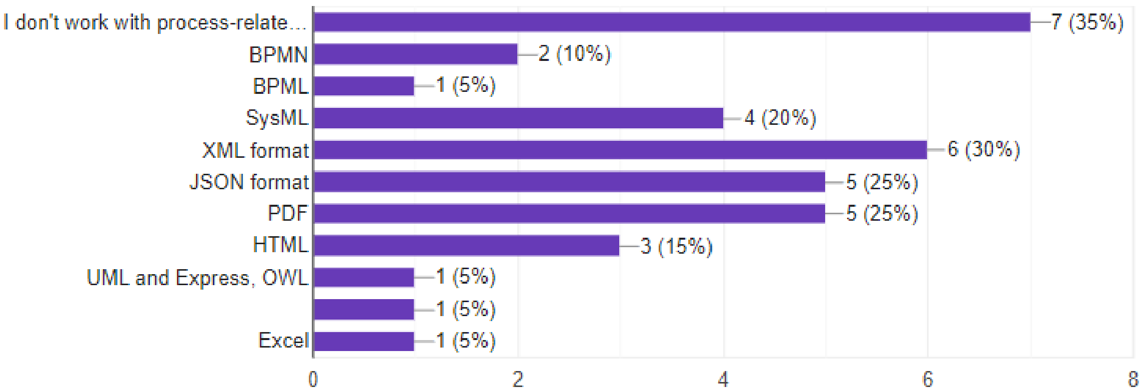
Part 2 – Data- and analysis-related questions

Q2.1 How do you represent the process-related data?

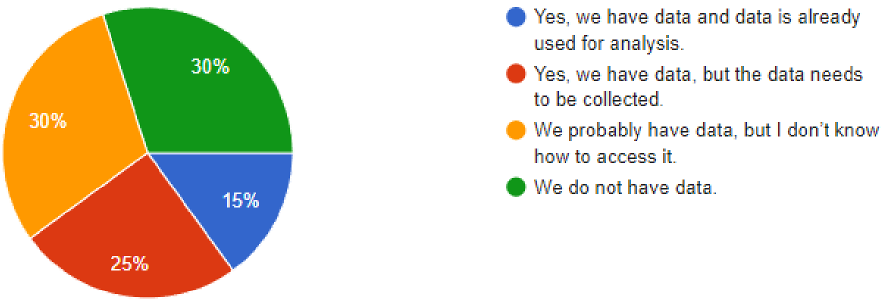
Options:

a. I don't work with process-related data.
b. BPMN
c. BPML
d. SysML
e. XML format
f. JSON format
g. PDF
h. HTML
i. Custom format
j. Other: ….

Answers:



Q2.2 Does your company have data sets related to the project's objectives (e.g., XML files)?

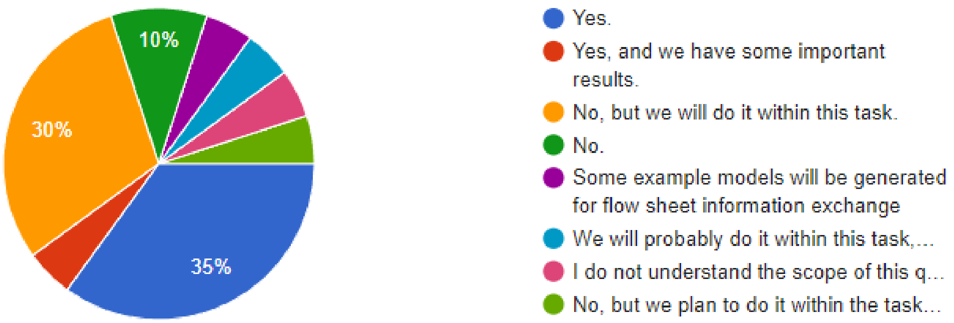


Q2.3 Could you provide reference data sets regarding the applied data models?

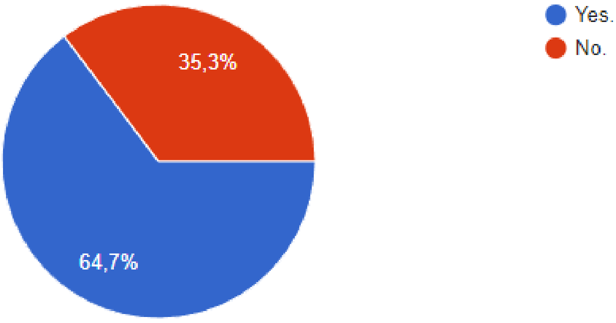
Q2.4 If possible (within the project), please give the contact of the data owner (company name, contact, etc.):

- We can share some more public data sets, but we have also lot of confidential data that cannot be shared. Same goes with the analyze results. Data issues can be discussed with me.
- We are a assosiation that works with tools / improve the use in industry of Interoperable data.
- not possible due to strict customer confidentiality requirements
- George Suciu _PhD, Director R&D
- University Politehnica of Bucharest

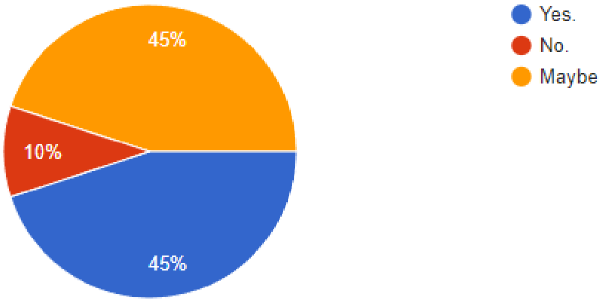
Q2.5 Have you ever analyzed your own data set?



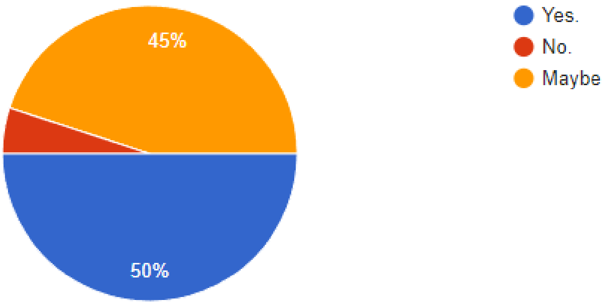
Q2.6 If you have results of analysis regarding your data set, is it possible to share them with designated partners?



Q2.7 Do you need to exchange information between closed, private industrial domains?



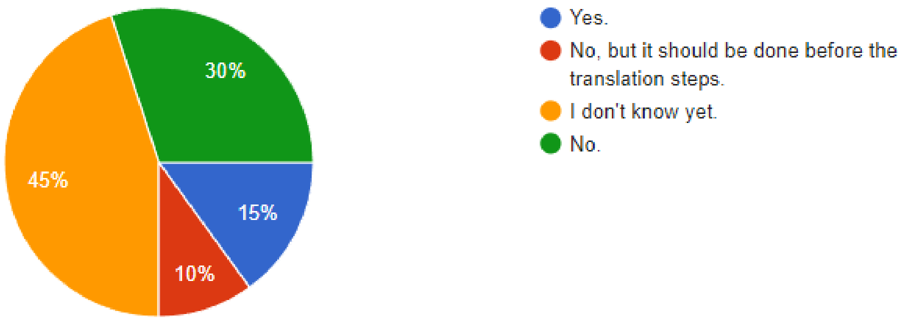
Q2.8 Do you need data model translation to solve interoperability problems?



Q2.9 If you need data model translation, from which standards to which ones should it be translated? (Please summarize your needs briefly, and specify the data model pairs):

- For example P&ID ISO 10628 (PDF) to DEXPI
- I would like to know Datamodel of Arrowhead fPVN
- Not sure yet
- All ticked in previous question
- We need a generic mechanism. Point to Point we have done using our mapping Framework for twenty years
- ISO 15926, ISO 10303 IEC/ISO81346
- require some analysis a bit for the specifics, but in general this is required
- Transform between own legacy data model and customer environment.
- Possibly from DEXPi+ to ISO 15926/IDO. Legacy system integration can be easier with graph based model.
- The data models used by the different tools that we are using (Altium- 3DExperience)

Q2.10 Do you apply data anonymization?


30%
45%
15%
10%
Yes.
No, but it should be done before the translation steps.
I don't know yet.
No.

Appendex 2: Understanding ISO 15926-4: An In-Depth

Purpose of ISO 15926-4:

The primary purpose of ISO 15926-4 is to establish a standardized framework for representing, exchanging, and sharing information related to the process industry. This standard is crucial in enhancing communication, collaboration, and data integration between different entities within the process industry, such as operators, suppliers, engineering firms, and regulatory authorities. It promotes consistency, accuracy, and efficiency in data exchange, reducing errors and minimizing risks in industrial processes.

Main Target of ISO 15926-4:

The main target audience for ISO 15926-4 includes professionals and organizations involved in the process industry, such as:

1. Engineers and designers: ISO 15926-4 enables them to share detailed process data and specifications accurately, facilitating the design and operation of industrial systems.
2. Plant operators: It helps them maintain and operate the plant efficiently by providing access to reliable and consistent data.
3. Regulators and safety authorities: ISO 15926-4 aids in compliance monitoring and safety management through standardized information exchange.
4. Suppliers and manufacturers: It allows them to provide precise technical data to their customers, ensuring that products and components meet industry standards.

Key Properties of ISO 15926-4:

The main properties of ISO 15926-4 are pivotal to its effectiveness in facilitating data exchange and interoperability within the process industry. These key properties can be summarized as follows:

1. Semantic Precision: ISO 15926-4 relies on a formal semantic framework that goes beyond merely encoding data; it captures the underlying meaning of the information. This approach ensures that data is represented unambiguously, enabling all stakeholders to share a clear and shared understanding of the exchanged information. Semantic precision eliminates the potential for misinterpretation, making it an essential element for achieving seamless communication and collaboration.

2. Ontology-Based: At the heart of ISO 15926-4 lies an ontology-based modeling approach. This methodology empowers users to create a structured, shared representation of concepts, their attributes, and the relationships between them in the context of the process industry. By employing ontologies, ISO 15926-4 enhances data modeling, making it more coherent, organized, and capable of capturing the intricacies of complex industrial systems. The use of ontology enables a deeper level of understanding and context for the data, making it an indispensable feature.

3. Information Integration: ISO 15926-4 excels in its ability to integrate diverse data sources and formats seamlessly. In a modern industrial landscape, data is generated and stored in various systems and formats. This property ensures that data from different sources can be harmonized and exchanged efficiently. Information integration promotes a unified data ecosystem, minimizing the need for data conversion and facilitating compatibility between disparate systems, thus reducing the complexities of data sharing and exchange.

4. Extensibility: The adaptability of ISO 15926-4 to evolving data needs sets it apart as a forward-looking standard. It is designed to be extensible, accommodating the changing demands of the process industry. This feature allows organizations to incorporate new data requirements and technological advancements without undergoing extensive overhauls of their existing systems. The standard's extensibility ensures it remains relevant and useful over time, aligning with industry trends and advancements without constant updates.

In essence, the key properties of ISO 15926-4 collectively form a robust foundation for data exchange and integration in the process industry. These properties enhance the precision, structure, compatibility, and adaptability of the standard, ultimately leading to more effective collaboration, streamlined operations, and improved decision-making in this critical sector.

Data Model Structure:

ISO 15926-4 relies on an ontology-based data model structure. This structure includes the following key elements:

1. Classes: These are fundamental building blocks representing concepts such as equipment, materials, properties, and processes.
2. Properties: These describe the characteristics or attributes of classes. For example, the properties of a piece of equipment might include its size, material composition, or operational status.
3. Relationships: These define how classes are related to each other. Relationships capture the connections between different concepts, such as equipment connected to pipelines.
4. Instances: These are specific real-world objects or instances of classes. Instances represent equipment, materials, or processes in a plant or industrial setting.

Language Models Used for Creating Data Models:

ISO 15926-4 primarily uses ontology modeling languages, such as OWL (Web Ontology Language) and RDF (Resource Description Framework), to create data models. These languages enable the definition of classes, properties, relationships, and the logical rules governing their interactions. Additionally, ISO 15926-4 promotes using standards like the ISO 15926-2 Reference Data Library (RDL) to ensure consistency in data modeling.

Limitations of ISO 15926-4:

While ISO 15926-4 offers a promising framework for data integration and information exchange in the process industry, it is essential to acknowledge its limitations and challenges for a more comprehensive understanding of its practical applicability. Here are further insights into the limitations of ISO 15926-4:

1. Complexity: Implementing ISO 15926-4 can be complex and require significant resources and expertise, particularly for organizations new to ontology modeling and data integration.
2. Adoption Challenges: Widespread adoption may be hindered by the need for stakeholders to align their data with the standard.

Use Cases of ISO 15926-4:

1. Engineering and Design: ISO 15926-4 aids in the creation and exchange of detailed engineering specifications, which are crucial in the design and construction of industrial systems.
2. Plant Operation and Maintenance: Operators can use ISO 15926-4 to access comprehensive data for efficient and accurate plant operation, maintenance, and asset management.
3. Regulatory Compliance: Regulatory bodies and safety authorities can leverage ISO 15926-4 to standardize data reporting, making it easier to monitor and enforce safety regulations.
4. Supplier Integration: Manufacturers and suppliers can use ISO 15926-4 to share product information with their customers, ensuring that equipment and materials meet industry standards.

Conclusions:

In conclusion, ISO 15926-4 is an integral part of the ISO 15926 framework, which focuses on data integration and interoperability in the process industry. It standardizes data exchange, enhancing communication, collaboration, and efficiency while reducing errors and risks. With its ontology-based approach, ISO 15926-4 provides a structured, semantically precise framework for sharing information across various industrial sectors, promoting a more connected and effective process industry.

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[1] I. 15926-4, Industrial automation systems and integration-Integration of life-cycle data for process plants including oil and gas production facilities-Part 4: Initial implementation, Geneva: International Organization for Standardization, 2019.

Appendix 3: S5000F Overview

S5000F is an international specification for in-service data feedback.
With the introduction of new and complex technical products, a proper support system must be made available in a timely manner. This requires a proper product surveillance in order to fulfil the product liability regulations and to ensure a proper and optimal exploitation of product capabilities. A process for information feedback thus becomes necessary so as to ensure cost-efficient and optimised operation of the product. Over the life cycle of a complex technical system or product, support costs are much higher than the acquisition costs. Therefore, this specification is a prerequisite for cost saving and optimized product exploitation. It describes the relevant data flow for the involved parties and information feedback when the data is analysed and turned into recommendations.
The specification S5000F [36] [37] has been designed to cover the information that is required to be feedback for both Integrated Product Support (IPS) and other domains. It should be kept in mind that in-service data feedback is one of the most important functions of in-service support. It enables fleet and support managers and technical system manufacturers to perform a thorough analysis of operational and maintenance performance, as well to use real data for analytics and simulations.
The results of this analysis can be the basis for:

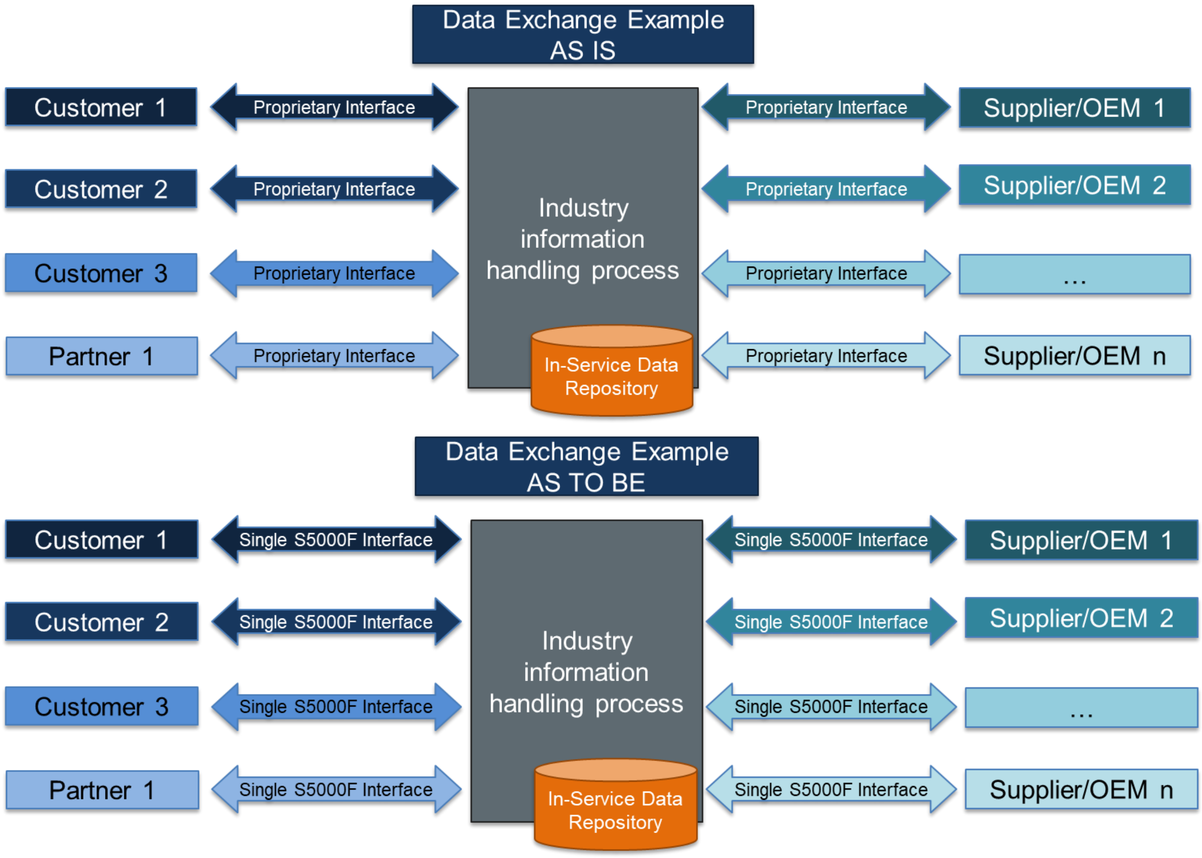
- Enhancement of the maintenance and support concept
- Improvement of the product by modifications and retrofit activities
- Sophisticated operational planning

The overall aim to be achieved by in-service data feedback is the increase of fleet and product availability and optimization of effectiveness. In addition, feedback information is a firm requirement by industry to agree to and manage performance-based logistic (PBL) contracts where the contractor takes over part or the full maintenance of the product and fulfils his obligations regarding product liability.
The purpose of using S5000F alone or together with other S-Series or IPS specifications is to obtain a structured way to handle the operational, maintenance and other data feedback from the operator, but also from the contractor, vendor, supplier, MRO center or any other involved stakeholder. By using the data model of S5000F (and the common data model for the S-Series of IPS specifications, SX002D) this can be performed in an efficient way.

S5000F interoperability with other S-series IPS specifications:

- A significant effort was carried out so as to ensure that S5000F is interoperable since the beginning with the other S-Series of IPS specifications.
- S5000F Issue 3.0 is fully interoperable with S3000L issue 2.0, as well as with S2000M Issue 7.0, S6000T Issue 2.0, SX000i Issue 3.0 and the next issue of S4000, and is published together with them in a common block release.
- Coordination is also performed with SX000i so as to ensure that the feedback corresponds to the activities defined in the global IPS framework. Similarly, S5000F is since the beginning fully interoperable with the S-Series Common Data Model (SX002D) and has included even elements of the future Issue 2.1. The interoperability with other S-Series specifications is also being monitored, so as to include them is future issues of S5000F.
- Similarly, the data environment is described by a detailed relationship model using standard UML technology (based on ISO Standard 10303, AP239, PLCS). This will allow in the medium term to integrate feedback data not only with IPS, but also with Engineering, using the ISO STEP standards. The goal is not to have an isolated feedback specification, but to integrate in a set of IPS, engineering and manufacturing specifications so as to achieve a true global lifecycle data exchange.

S5000F, as part of the ASD S-SERIES Specifications, provides a standard data exchange mechanism between two sources, using a common format, for the feedback of in-service data. At the moment the specification has been released, in 2021, in its third issue.



Key properties:

- Scalable: can be implemented on selected use cases and then progressively extended
- Integrable: since usage is limited to data exchange, it can be easily integrated with existing legacy systems through import/export functions
- Interoperable: fully interoperable with other S-SERIES standards (S1000D, S2000M, S3000L, S4000P…)
- Guided: the specification provides reference use cases, with relevant data defined (including mandatory and optional data if requested)
- Tailorable: possibility to
  - add project-specific codes, and remove unnecessary (unused) ones
  - define project-specific use cases
  - add project-specific information without "breaking" the specification
- Relational: the data model provides the information about how the data received are related with each other, supporting warehousing and analytics activities.
- Agnostic: the implementation of S5000F does NOT require changing the existing legacy IT systems. It may require some adjusting of the internal processes for data validation. S5000F does not mandate how to exchange the data information, only the format – so it can be used web services, an ad-hoc protocol, FTP, e-mail…

The S5000F data exchange is based on XML, with a message structure in line with the other S-SERIES specifications. It is made by:

- **Class**, a block in the data model diagram, an equivalent of a database table
- **Attribute,** an item within a block, a field in that table
- **Relationships,** arrows between the blocks, the relationships between the classes.

As a general rule, what should be done to implement the standard is to:

- Identify the activity that require exchange of data and relevant use cases
- Perform a guidance meeting to develop a technical data exchange or guidance document that covers all the exchange aspects between two parties
- Develop an export capability that generates the XML data to be transmitted
- Develop an import capability that allows to import the XML data received.

Example Use Cases:
The specification provides a list of Use Cases to tailor to. They are mainly derived from the aerospace industry but in general they can be adopted for any business field (automotive, naval, industry, train). The main categories of use cases are:

- Reliability, Maintainability, Availability, Capability, Testability
- Maintenance
- Safety
- Supply support
- Life Cycle Cost analysis
- Warranty
- Product health and usage monitoring
- Obsolescence
- Fleet management
- Software support
- Configuration
- In-service contracts
- Environmental and disposal data.

Appendix 4: IEEE 1451: Overview, Key Properties, Data Model Structure, Limitations, and Use Cases

In the ever-evolving landscape of computer science, the foundational principles of interoperability, compatibility, and reliability stand as cornerstones. These principles are not only paramount but are also the key drivers in the quest for seamless integration across diverse systems. Among the array of standards that have emerged to meet these demands, IEEE 1451 takes center stage with its profound significance and dedicated focus on creating a consistent framework for smart transducers.
But what is the smart transducer? A smart transducer is like a clever sensor or device that can not only measure things like temperature, pressure, or light but can also understand and talk to other devices or systems, making it easier to gather and share information. It's like having a sensor that's not just good at sensing but also good at sharing what it senses with the world. IEEE 1451 is engineered to serve a singular and critical purpose: establishing a universal standard for instrumentation and measurement systems. At its core, this standard aims to forge a robust communication interface and an encompassing framework that paves the way for unparalleled interoperability between smart sensors, actuators, transducers, and the intricate web of network infrastructure that supports them [1]. What makes IEEE 1451 particularly noteworthy is its thoughtfully designed architecture. It readily accommodates a spectrum of communication protocols, embracing both wired and wireless connectivity. Furthermore, it offers a methodical approach to data modeling for smart transducers, simplifying the journey for manufacturers who aspire to create new devices that harmonize effortlessly with existing systems. At the heart of IEEE 1451 lies a set of meticulously crafted data models that intricately detail the physical and functional attributes of smart transducers. These models, rooted in the Transducer Electronic Data Sheet (TEDS), bestow upon smart transducers the invaluable plug-and-play functionality capability [1]. Additionally, The IEEE 1451.4 standard does not prescribe a specific programming language for the NCAP's data model (see fig. 1).

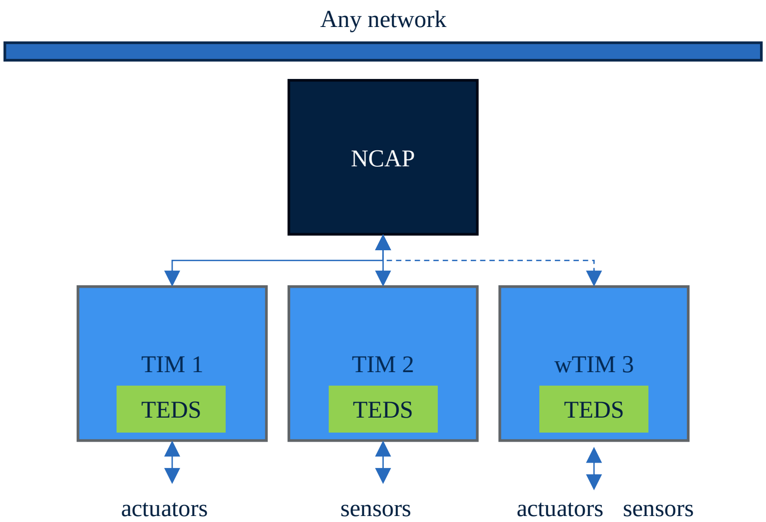


Figure 1- The example framework, as described in IEEE1451, consists of actuators that connect to the Network Capable Application Processor (NCAP) via the Transducer Interface Module (TIM). Technical information for each sensor and actuator is stored in the Transducer Electronic Data Sheet (TEDS). Additionally, the framework supports wireless communication through the Wireless Transducer Interface Module (wTIM). The NCAP provides an interface for external services to connect to the smart transducers and retrieve information or data over any network.

Instead, it focuses on defining communication protocols, data exchange formats, and the structure of information shared between external systems and transducers. However, it is imperative to acknowledge that IEEE 1451, while a robust and far-reaching standard, does have certain limitations. It does not provide an all-encompassing solution for seamless integration into existing systems, and it does not purport to cover every conceivable facet of smart transducers. Nevertheless, the standard has been embraced and widely adopted in a rich tapestry of applications, from the complexities of industrial automation to the delicate domain of healthcare and environmental monitoring [2]. In the chapters that follow, we embark on a comprehensive exploration of IEEE 1451, delving into its purpose, main target, key properties, structure of data models, language models used for ~~creating data models, its limitations, and an extensive survey of its diverse use cases. Finally, we distill our~~ insights into a concluding reflection on the enduring significance of IEEE 1451 in the ever-evolving landscape of computer science.

Purpose of IEEE 1451: Facilitating Seamless Communication

IEEE 1451 serves a multifaceted purpose to address the complexities and challenges of smart transducers and sensor networks. Let's delve deeper into the purpose and significance of this standard:

Interoperability: One of the central purposes of IEEE 1451 is to establish a common ground where smart transducers, often from different manufacturers and utilizing various networking protocols, can seamlessly communicate. By doing so, the standard promotes interoperability, ensuring that devices from diverse sources can collaborate harmoniously within a network or system [2].

Simplifying Integration: The standard was developed to simplify the integration of smart transducers into various applications and systems. Whether in industrial automation, healthcare, environmental monitoring, or any other field, IEEE 1451 streamlines the process of incorporating smart sensors and actuators. This simplification translates into time and cost savings for those involved in system integration [3].

Unified Platform: IEEE 1451 provides a unified platform that bridges the gap between smart transducers and different applications or networking systems. This unity ensures that data generated by sensors and actuators can be readily utilized by the broader network or application without requiring extensive and customized integration efforts [4].

Addressing Diverse Networking Protocols: The standard acknowledges the diversity of networking protocols employed by various transducers and devices. By accommodating wired and wireless communication protocols, IEEE 1451 is versatile, ensuring that it can be applied in various networking environments [5].

Plug-and-Play Functionality: IEEE 1451's incorporation of a Transducer Electronic Data Sheet (TEDS) enables plug-and-play functionality. This feature allows smart transducers to be easily recognized and integrated into a network without requiring intricate manual configuration [6].

Reducing Integration Complexities: The purpose of IEEE 1451 is to reduce complexities associated with integrating various sensors and actuators into a unified system. It promotes a standard framework for communication and data exchange, reducing the need for custom adaptations or extensive compatibility testing [7].

Enabling Cross-Industry Applicability: IEEE 1451 is designed to be adaptable to various industries, including manufacturing, healthcare, environmental monitoring, and more. Its flexibility allows it to provide a common interface and communication standard, regardless of the specific industry or application [8].

IEEE 1451 aims to improve interoperability, simplify integration, and create a common communication platform for smart transducers and different applications. This standard serves as a unifying factor, making connections between sensors and actuators with varying networking protocols more seamless, resulting in more efficient, cost-effective, and dependable systems across industries.

Main Target of IEEE 1451

The primary objective of IEEE 1451 is to create a standardized framework for smart transducers, a goal that carries profound implications for various industries and applications.

Industrial Automation:

One of the pivotal domains where IEEE 1451 makes a significant impact is in industrial automation. In this context, the standard seeks to streamline the integration of smart transducers into manufacturing plants and factories [2]. By providing a common interface, IEEE 1451 facilitates the connection of diverse sensors and actuators to the control systems responsible for overseeing and optimizing industrial processes [3]. Whether it's monitoring temperature, pressure, or the functioning of robotic machinery, the standard ensures that these smart transducers can work harmoniously within the industrial ecosystem [4].

Building Automation:
The field of building automation, which encompasses intelligent control of heating, ventilation, lighting, and security systems, also benefits from IEEE 1451's main target. The standard empowers building automation systems to incorporate an array of smart transducers. This leads to more efficient and energy-conscious building management. For instance, temperature sensors and occupancy detectors, interconnected through IEEE 1451, enable precise control over heating and lighting, contributing to energy savings and improved occupant comfort [6].

Environmental Monitoring:
In environmental monitoring, the standard serves as a cornerstone for deploying smart sensors and actuators. These devices are vital for collecting data on various environmental parameters, from air quality to weather conditions. By adhering to IEEE 1451, environmental monitoring systems can seamlessly combine sensors and actuators from different manufacturers. This facilitates the creation of comprehensive and reliable environmental monitoring networks, which are indispensable for applications such as weather forecasting, pollution control, and climate research.

In essence, IEEE 1451's core mission is to offer a universal interface for the seamless integration of smart transducers into a diverse array of applications. By doing so, it ensures that these devices can communicate effortlessly with different network systems, leading to a unified platform for data acquisition and control. This unification brings about efficiency, reliability, and a foundation for innovation in industries ranging from manufacturing and construction to environmental protection. IEEE 1451 is the bridge that connects the physical world of sensors and actuators with the digital realm of data management and control, fostering progress and enhanced capabilities across numerous sectors.

Key Properties of IEEE 1451

The IEEE 1451 has the following key properties:
Plug-and-Play Compatibility: One of the standout features of IEEE 1451 is its plug-and-play compatibility. This key property simplifies the integration of smart transducers into various network systems. When a smart transducer is connected, it is automatically recognized and configured by the system without the need for complex setup procedures. This capability streamlines the installation process, reduces setup time, and enhances the overall user experience [3].
Interoperability: IEEE 1451 places a strong emphasis on ensuring interoperability between different systems. By providing a standardized framework for communication, the standard facilitates the seamless exchange of data and control commands between smart transducers, transducers, and network systems. This interoperability is fundamental in environments where diverse devices from multiple manufacturers need to work together cohesively. It prevents compatibility issues and fosters a more efficient and collaborative ecosystem of interconnected devices [6].
Scalability: The scalability of IEEE 1451 is another critical attribute [7]. It allows the standard to be employed in systems of varying sizes, from small-scale applications to large-scale industrial automation systems. This adaptability is crucial in an ever-evolving technological landscape, where the scope and complexity of systems can change over time. The standard's ability to scale ensures that it remains relevant and effective as systems grow or evolve, offering a future-proof solution for a wide range of applications.
Flexibility: IEEE 1451's flexibility is a key property that enables it to be tailored to meet the specific requirements of diverse applications. This customization capability allows system designers and manufacturers to adapt the standard to their unique needs. Whether it's adjusting communication protocols, data models, or other parameters, the flexibility of IEEE 1451 empowers users to fine-tune the standard to achieve optimal performance and functionality for their particular use cases. This

adaptability enhances the versatility of the standard and extends its applicability across various industries and applications.

In brief, IEEE 1451 is a substantial standard in smart transducers and network systems, whose key properties include plug-and-play compatibility, interoperability, scalability, and flexibility. These features collectively ensure that the standard is seamlessly integrated with various systems, promotes collaborative interaction, adapts to different system sizes, and can be customized to meet specific application needs.

IEEE 1451's robust feature set makes it an indispensable tool for achieving efficient and effective smart transducer integration in various technological landscapes. Its properties allow it to effortlessly integrate with various systems, promote collaboration, and adapt to the requirements of different applications.

Structure of Data Models

The structure of data models in IEEE 1451 is meticulously designed to ensure seamless and standardized communication between smart transducers and network systems. It comprises three distinct layers, each with its own set of responsibilities [9]:

Physical Layer: The physical layer serves as the foundational level of the data model structure. Its primary role is to manage the physical connectivity between smart transducers and the broader network system. In this layer, the practical aspects of how smart transducers are physically linked to the network are defined. This includes considerations such as the types of cables, connectors, and interfaces used for the physical connection. The physical layer ensures that the transducers are physically compatible with the network, allowing for the reliable transfer of data.

Communication Layer: Positioned above the physical layer, the communication layer provides a standardized and well-defined framework for the exchange of data between smart transducers and the network system. It encompasses various communication protocols and mechanisms that enable data to flow smoothly and consistently. These protocols are critical in ensuring that data is transmitted accurately, securely, and efficiently. The communication layer plays a pivotal role in maintaining interoperability and reliability in the data exchange process.

Application Layer: At the top of the data model structure is the application layer, which is responsible for providing a common and user-friendly interface for diverse applications to access the data generated by smart transducers. This layer abstracts the complexities of the lower layers, making it easier for software applications to interact with the transducers. By offering a standardized interface, the application layer ensures that software developers can create applications that work seamlessly with various smart transducers, regardless of their underlying physical and communication characteristics.

The hierarchical structure of these three layers forms a cohesive and organized approach to managing data and communication within the IEEE 1451 framework. This layered structure simplifies the development and integration of smart transducers into various systems and applications, fostering interoperability, compatibility, and reliability in the world of smart sensor technology.

Language Models Used for Creating Data Models

The IEEE 1451 standard does not specify the use of language models for creating data models [9]. Instead, it provides a framework for defining data structures and semantics for transducer electronic data sheets (TEDS) that can be used to represent various types of sensors and their associated data.

TEDS is a set of data structures and definitions that provide a consistent way of representing transducer data and metadata. It includes a basic TEDS section that contains essential identification information, followed by one or more optional sections that contain additional data specific to the transducer type.

To create a TEDS file, manufacturers typically use software tools provided by the IEEE 1451 committee ~~or third-party vendors that support the standard. These tools typically offer graphical user interfaces or~~

APIs that allow users to enter the relevant data for their transducers, such as sensor characteristics, calibration data, and manufacturer information. The resulting TEDS file can then be uploaded to the transducer or stored in a database for later retrieval.
While natural language processing techniques could be applied to generate TEDS files automatically based on textual descriptions of transducer specifications, there is currently no established practice or tooling ecosystem supporting this approach within the context of IEEE 1451. Therefore, manual entry or import from spreadsheets or other structured data sources remain the predominant methods for generating TEDS files.

Limitations of IEEE 1451

Every standard has its own set of limitations, and IEEE 1451 is no exception. This standard presents several limitations that are important to consider:
Security and Authentication: One of the primary limitations of IEEE 1451 is its primary focus on creating a standardized framework for smart transducers. While the standard excels in facilitating interoperability and communication, it does not comprehensively address the critical aspects of security and authentication. In today's interconnected and data-driven world, safeguarding the integrity, confidentiality, and authenticity of data is of paramount importance. IEEE 1451 does not offer specific guidelines or protocols for securing communication between smart transducers and the network, leaving this responsibility to be addressed through supplementary security measures. Consequently, users and implementers must explore external security solutions to protect their systems against unauthorized access, data breaches, and cyber threats.

Data Storage and Management: Another limitation of IEEE 1451 is its relatively limited framework for data storage and management. While the standard provides a robust structure for real-time data exchange between smart transducers and the network, it does not comprehensively address the long-term storage and management of data. In applications where historical data analysis, auditing, or regulatory compliance is essential, additional solutions are required to manage and archive data efficiently. This limitation necessitates the integration of supplementary systems and protocols for data storage, backup, and retrieval, which can introduce complexity and additional costs to the overall system.

Wireless Communication Challenges: IEEE 1451, initially designed with a focus on wired communication, faces challenges when addressing the intricacies of wireless sensor networks. While efforts are ongoing to extend the standard to encompass wireless communication, this remains a limitation for applications centered on wireless technology. As the demand for wireless sensor networks continues to grow in fields like the Internet of Things (IoT) and remote monitoring, the absence of a comprehensive wireless solution within IEEE 1451 underscores the need for supplementary standards and protocols to bridge this gap.

Complexity and Learning Curve: Owing to the intricacies of the IEEE 1451 standard, it can be perceived as complex by users and implementers. Implementing the standard may require a steeper learning curve, particularly for those new to it. This complexity can lead to challenges in its adoption, potentially deterring organizations and developers from leveraging the benefits of IEEE 1451. As a result, supplementary documentation and educational resources are often required to facilitate the effective implementation and utilization of the standard.

Compatibility Challenges: While IEEE 1451 strives to promote interoperability, there may still be compatibility challenges in cases where existing systems and devices do not fully align with the standard's requirements. Legacy systems and proprietary protocols may pose obstacles to seamless integration. Overcoming these compatibility issues can require additional effort and investment in adapting or upgrading existing systems to align with IEEE 1451.

Despite its limitations, it's important to recognize that IEEE 1451 remains a valuable framework for achieving interoperability and standardization in smart transducers. It serves as a foundational structure upon which additional solutions, protocols, and security measures can be built to address the evolving needs of complex and interconnected systems. The ongoing evolution of IEEE 1451 and its potential interoperability with other standards offer promising avenues to mitigate some of these limitations, making it an increasingly robust and adaptable framework. In conclusion, IEEE 1451 is an essential tool for smart transducers, and its continued development will only enhance its usefulness in the future.

Use Cases of IEEE 1451

Beyond industrial automation, building automation, and environmental monitoring, IEEE 1451's versatility extends to various applications across diverse industries. Let's explore additional use cases where this standard proves its value:

Reference	Technology Components Used	Industry	Connectivity
Gas sensor (nose) [1]	Plug-and-play, self-calibration	Gas Sensing	Wired
Wastewater treatment [2]	Edge processing and interoperability	Wastewater	Wireless
Microphone [3]	Edge processing and TEDS to save sensor characteristics	Audio	Wired
FPGA process automation [4]	Interface independence and TEDS reconfigurability	Automation	Wired and Wireless
Zigbee Study [5]	Zigbee TII, Interoperability and TEDS	Academic Research	Wireless
Smart Comfort Sensing System [6]	Interoperability, wireless communication & TEDS	(Building) Automation	Wireless
pH sensor [7]	Self-calibration through Calibration TEDS, Adaptation to USB	(Fish) Farming	Wired

Smart Transducers for Industrial Automation [8]	Mixed Mode Interface, TEDS and plug-and-play	Industrial automation	Wired
e-Bike Monitoring System [10]	Bluetooth TII, edge computing and TEDS	Vehicular Sensing Networks	Wireless
Smart Transducer [11]	TEDS and 10-line TII	Proof-of-Concept	Wired
IoT Interface for Industrial Analog Sensor [12]	TEDS and Ethernet TII	Industrial Internet of Things	Wired

1. Healthcare: In the scope of healthcare, IEEE 1451 provides an invaluable framework for smart transducers, particularly in the context of patient monitoring and medical device integration. Smart sensors equipped with IEEE 1451 can seamlessly communicate with medical equipment, ensuring the collection of vital patient data in real-time. This enables healthcare providers to deliver more precise and responsive care, while also streamlining the management of medical devices and ensuring their compatibility with hospital information systems.
2. Transportation and Vehicle Systems: The standard plays a crucial role in the transportation sector, facilitating the integration of sensors and actuators in vehicles and transportation systems. In the automotive industry, IEEE 1451 can be used to create a standardized interface for various sensors, enabling functionalities like engine diagnostics, airbag systems, and anti-lock braking. In public transportation systems, it ensures seamless integration of sensors for fare collection, passenger counting, and safety monitoring, contributing to safer and more efficient transit services.
3. Research and Development: Research institutions and laboratories benefit from IEEE 1451 in various applications. This includes environmental science, materials research, and scientific experimentation. By utilizing IEEE 1451-compliant sensors, researchers can effortlessly integrate these devices into their data acquisition systems. This integration streamlines the process of real-time data collection and experimentation across different fields of study.
4. Energy Management: In pursuing sustainable and efficient energy management, IEEE 1451 plays a pivotal role. Smart sensors compliant with this standard can be employed in energy monitoring and management systems, contributing to reduced energy consumption and lower operational costs. Whether in industrial settings, commercial facilities, or residential properties, the standard facilitates the real-time collection of data on energy usage and environmental conditions.
5. Agriculture and Precision Farming: Modern agriculture increasingly relies on technology for precision farming. IEEE 1451-compliant sensors and actuators can be applied in agriculture for soil quality monitoring, automated irrigation, and climate control in greenhouses. This ensures optimal conditions for crop growth and efficient resource usage, enhancing agricultural productivity.

6. Smart Cities: As cities worldwide evolve into smart cities, IEEE 1451 serves as a foundational standard. It supports the integration of various sensors and actuators to enhance urban services. This includes applications like traffic management, waste collection optimization, and environmental monitoring for air quality and weather data, ultimately improving city livability and sustainability.
7. Security Systems: In security systems, IEEE 1451 enables the integration of smart sensors for surveillance and access control. These sensors communicate with security systems to enhance monitoring and response capabilities, ensuring safer environments in commercial, industrial, and residential settings.

To summarize, the influence of IEEE 1451 extends beyond select industries and has far-reaching implications in healthcare, transportation, research, energy management, agriculture, smart cities, and security systems. This versatile standard underscores its relevance and significance by providing a framework for smart transducers that are interoperable, compatible, and dependable across different domains, leading to enhanced effectiveness, security, and ecological stewardship in multiple sectors.

Conclusion

IEEE 1451 is a crucial standard in computer science that provides a structured and reliable framework for smart transducers. It establishes a common interface that connects smart transducers with various network systems, ensuring plug-and-play compatibility, interoperability, scalability, and flexibility.

IEEE 1451 utilizes a structured approach to data models, which are organized into three layers, making it easy to represent the physical and functional attributes of smart transducers. The IEEE 1451 standard does not specify the use of language models for creating data models. Instead, it provides a framework for defining data structures and semantics for transducer electronic data sheets (TEDS) that can represent various types of sensors and their associated data.

Despite its comprehensive scope, it is important to note that IEEE 1451 is not a universal solution for every integration challenge or all aspects of smart transducers. However, its practical effectiveness and widespread acceptance demonstrate its pragmatic utility.

IEEE 1451 has been adopted across a broad range of fields, including industrial automation, building automation, and environmental monitoring, where it has streamlined the integration of smart sensors and actuators into complex processes.

In summary, IEEE 1451's versatility and its role in promoting interoperability and seamless integration of smart transducers underscore its importance in computer science. By offering a unified framework and well-structured data models, it equips manufacturers with the tools necessary to develop devices compatible with existing systems and scalable for future applications. Its widespread adoption in various fields is a testament to its enduring practicality and value.

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Appendex 5: About ISO 23726 – 3 Industrial Data Ontology (IDO)

Introduction

An engineering asset, such as a new offshore renewables energy field, an existing sub-sea development, or an aircraft model, is a system of systems. Each system has multiple stakeholders, and each stakeholder has specified the use of structured vocabularies (e.g., from ISO, IEC, ASME, DIN), data model(s) and design standards. The exchange of information at each stage of the life cycle, and within a life cycle phase, such as design, is therefore complicated. Errors in information exchange and integration can lead to risks, such as cost overruns, safety events and product delays. Management of these risks include controls such as facilitating automated data exchange. This semantic interoperability involves computers being able to unambiguously understand data and its context and this is achieved through the reasoning ability of an ontology.

What is IDO?

IDO is an OWL 2 ontology (https://www.w3.org/TR/owl2-syntax/). IDO is designed to support machine automated reasoning over information used in the design and through-life operation of complex, long-life, engineering assets.

IDO is suitable for industrial use cases, to create vocabularies and asset models, and exploit OWL DL reasoning for quality assurance and inference of implicit knowledge.

IDO provides "usable" guidance for creating ontology patterns and examples of patterns commonly used to capture important data and relations in the engineering design process and inoperation and maintenance. The use, and reuse, of approved patterns reduces risks that modellingmistakes will be made and increases the speed of the model development and quality checking processes.

Why IDO?

The intended users of IDO are involved in the design, construction, manufacturing, operation, maintenance, and disposal of assets and discrete or continuous processing systems in the engineering sector.

IDO was developed in response to demand from the industrial engineering community for ontology-based solutions to the problem of semantic interoperability across information systems associated with the multiple stakeholders involved in complex systems engineering projects and through life asset management.

IDO draws on the heritage of existing ontologies.

IDO has a track-record of use in the oil and gas sector under the title of ISO/DTR 15926-14. It has been used for OWL DL reasoning over material master data in the design phase as well as for representing as-built process plants with millions of parts. It enables annotation of work orders for use in language models. IDO is also coherent with, and supports, modelling done with IEC 81346-1:2022 Industrial systems, installations and equipment and industrial products – Structuring principles and reference designations – Part 1: Basic rules and its sub-parts which provides an important link for the users of these standards to the models on which the data they are referring to in IEC 81346 is based.

IDO draws on the heritage of existing ontologies published (or in the process of being published) by ISO and IEC such as ISO/IEC 21838-1:2021) Information technology – Top-level ontologies (TLO) – Part 1: Requirements; ISO/IEC 21838-2:2021 (Top-level ontologies (TLO) – Part 2: Basic Formal Ontology (BFO)), ISO/IEC DIS 21838-3 – Top-level ontologies (TLO) – Part 3: Descriptive ontology for linguistic and cognitive engineering (DOLCE)), ISO 15926-2:2003 Industrial automation systems and integration – Integration of life-cycle data for process plants including oil and gas production facilities – Part 2: Data model; and ISO/TS 15926-12:2018 Industrial automation systems and integration – Integration of life-cycle data for process plants including oil and gas production facilities – Part 12: Life-cycle integration ontology represented in Web Ontology Language (OWL).

IDO is targeting industrial users.

What IDO provides its industrial stakeholder community is a “usable” ontology. IDO provides 1) language that is accessible to engineers and 2) industrially relevant modelling patterns, while retaining the technical capability to perform OWL DL reasoning with a well-founded ontological base. This combination of user-centric characteristics is the primary motivation for the standardisation of IDO.

Figure 1 provides an overview of the classes in IDO . Figure 2 provides an example of a pattern in this case for describing the purpose of a typical engineering asset (a compressor) and the associated classes and relations necessary to distinguish it from other engineering assets.

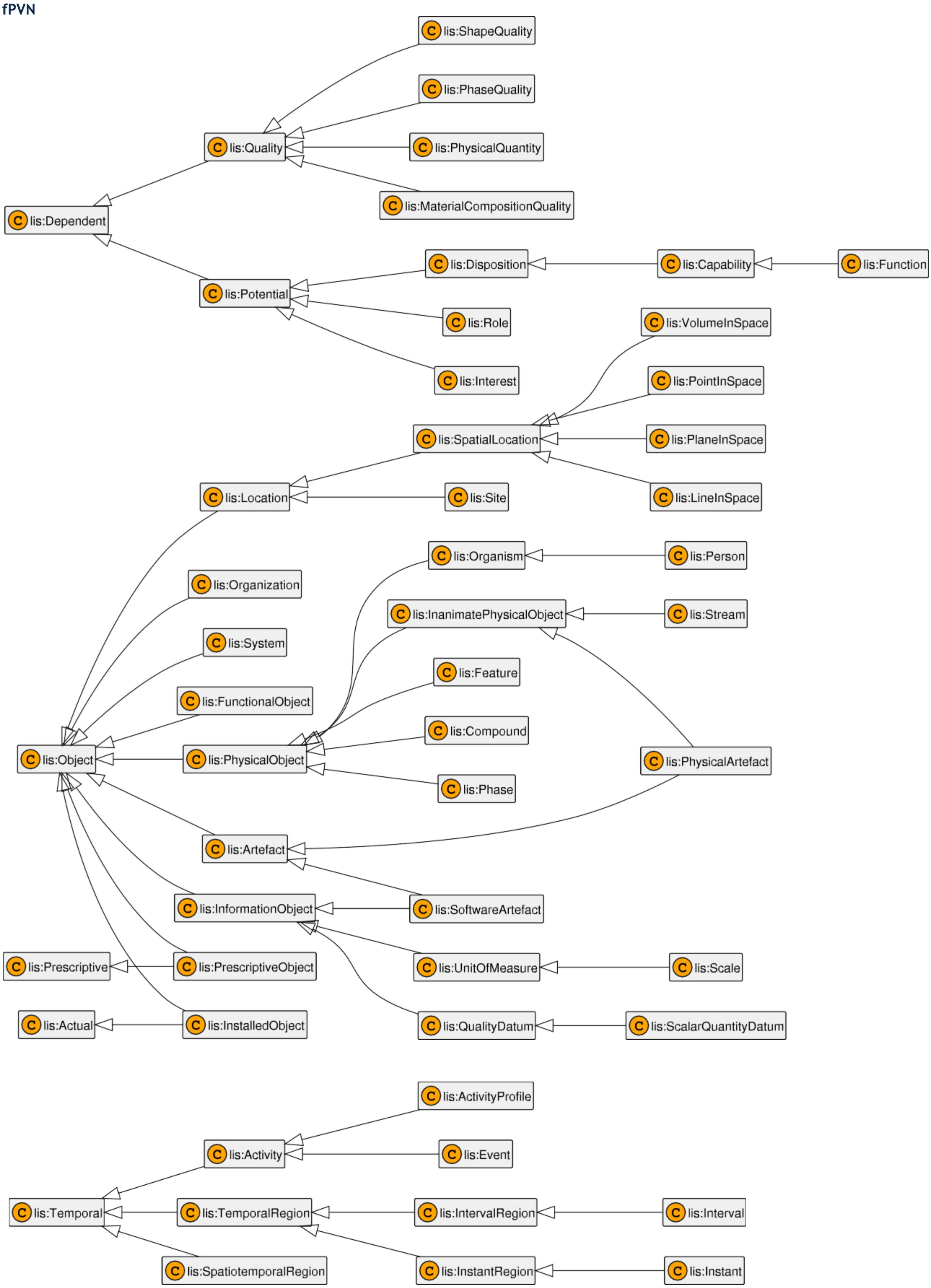

Figure 1 — The full IDO class hierarchy

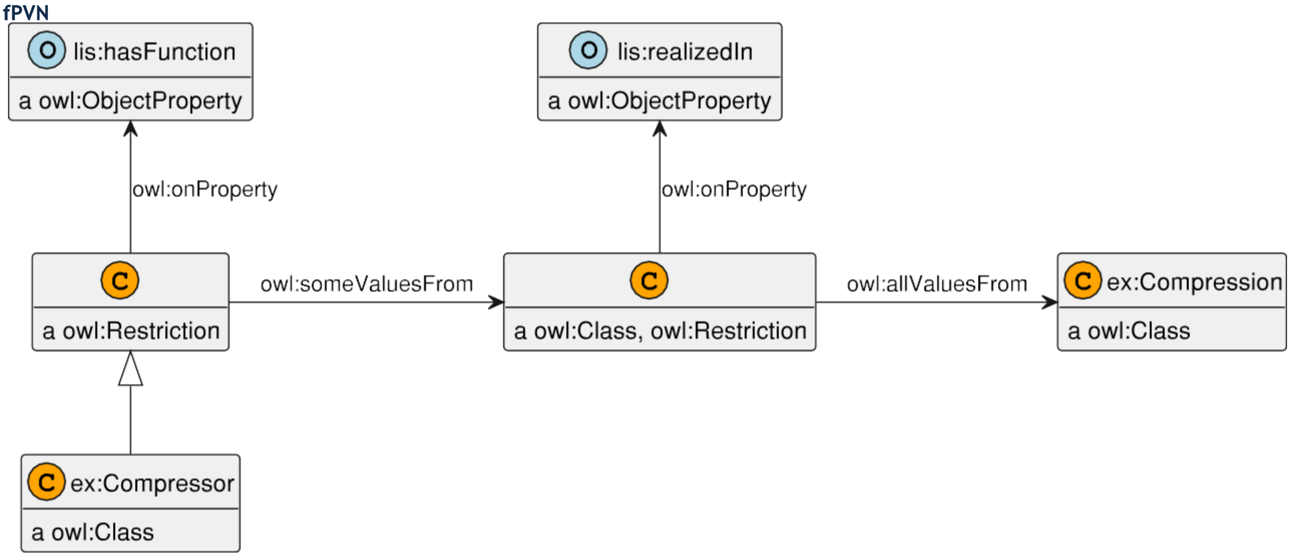

Figure 2 — IDO pattern for the function of a class of artefacts (in this case, *Compressor*)

Plans for ISO standardization and usage

At the time of writing, IDO is in progress for standardization under ISO/TC 184/SC 4. It is the initial part of a new multi part standard ISO 23726 Ontology Based Interoperability (OBI) (see section 7 below). It is anticipated to be published as an International Standard (IS) by ISO in the second half of 2025.

Even though IDO has not yet been published a standard it can be used. As already stated, (See section 2), it has been successfully applied for OWL DL reasoning in industrial applications.

POSC Caesar Association (PCA) publishes a dereferenceable (classes and properties have unique IDs and URIs) version of IDO here https://rds.posccaesar.org/ontology/lis14/ont/core/. PCA also publishes reference data based on IDO here https://rds.posccaesar.org/ontology/plm/. The latter is work in progress, and more content can be expected in the time to come. At the time of writing there are entities for "Equipment", "Process" "ChEBI" (Chemical Entities of Biological Interest), "UoM" (Unit of Measure) and "Documents".

The multipart standard ISO 23726 Ontology Based Interoperability(OBI)

Introduction

The objective of the new standard is to facilitate digitalization across various industries and domains by establishing a common digital vocabulary that enables the utilization of reference data within diverse standards, encompassing both ISO/TC 184/SC 4 and other standardization organizations.

The objective requires a commitment to compatibility across all parts of the standard: The digitalized requirements of each part must be expressed in a single, shared language, and the ability to verify consistency as the standard evolves is crucial. The Industrial Data Ontology (IDO; see section 4) serves a foundational role in the new standard to meet these requirements, as a basic language with which specialized modules can be expressed, and with the ability to verify consistency at scale, by means of OWL 2 DL reasoning.

Each part of the new standard will therefore utilize IDO *models* to represent knowledge, structured as OWL 2 DL compliant ontologies.

The volume and complexity of industrial data calls for support from automated systems. The importance of consistency management in industry is best justified by pointing to a selection of use cases.

Scope

the purpose of the new standard is to serve the representation and integration of industrial data and industry standards. This means, to build vocabularies and asset models, and to manage asset models which employ reference data libraries. The new standard is intended for use in all life cyclephases of industrial assets and processes.

It is anticipated that future parts of the standard will be introduced to support the requirements of specific industries, including, but not limited to the following four types of standard content:

1. Methodology and implementation guides

Best practice modelling for various industrial disciplines, e.g., the CIM (Common Information Model, BIM (Building Information Modeling)/IFC (Industry Foundation Classes) communities have shown interest in IDO.

2. Integration and application of existing standards

Detailed specifications for integration and re-use of existing reference data libraries. Examples include ISO 10303, ISO 15926, IEC CDD (IEC 61987), IEC 61360-1, eCl@ss, S2000M, S5000F and

Norwegian NORSOK standards.

3. New domain ontologies and vocabularies (Reference data)
4. Libraries of modelling patterns (templates)