MANUFACTURING-X
GUIDANCE BOARD

COLLABORATIVE ENGINEERING

Why & How to use AAS for Collaborative Engineering?

Whitepaper (Version 1)

Manufacturing-X
Guidance Board

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Open Industry 4.0 Alliance Implementation GmbH
Willy-Brandt-Platz 6
81829 Munich, Germany

This whitepaper was created by the Manufacturing-X Topic Group "Collaborative Engineering" representing the projects Catena-X, Construct-X, DAVID, Decide4ECO, DIAMOND, Factory-X, Fluid4.0, Process-X, Robot-X and VWS4LS. These projects work(ed) on how the Asset Administration Shell (AAS) as Digital Twin for Industrie 4.0 can best be used to facilitate collaborative engineering in digital ecosystems wihtin their specific domains.

The present version 1 of the whitepaper has been officially adopted by the Manufacturing-X Guidance Board and approved for publication as a guiding document. Further versions of the whitepaper may follow to reflect the progress in the dynamic field of collaborative engineering based on AAS.

Authors

Björn Sautter, Festo (Topic Group Lead; Factory-X)
Alexander Dettmann, YardStick Robotics GmbH (Robot-X)
Andreas Schüller, YNCORIS (Process-X)
Benjamin Beck, Construction Future Lab (Fluid4.0)
Christian Kosel, ARENA 2036 (VWS4LS, Construct-X)
Denis Ritz, TU Dresden (Fluid 4.0)
Hesam Rezaee, Ruhr Universität Bochum (Factory-X)
Iris Gräßler, Heinz Nixdorf Institut Universität Paderborn (Decide4ECO)
Marvin Manoury, Fraunhofer IPK (Catena-X)
Michael Ach, BMW (DIAMOND)
Miriam Schleipen, EKS InTec (DIAMOND)
Paul Remde, Construction Future Lab (Fluid4.0)
Sandeep Rudra, IDTA (DAVID)
Sascha Schaper, TRUMPF (Factory-X)
Sven Rarbach, Heinz Nixdorf Institut Universität Paderborn (Decide4ECO)
Stephan Grimm, Siemens (Factory-X)

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1 Motivation and aim of the Manufacturing-X Guide

The Manufacturing-X initiative aims at enhancing the competitiveness, resilience, and sustainability of the manufacturing industry through enabling **secure and sovereign data exchange in trusted federated digital ecosystems** [1]. These ecosystems will strengthen companies in the face of global competition, increasing digitalization, and growing regulatory requirements while securing their digital sovereignty [2]. The seamless exchange of engineering data between different actors along integrated toolchains in collaborative engineering processes is one of several use cases for the benefit of data exchange. Collaborative engineering requires a semantically aligned single or authoritative source of truth to achieve end-to-end data consistency across the engineering disciplines, tools and organizations involved throughout the product or production system development, and thus to achieve great efficiency gains (faster, simpler, better, more costeffective, etc.).

To support semantic interoperability between different industry domains represented by different Manufacturing-X projects, the Collaborative Engineering Topic Group has published this whitepaper with the focus on **semantically aligned engineering data based on the Asset Administration Shell (AAS) concept**. The paper shall provide guidance to people such as decision makers, mechanical engineers, or software architects who are involved in the development of complex mechatronic systems or the provision of corresponding engineering tools and software.

Overall objective of the paper is to …

- **illustrate the benefits** of using industry-standardized information models and transmission mechanisms, notably the AAS technology, in collaborative engineering during the development phase of mechatronic systems [3, 4],
- **provide guidance on** how these benefits could be realized in engineering data ecosystems, and to
- **give an overview of the status** of what is already working and what is not yet working.

2 Introduction to collaborative engineering in ecosystems

The engineering of complex mechatronic systems such as construction machinery, machine tools, process plants, robots, etc., which are used in various industries such as in construction, manufacturing, food processing, or chemical and pharmaceutical industries, etc. is very knowledge and time intensive. Numerous actors, disciplines, tools, and companies are typically involved in the engineering process. A lot of coordination between the engineering partners and the transfer of a large amount of engineering data is necessary.

Today, the necessary data is usually provided in a wide variety of formats (e.g., PDF) and with inconsistent attributes and units of measure. Engineers manually search for the right data (e.g., on suppliers' websites) and collect it in a laborious process (e.g., by email, by typing it out of PDF files, etc.). This is very time-consuming and prone to errors. However, speed is playing an increasingly important role in global competition – while at the same time technical engineering know-how is at risk of being lost due to demographic change.

Against this backdrop, the development and deployment of **future-oriented digital data ecosystems for collaborative engineering** is of strategic importance for securing both technological sovereignty and industrial competitiveness in a global context, as it aims at …

- **leveraging distributed information** in a single or authoritative source of truth for engineering assets
- **facilitating seamless collaboration** based on interoperable standards, and thus
- **increasing speed and efficiency** in (semi-)automated workflows, and
- **providing digital twins**, which can be used as digital thread in all subsequent phases of the product life cycle (e.g. for optimizing operations or realizing circular end-of-life scenarios).

2.1 Phases and partners in collaborative engineering

The scope of this publication covers the collaborative engineering of mechatronic systems based on the reference system VDI 2206:2021 focusing on three **engineering phases**:[1]

1. **Requirements engineering and concept design** in accordance with customer requirements
2. **Discipline-specific design and engineering** of all elements of the mechatronic systems
3. **Simulation and virtual commissioning** for assurance of properties of all elements including the overall system.

To illustrate collaborative engineering and the transfer of engineering data between **different partners**, the following four different roles are distinguished:[2]

- the customer / user of the complex mechatronic system,
- the manufacturer / supplier and integrator of the mechatronic system,
- the subsystem / part solution supplier and
- the component / automation product supplier.

Regarding the transfer of engineering data between the different actors in the digital ecosystem for collaborative engineering, this publication focuses on the …

- **information flow regarding technical requirements**, cascading from the customer to the solution, part-solution and component suppliers, and on the
- **provisioning of technical information** ascending from component suppliers to part solution and solution suppliers up to the final customer.[3]

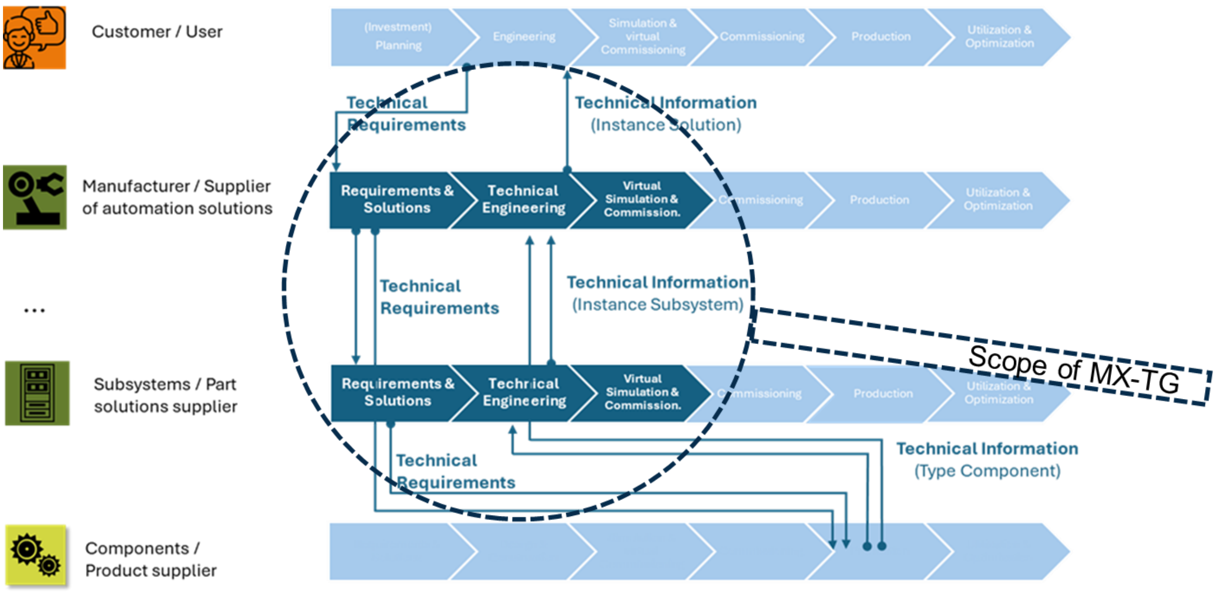

Figure 1: Scope of the MX Topic Group on Collaborative Engineering

[1] These three phases may slightly differ from the various X-projects perspective as Annex 1 illustrates.

[2] There may be more partners and roles involved. And the roles may vary depending on the industry or domain (see Annex 2).

[3] Regarding the provisioning of technical information, type information (data on a product type), which is provided in the initial engineering phases, can be distinguished from instance information (data on a product configured for a specific application context) in the virtual commissioning phase.

As shown in Figure 1, the focus of this whitepaper is on the **flow of information in connection with the three major engineering phases** (dark blue boxes) at the level of the manufacturer/supplier of the mechatronic system and the various subsystem/partsolution providers – i.e., the players who engineer the complex mechatronic system based on the customer's requirements and the appropriate automation components in an engineer-to-order process.

While **type information** – i.e., generic product information e.g. in a product catalogue – is normally provided by component/product suppliers in the initial engineering phases, **instance information** – i.e., specific information about individually configured and manufactured mechatronic components or systems – comes into play in later engineering phases, e.g. for virtual commissioning.

2.2 Collaborative engineering from manufacturer perspective

The following illustration shows a collaborative engineering process from the perspective of the manufacturer of a mechatronic system in a simplified form with three different engineering personas – representing the three major phases of collaborative engineering:

- **Daniel Designer** is responsible for conceptualizing and designing the mechatronic system based on the customer requirements.
- **Egon Engineer** is responsible for detailed engineering, e.g. for the electrical design of the mechatronic system.
- **Simon Simulation** is responsible for the simulation and finally for the virtual commissioning of the mechatronic system.

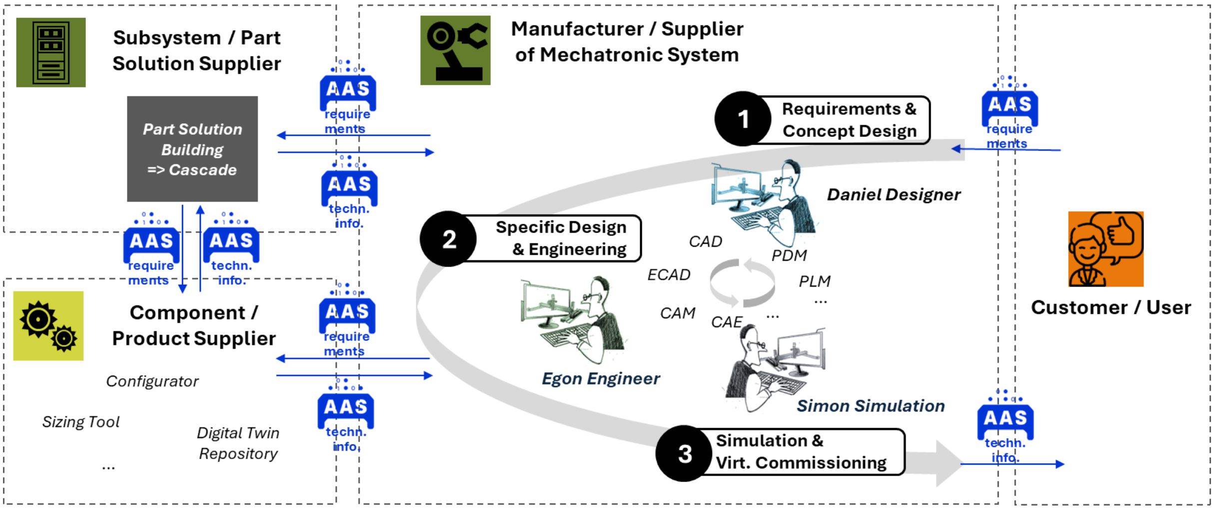

Figure 2: Fictitious collaborative engineering process supported by AAS

As Figure 2 illustrates, the AAS can be used for both the communication of technical requirements and the standardized provision of technical information throughout the entire collaborative engineering process. The AAS can be seen as a unified data container across different authoring systems, for example to provide a product's 3D data for the CAD system, the parameters for a simulation model, and the representation for a circuit diagram.

Basically, there are three main building blocks that must work together to enable efficient collaborative engineering in digital ecosystems:

1) standardized **data formats and information models** for syntactic and semantic interoperability according to the specific engineering requirements
2) decentrally organized data infrastructure with standardized **communication interfaces** for secure and consistent access to requested information in single or authorative sources of truth

3) engineering related business applications, clients, software, and tools (e.g. PDM/PLM, CAD, CAE, product configurators, sizing tools, etc.), that can all access and process the specific information in the authoritative sources of truth, to achieve seamless data consistency along with **integrated engineering toolchains**.

In the following chapter, the general concept of the AAS is introduced in relation to these building blocks. Chapter 4 then gives some guidance about basic AAS elements, which should be addressed in any case, and how to use the AAS for the provisioning of the relevant engineering data which is needed in the three major engineering phases. Chapter 5 reveals some important interrelations with complementary standards and activities from different domains. Chapter 6 concludes with an outlook and some open questions that still need to be clarified.

3 AAS in collaborative engineering

This chapter introduces the AAS concept and provides information to understand why we recommend using AAS for collaborative engineering in digital ecosystems. Chapter 4 then gives some guidance on how to specifically use the AAS for collaborative engineering.

3.1 What do I need to know about the AAS?

The AAS was developed as a **digital twin representation for physical or virtual industrial assets** (e.g. device, machine, plant, software) **over its entire life cycle** based on international Industrie 4.0 standards [5]. The structure and metamodel of the AAS were specified and standardized in the international IEC 63278 series of standards.[4] For each asset (even if it is not yet produced), all required information – including relevant data and digital models – is captured in submodels (e.g. *Digital Nameplate*, *Generic Frame for Technical Data* or *Provision of Simulation Models*) with corresponding *SubmodelElements* (e.g. *SubmodelElementCollection* (SMC): TechnicalProperties) in machine-readable form (Figure 3).

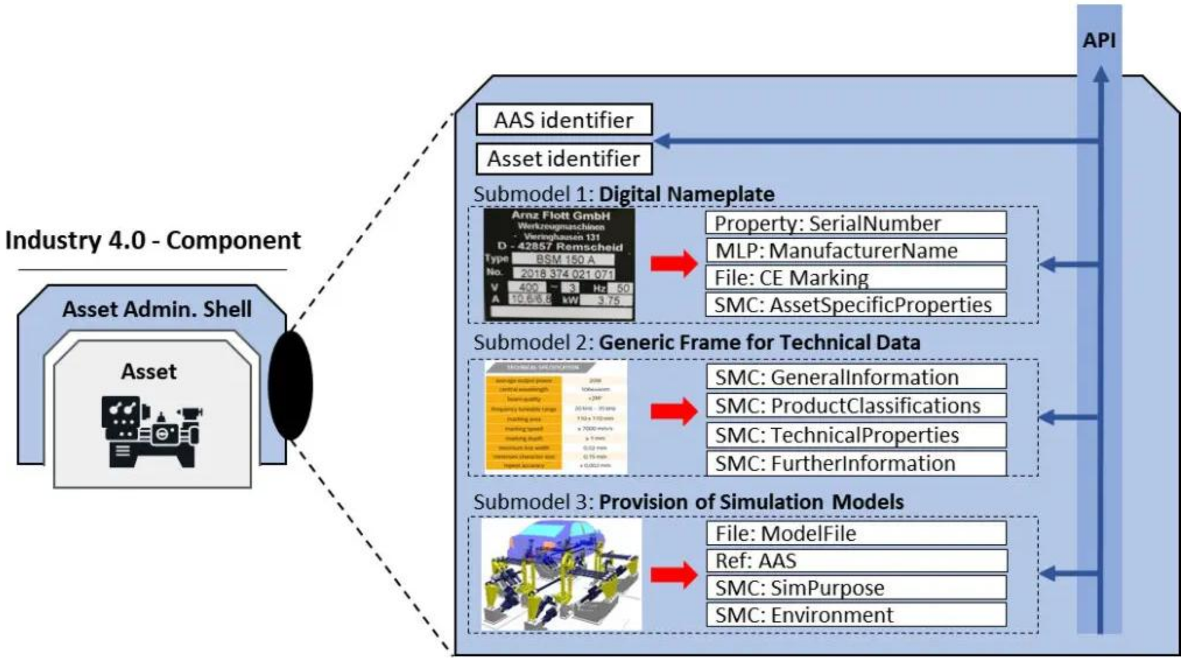

Figure 3: AAS as a representation of the digital twin for industrial assets (Source: Fraunhofer IPA)[5]

[4] See Annex 3 for concrete AAS specifications of key aspects for standardized Digital Twins

[5] https://interaktiv.ipa.fraunhofer.de/digitalisierung/asset-administration-shell-fuer-ki-lebenszyklusmanagement-in-der-produktionsindustrie [accessed on 20 February 2026]

Syntactic and semantic interoperability is ensured by **standardized AAS Submodel Templates** (SMTs) that define the structuring and representation of data for specific domains or topics.[6] These templates are developed within the AAS community and standardized by the Industrial Digital Twin Association (IDTA) to enable consistent interoperable exchange of asset information.[7]

All asset information can be decentrally stored in an AAS repository, hosted by an AAS server, and externally accessed via **REST API as standardized communication interface.**[8] In combination with the globally unique identification link for each asset and its related digital information in form of a URL, standardized in IEC 61406, the AAS can be seen as a single or authoritative source of truth for the collaborative development of complex, mechatronic systems [3]. This makes the AAS also an ideal candidate for provisioning mandatory product information along the entire product lifecycle in the Digital Product Passport for Industry 4.0 (DPP4.0).

Both described AAS aspects – interoperability based on AAS Submodel Templates and REST API as standardized communication interface – as two essential building blocks for efficient collaborative engineering in digital ecosystems explain why the AAS plays a major role in the **Manufacturing-X (MX) Port concept** for seamless, secure, and scalable data sharing across industries (Figure 4).[9] In both example MX-Port configurations "Leo" and "Hercules", the …

- **AAS REST API** in combination with the unique identifier for each asset is used for the secure exchange of asset data in a uniform way (**MX Gate**), and
- **AAS Submodels** are used to provide for each asset all required information and engineering data (e.g. geometry, interface definitions, control logic, supplier metadata, compliance information, etc.) in a semantically interoperable and machine-readable form (**MX Converter**).

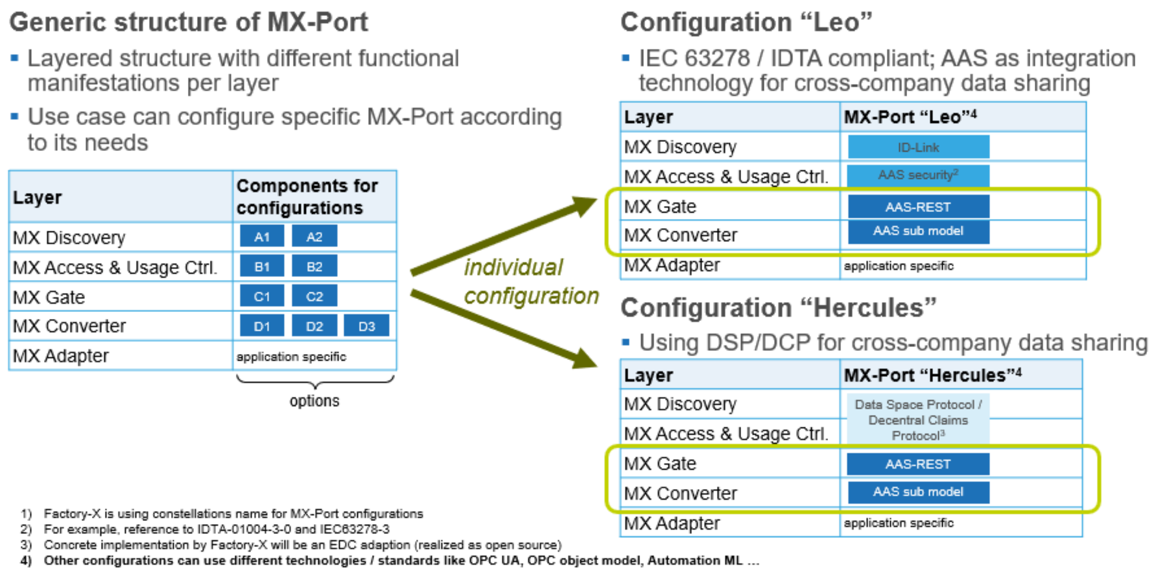

Figure 4: AAS-REST and AAS submodels as important elements of individual MX Port Configurations [6]

The MX Adapter layer refers to the specific business applications and clients, which should be enabled to use the MX Port. This relates to the third building block for efficient collaborative engineering in digital ecosystems: the seamless data consistency along **integrated engineering toolchains**. Figure 5 illustrates how an AAS server can be used as single source of truth to support multi-client applications

[6] To ensure semantic interoperability, the various elements of SMTs need to be semantically grounded in external reference vocabularies like ECLASS by means of utilizing referential semantic IDs.

[7] Overview of all IDTA registered AAS Submodel Templates: https://industrialdigitaltwin.org/en/content-hub/submodels and https://smt-repo.admin-shell-io.com/

[8] For more and practical hands-on information please consult: https://industrialdigitaltwin.org/en/ and https://admin-shell-io.com/

[9] More information about the AAS in general and its role in the Manufacturing-X context can be found in the upcoming whitepapers of the MX Topic Groups on "Asset Data Modelling" and "Data Transfer" (see: https://mx-guidanceboard.org/topic-groups)

throughout the complete engineering of a mechatronic system – from general system design (client 1), to selection of appropriate components (client 2), internal verification and documentation (client 3), generation of simulation models (client 4), and finally parametrization of controllers (client 4).

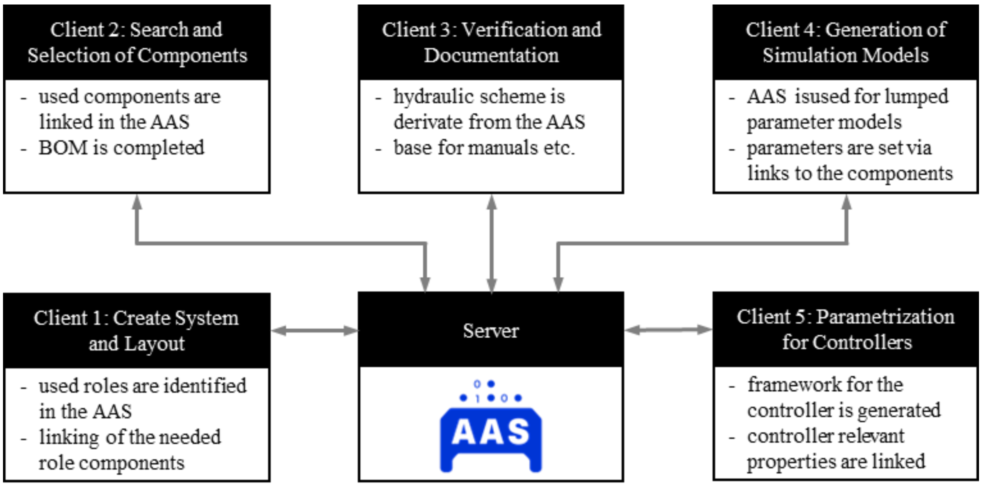

Figure 5: Example of AAS as single source of truth for engineering a hydraulic drive system [3]

3.2 Why should I use AAS in collaborative engineering?

As described in Chapter 2, engineering complex mechatronic systems typically involves many stakeholders working with diverse engineering tools across project phases. Because data formats, models, and interfaces are not unified, transferring and processing engineering data requires time-consuming, error-prone manual work, which increases costs. The same information often exists in multiple systems and is incrementally updated during development, forcing engineers to spend considerable time locating the most current, correct version.

Replacing manual workflows with an AAS-based approach streamlines this (Figure 6). Today, manufacturers often create PDF datasheets from customer requirements, suppliers manually enter those specs into catalogs, and quotations are exchanged and validated by hand. Using AAS provides standardized semantics and interfaces, enabling manufacturers and suppliers to reduce software interface development and maintenance effort, and to lower overall process costs – in particular when an AAS server is used as single or authoritative source of truth as illustrated in the previous section

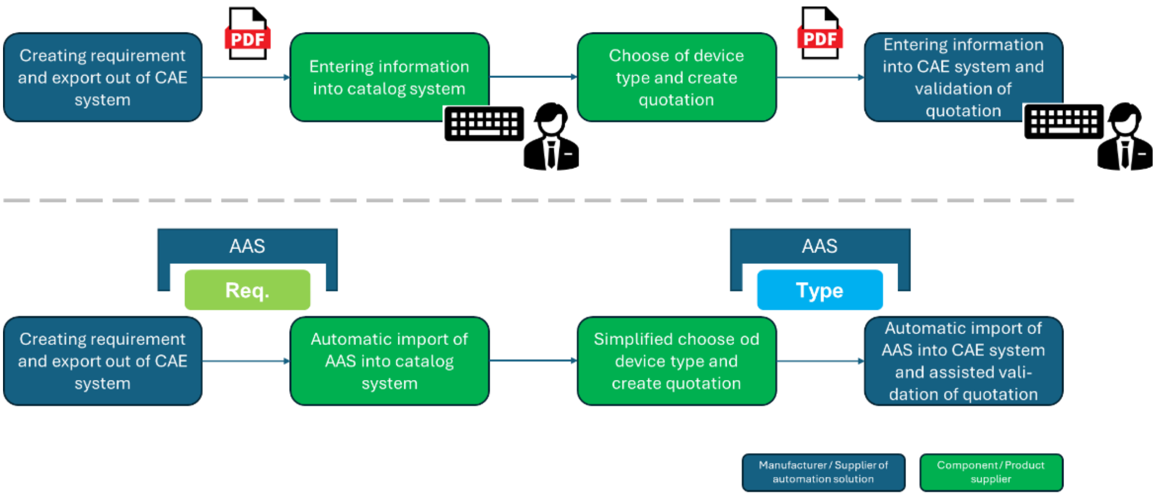

Figure 6: Example of simplified Computer-aided Engineering (CAE) information exchange using the AAS [7]

As Figure 7 shows, the consistent use of AAS throughout the entire engineering process – e.g. for a machine – can drastically **reduce development time** by up to two thirds and at the same time significantly **lower error rates** through automated processes.

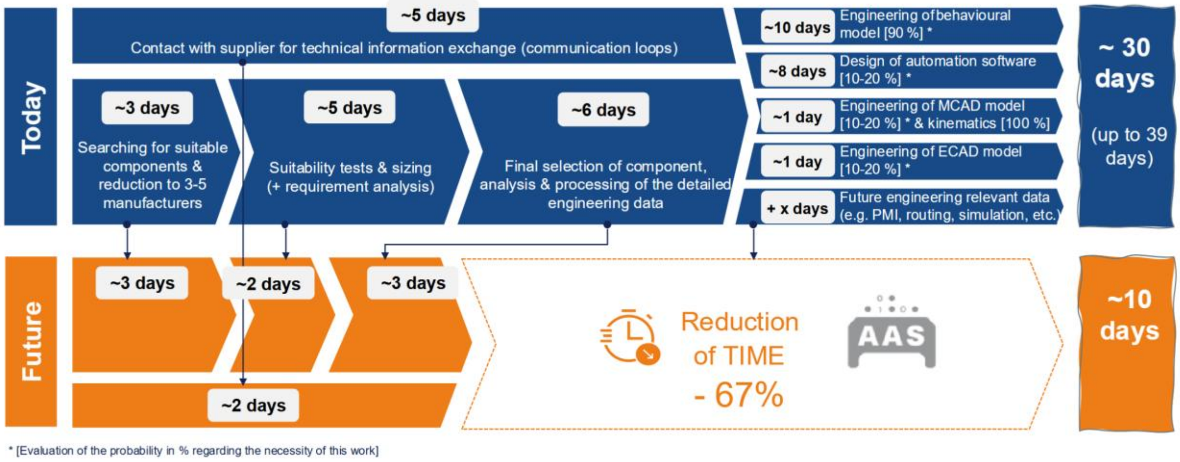

Figure 7: Example of significant efficiency gains from end-to-end machine engineering using the AAS [8, 9]

Important **prerequisites** for realizing these efficiency gains in collaborative engineering processes are:

- **Engineering software and tools** used by companies for PLM, CAD, simulation, control programming, etc. **integrate the AAS concepts** (MX Port and dynamic AAS submodel structures) and do not rely on proprietary interfaces and formats.
- **Required engineering data** is provided **in the appropriate AAS submodels** with the correct and unambiguous semantic[10], so that users can realize the added value of this end-to-end data consistency and make the generated digital twins available for subsequent phases of the product life cycle (e.g. for optimizing operations or realizing circular end-of-life scenarios).

Regarding the second bullet point, Chapter 4 explains how to use the AAS, and which submodel template should be used for which use case, while Chapter 5 reveals some important interrelations with complementary concepts, standards and formats.

4 How should I use AAS in collaborative engineering?

We recommend using at least the following basic AAS elements - regardless of the specific phase in collaborative engineering - to enable seamless end-to-end exchange of asset information:

ID-Link or GlobalAssetID as unique identifier for assets

The ID-Link or Global Asset Identifier (GlobalAssetID) is a globally unique, persistent identifier assigned to an asset so it can be unambiguously referenced across systems, organizations and over the asset's lifecycle. This identifier is standardized in IEC 61406, can be freely defined by each asset manufacturer – in practice often in form of an URL to enable interoperability via webservices – and is linked to exactly one AAS data set. This ID is maintained as a minimum requirement across all phases – from planning through engineering to operation. All relevant information can be dynamically retrieved via the AAS server infrastructure without redundant data storage when needed, thus providing a single or authoritative source of truth for the collaborative development of complex, mechatronic systems.

[10] Existing semantics (ECLASS, IEC Data Dictionary, GS1, etc.) and file formats (*.step, FMU, *.pdf, etc.) have not to be reinvented but seamlessly integrated into the specified submodels.

Basic Set of AAS Submodels

The following four AAS Submodels provide all basic information typically required or used for the digital twin of an asset (whether a simple component, a subsystem or a complex mechatronic system).

Table 1: Basic set of published AAS Submodel Templates (SMTs)

AAS SMT	Vers.	Name	Description	Links[11]	Use in MX projects[12]
IDTA # 02002	1.0	**Contact Information**	Contains contact information for the asset, including addresses, phone numbers, e-mail, availability of contact persons, and preferred means of communication. In engineering this SMT is e.g. helpful to get in contact with the right person in case of ambiguities or if further in-depth clarifications are needed.	Pdf - GitHub	all projects
IDTA # 02003	2.0	Generic Frame for **Technical Data** for Industrial Equipment in Manufacturing	Contains technical data of the asset and associated product classifications. Central element is the provision of properties, ideally interoperable by means of dictionaries like ECLASS or IEC CDD. For interoperable exchange of engineering data this is the major SMT, in particular in the initial phase of concept design where the appropriate assets can be found according to the technical requirements.	Pdf - GitHub	all projects
IDTA # 02004	2.0	**Handover Documentation**	This SMT defines a set of meta data for the handover of documentation from the manufacturer to the operator of industrial equipment. All relevant and legally required documents must be created during the engineering process and made available to the client.	Pdf - GitHub	all projects
IDTA # 02006	3.0	**Digital Nameplate** for Industrial Equipment	A digital nameplate is the machine-readable, structured equivalent of a physical nameplate, ensuring interoperable exchange of asset information through dictionaries like ECLASS or IEC CDD. For engineering purposes this SMT is important as it contains relevant information such as essential technical data, the manufacturer and the serial number, relevant information for legally required identification, traceability and safety (e.g., CE marking).	Pdf - GitHub	all projects

As Table 1 shows, every project consortium participating in the MX Topic Group "Collaborative Engineering" employed these four basic AAS submodel templates (or adaptions of it) in their engineering workflows. In addition to this basic information, further asset-related information is required during the various engineering phases. In the following, the specific engineering phases are described in more detail.

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11 Compare also the AAS SMT Repository under https://smt-repo.admin-shell-io.com/

12 Side notes for Catena-X: These models are not explicitly used but similar modeled (modeled in SAMM with an AASX output). They contain similar content and sometimes are derived such as the IDTA-02035-1 Digital Nameplate: for Battery Passports.

4.1 Requirements engineering & conceptual design

In the initial phase of engineering a complex mechatronic system, primary goals are:

- Systematically **capture stakeholder needs** and translate them into actionable specifications.
- **Identify and design suitable solutions** from components and configured subsystems that satisfy those needs.

Requirements typically cascade from the customer down to solution, part-solution and component suppliers (see Figure 1), with the number of potential partners growing at each level. Solution builders – such as manufacturers of new machines (e.g., for production or construction), new platforms (e.g., for vehicles), or other mechatronic systems for a wide range of applications – aim to design the best solutions. However, discovering suitable suppliers and selecting the best components often remains a **time-consuming, manual, experience-driven process** that can lead to suboptimal results.

System design spans multiple engineering domains and usually begins with high-level abstractions. From these abstract schematics - outlining basic components and functionalities – the overall solution evolves in an iterative process through virtual prototypes and demonstrators towards final implementation. Within each domain, the system structure is shaped by application-specific requirements, and component **choices are determined by multiple dimensions, calculations and interdependent design decisions**. For example, selecting a particular DC voltage for a circuit influences motor sizing, gearbox requirements and the set of suitable parts across electrical, hydraulic, pneumatic and mechanical domains (higher voltage might permit a smaller motor but necessitate an additional gearbox).

Beyond technical aspects, components must also satisfy non-technical constraints like manufacturability, reusability, documentation, storage, transport or marketing requirements. Making optimal design and component-selection decisions therefore demands a **large and diverse set of data**. Gathering this information is complicated by the fact that each supplier provides and distributes data differently, so engineers face significant effort in collecting and evaluating heterogeneous information. As a result, today's engineering processes remain data-intensive, laborious and complex, underlining the need for more efficient, integrated approaches to component discovery and system design.

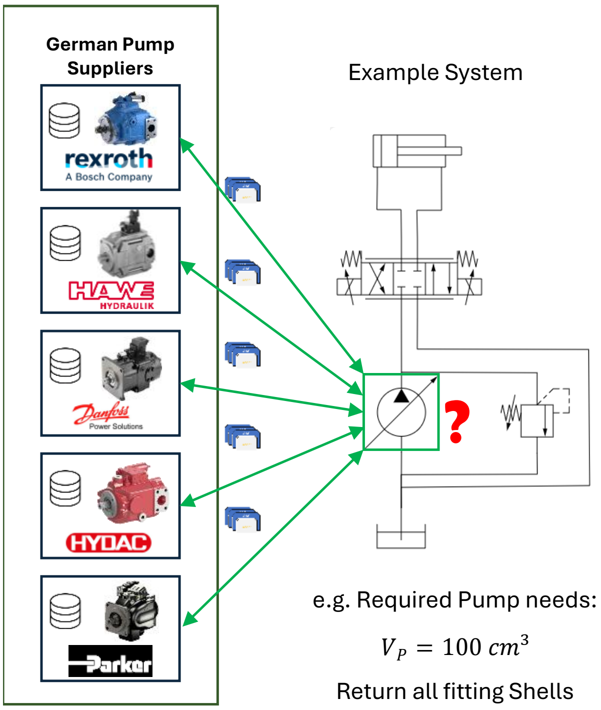

Figure 8: Example of using AAS for identifying and selecting a suitable pump for a hydraulic system

As introduced in the previous Chapter, AAS submodels can capture a wide range of product-related information in a structured, standardized, and machine-readable form, and can be easily exchanged via the standardized AAS REST API. Figure 8 shows an application example of using AAS for identifying and selecting suitable pumps, comparing across different suppliers, for a hydraulic system according to the technical requirements (e.g. displacement of 100 cm³ and handling a system pressure of 300 bars).

The AAS submodel ***Generic Frame for Technical Data for Industrial Equipment in Manufacturing*** plays a key role in identifying and selecting the right products or solutions that match the specific technical requirements. In cases where information is needed about industrial equipment composed of multiple components or assets, the AAS submodel ***Hierarchical Structure enabling Bills of Material*** plays an important role as it captures the individual AAS entities and relationship elements. Table 2 summarizes the AAS Submodel Templates (SMTs), which are often used in this initial engineering phase.

Table 2: Important AAS SMTs for requirements engineering & conceptual design

AAS SMT	Vers.	Name	Description	Links[13]	Use in MX projects
All four AAS SMTs from the basic set – listed in Table 1 – are helpful in the requirements engineering & conceptual design phase. *Generic Frame for **Technical Data** for Industrial Equipment in Manufacturing* is the key AAS SMT for identifying and selecting assets according to the specific technical requirements					
IDTA # 02011	1.1	Hierarchical Structure enabling **Bills of Material**	Relevant SMT for industrial equipment or solutions composed of multiple assets to capture the hierarchical structure using AAS entities and relationship elements.	Pdf - GitHub	Factory-X, Fluid 4.0, Process-X, Robot-X
IDTA # 02011-1	1.0	Extension based on IEC 81346	There is also an extension for IEC 81346 based structuring of machines, plants or systems to describe various aspects of composed assets.	Pdf - GitHub	

Further AAS SMTs come into play for specific domains or topics. For example, Factory-X uses the AAS SMT *Sizing of Power Drive Trains* for automated and vendor-independent finding of best electric drive systems – solutions which could be composed of components from different vendors. Another example is the AAS SMT *Carbon Footprint*, e.g. used in Decide4Eco, for eco-efficient engineering (see Table 3).

Table 3: Examples of AAS SMTs which also could be helpful in the initial engineering phase

AAS SMT	Vers.	Name	Description	Links[13]	Use in MX projects
IDTA # 02021	1.0	Sizing of Power Drive Trains	This SMT enables interoperable exchange of information required for sizing electrical drive systems in industrial automation, covering components like drives, motors, gearboxes, and transformations along with their parameters.	Pdf - GitHub	Factory-X, Fluid 4.0
IDTA # 02023	1.0	Carbon Footprint	This SMT provides the means to access an asset`s Carbon Footprint. It increases the interoperability between parties interested in documenting, exchanging, evaluating, or optimizing the environmental footprint of their assets, and might be part of larger initiatives, such as the Digital Product Passport or the Product Environmental Footprint.	Pdf - GitHub	Decide4 Eco, Process-X

[13] Compare also the AAS SMT Repository under https://smt-repo.admin-shell-io.com/

Some Notes and recommendations

Effective requirements engineering depends on the quality and the accurate representation of the information needed. Thus, it is important to rely on standardized AAS templates such as the *Generic Frame for Technical Data for Industrial Equipment in Manufacturing* and to provide the information as recommended. By augmenting technical data with metadata (e.g., the physical units used for dimensions, weight, power, etc.), ambiguities are reduced and unnecessary clarifications requests between data providers and users are prevented. In this context, the proper use of existing dictionaries such as ECLASS or IEC CDD – providing standards for classifying and describing products and services – and the respective **semantic identifiers (IDs)**[14] – unambiguously defining e.g. the designation, definition, format and, for technical properties, the unit of data – is recommended.

The example of selecting a fitting hydraulic pump (Figure 8) exactly refers to the use of globally unique Semantic IDs for identifying appropriate product groups. To increase the performance of searching and analyzing the appropriate AAS data from multiple servers with many Semantic IDs, it is advisable to use **query languages** which are already established on the web. In the mentioned hydraulic example, the requirements have been implemented inside the query such as "I need a pump with a specific displacement and resilience to a certain pressure", and the sever then returned the IDs of the AAS or even the IDs of the AAS submodels, which fulfilled the addressed conditions.

For improved, efficient, and effective searching for suitable products – or more generally, for potential suppliers and their engineering, sizing, or design tools within the heterogeneous digital engineering data ecosystem – various options are currently being explored and under development. For the MX-Port configuration "Leo", for example, a **company lookup service** (kind of "yellow pages") is foreseen for the discovery of data providers such as potential product suppliers in the initial engineering phase [10]. **Further AAS SMTs** are currently under development to better support the requirements engineering and solution finding, such as the *Capabilities for Industrial Applications* or the *Requirement model for Assets and Entities* (Table 5). To stay up to date, it is advisable to use the relevant information channels of the IDTA or to consult the IDTA AAS repository regularly.[15]

Table 4: Examples of AAS SMT in development or in review for the initial engineering phase

AAS SMT	Vers.	Name	Description	Contribution from MX projects
IDTA # 02020	in re-view	Capabilities for Industrial Applications	This SMT is foreseen to model process or product requirements (i.e., required capabilities) and resource capabilities (i.e., provided capabilities). Thus, a reliable comparison between required and provided capabilities should be supported.	Factory-X
IDTA # 02085	in de-velop-ment	Requirement model for Assets and Entities	This SMT shall allow assigning functional and non-functional requirements to assets and entities of AAS. It shall allow specifying such requirements at early stages of the life cycle, tracking and refining them over the course of the life cycle, to provide test criteria.	Factory-X

Besides the above-mentioned AAS SMTs standardized by the IDTA there are also initiatives addressing the requirements exchange with their own standards, still relying on the AAS specifications. Table 5 lists such an example model from Caten-X with specific references.

[14] The International Registration Data Identifier (IRDI) is commonly used in the AAS context as standardized identifier to reference semantic concepts, data elements, or data specifications in a globally unique and machine-interpretable way.

[15] AAS SMTs from IDTA: https://industrialdigitaltwin.org/en/content-hub/submodels and https://smt-repo.admin-shell-io.com/

Table 5: Example of further AAS related models for requirements engineering in Catena-X

Identifier	Name	Description	Links
urn:samm:io.catenax.requirement:1.0.0#	Requirement	This is the SAMM modeled aspect model for requirements in Catena-X. It is based on the ReqIF standard and is meant for the customer-supplier-interaction in the specification of requirements.	- AASX-File - Related standard Document - Further documentation

4.2 Discipline-specific design & engineering

The collaborative engineering of technical products is driven by the interaction of **various engineering disciplines** with their respective domains. For example, mechanical engineers develop structural components, electronics engineers design circuitry and control units, and software engineers implement algorithms and interfaces. Core disciplines for mechatronic systems are mechanical, electrical, and software engineering. Application-specific disciplines such as optics, hydraulics, acoustics, etc., can further expand the scope of the engineering work.

In practice, the various domain experts – who may be based in different organizations (e.g. suppliers of specific part-solutions such as control cabinets for machine tools) – often work in parallel on their domain specific solution using specific software and tools, and then iteratively integrate them into the overall solution. This entails substantial coordination effort, especially when changes to requirements, specifications or system architecture are made, and a seamless exchange of information is hindered by data silos. For example, technical documentation such as drawings, specifications, simulation results, etc. is often not easily accessible (see Figure 9). This can lead to delays, mismatched versions, and integration errors in the overall system, thus hindering engineering productivity due to missing end-to-end data continuity.

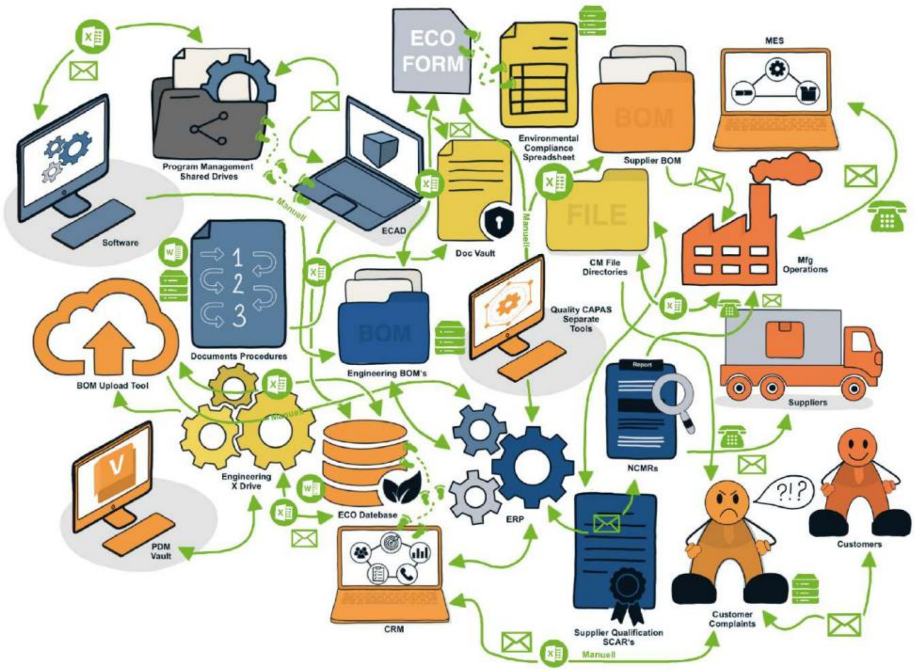

Figure 9: What's "working" today - disconnected data silos [11]

Against this background, the AAS as authoritative or single source of truth and as standardized data container for the various engineering data – which should be seamlessly exchanged between the different engineering domains and tools – is a big enabler for productive collaborative engineering of complex mechatronic systems.

Depending on specific engineering disciplines and domains different AAS Submodels are used to structure and provide the required data and information. Table 6 gives an overview of some AAS SMTs, which could be helpful in the context of discipline-specific design and engineering. For example, the AAS SMT *Provision of 3D Models* is often used to provide the meta data and 3D Model files, which clients need to select the required information (e.g. geometric information or specific capability of the 3D file) and the suitable file for their specific system or tool landscape (e.g. CAD, PLM, PDM, Simulation).

Table 6: Relevant AAS SMTs in discipline-specific design & engineering phase

AAS SMT	Vers.	Name	Description	Links[16]	Use in MX projects
All four AAS SMTs from the basic set – listed in Table 1 – are helpful in the discipline-specific design & engineering phase. *Generic Frame for **Technical Data** for Industrial Equipment in Manufacturing* is the key AAS SMT for getting all relevant technical asset data needed in the various engineering disciplines.					
The AAS SMT *Hierarchical Structure enabling **Bills of Material*** – listed in Table 2 – is important in this phase as it represents the hierarchical structure of the entire mechatronic system and the relationship elements relevant for the various collaborative discipline-specific design & engineering activities. The SMT can serve as an index, pointing to Assets and AAS in a decentralized collaborative engineering network of multiple actors.					
IDTA # 02026	1.0	Provision of **3D Models**	This SMT defines metadata to enable searching, integrating, and validating 3D model files, which can be linked online or included within the submodel. This SMT complements existing 3D model file formats instead of replacing or redefining them.	Pdf - GitHub	Factory-X, Fluid 4.0, Robot-X

Some Notes and recommendations

Collaborative engineering based on AAS is a dynamic field of development in which several solutions are still in progress. Several AAS SMTs relevant for the various disciplines and domains of designing and engineering a complete mechatronic system (Table 7). For example, the new AAS SMT *Automation Engineering* aims to further enhance the AAS-based engineering grounded on relevant standards such as IEC 81346 and IEC 61355, as well as existing AAS SMTs such as *Hierarchical Structures enabling Bills of Material* and *Generic Frame for Technical Data for Industrial Equipment in Manufacturing*. Further examples of new AAS SMTs driven by projects involved the Manufacturing-X Topic Group “Collaborative Engineering” are *Interface Connectors* and *Characteristic Curves*. To stay up to date, it is advisable to use the relevant information channels of the IDTA or to consult the IDTA AAS repository regularly.[17]

In addition to the models standardized by the IDTA there are also further initiatives addressing the discipline specific design & engineering with their own standards, still relying on the AAS specification. Table 8 lists some example models from the Catena-X consortium with the respective references.

[16] Compare also the AAS SMT Repository under https://smt-repo.admin-shell-io.com/

[17] Overview of all IDTA registered AAS Submodel Templates: https://industrialdigitaltwin.org/en/content-hub/submodels and https://smt-repo.admin-shell-io.com/

Table 7: Examples of AAS SMTs in development relevant for discipline-specific engineering

AAS SMT	Vers.	Name	Description	Contribution from MX projects
IDTA # 02037	in de-velop-ment	Automation Engineering	This SMT shall cover electrical, hydraulic, pneumatic, and control engineering by structuring, placing, and connecting components within engineering tools, while extending AAS concepts to plant and system engineering. It includes information on how the individual components inside the systems are connected to each other. That information is highly valuable, especially inside the electrical and fluid domain. It also provides the possibility to structure components as assemblies and therefore enables the principle of clustering components to (sub) systems. On top of that, future developments enable the possibility to generate schemes, based on the information which components are linked to each other.	Factory-X, Fluid 4.0, Process-X
IDTA # 02062	in de-velop-ment	Interface Connectors	Information model that describes the interfaces of an asset that are planned or integrated as part of the engineering process of production systems. This includes all kinds of connections including electrical, mechanic, pneumatic etc.	DIAMOND
IDTA # 02086	in de-velop-ment	Characteristic Curves	This SMT shall be used for the standardized description of characteristic curves and multidimensional characteristic maps, as well as corresponding approximation descriptions. It shall help to get the required data points needed e.g. for parameterization in controller development and simulation in a machine-readable syntax.	Fluid 4.0

Table 8: Examples of further AAS related models for discipline-specific design & engineering in Catena-X

Identifier	Name	Description	Links
urn:samm:io.catenax.part_type_information:1.0.0#PartTypeInformation	PartTypeInformation	This semantic model describes a part/material at type level. The original intent is to attach this aspect to a material-specific twin in an AAS but is not limited to that use case. The aspect allows several identifications: of a component from a manufacturer ID and/or part type and optionally a validity period in order to determine the unique ID with which the part is identified within Catena-X at a given time.	- AASX-File - Related standard Document (CX-0126) - Further documentation
urn:samm:io.catenax.single_level_bom_as_planned:3.0.0#SingleLevelBomAsPlanned	SingleLevelBomAsPlanned	The aspect SingleLevelBomAsPlanned provides information on the child parts (one structural level down) from which a given object is to be assembled or produced. It describes the relationship of parts/materials in a planned stage. It does not hold serial number or batch specific information but supports navigation through the potential supply chains (top-down) for a given material/part number.	- AASX-File - Related standard Document (CX-0126) - Further documentation

urn:samm:io.catenax.single_level_usage_as_planned:2.0.0#SingleLevelUsageAsPlanned	SingleLevelUsageAsPlanned	It is required to link a planned part with its predecessor items and its successor items, and is the submodel to build a successor linkage between the digital twins. It contains the customers and the unique identifiers of the successor items (usage) of a planned product and therefore allows bottom-up navigation through the supply chain by Catena-X identifiers.	- AASX-File - Related standard Document (CX-0126) - Further documentation
urn:samm:io.catenax.masterdatamanagement:1.0.0#	Digital Engineering Master data	This semantic model, developed for the Catena-X data space, defines a standardized structure for exchanging master data on which products are engineered.	- AASX-File - Related standard Document (CX-0154)
urn:samm:io.catenax.single_level_scene_node:1.0.0#	Scene node	The Single Level Scene Node aspect model provides a standardized structure for exchanging geometry data within the Catena-X ecosystem. It represents 3D objects and scenes through a hierarchical organization that captures both spatial relationships and metadata.	- AASX-File - Related standard Document (CX-0156) - Further documentation

4.3 Simulation & virtual commissioning

As the requirements for complex mechatronic systems increase, testing on real prototypes becomes more and more insufficient to cover all functionalities. The rising number of software features demands an efficient way for verification. Virtual commissioning (VC) is an established process for **validating control software and system functions before physical commissioning**. For VC, usually Hardware-in-the-loop (HiL) or Software-in-the-loop (SiL) simulations are used, that combine a real or virtual control system with simulation models of a mechatronic system.

The virtual prototype, consisting of different kinds of simulation models, ideally results from previous engineering phases. Information from the mechanics, electrics, fluidics and software domain need to be combined to build these models. As VC marks the last development phase of a mechatronic system, it especially profits from the seamless availability of engineering data. The AAS along with other domain-specific neutral and standardized data formats (STEP, AML, SSP, FMI, …) serve as the main enabler for efficient VC, as they facilitate simulation model creation with low effort.

To realize an integrated toolchain towards efficient VC, two dimensions of data exchange need to be covered: across company borders in the manufacturing supply chain and across engineering tools of different domains. The AAS provides a valuable concept and respective AAS SMTs for both dimensions (see Table 9). For the inter-company exchange, e.g. all relevant information about supplier components such as technical parameters, 3D and simulation models can be transferred via the AAS SMTs *Generic Frame for Technical Data for Industrial Equipment in Manufacturing*, *Provision of 3D Models* and *Provision of Simulation Models*. For the intra-company exchange, AAS SMTs such as *Hierarchical Structure enabling Bills of Material* (or complementary data models) support the transfer of relevant information about the mechatronic system including the hierarchical structure, the topology, and the connected supplier components across the different engineering tools (e.g. MCAD, ECAD). Table 9 summarizes the key AAS SMTs which are relevant in the simulation and virtual commissioning phase.

Some Notes and recommendations

There is a great need for multi-faceted information about the relationships, structures, and interfaces between the individual components of a complete mechatronic system or a configured subsystem including their (physical) behavior which is needed for simulation and virtual commissioning. As automation components become increasingly complex, the demand for such precise and reusable behavioral models is growing. In this context, there are different approaches for data modeling:

- The AAS SMTs *Hierarchical Structure enabling Bills of Materials* and *Automation Engineering* can be used to model hierarchical structures and the typology of the mechatronic system – as an alternative to the *AutomationML* standard (see Chapter 5.1).
- The AAS SMT *Provision of Simulation Models* is often used to provide behavioral models of components, e.g., as a wrapper for simulation models in the tool-independent *FMI* or other standards like *STEP*, etc. (see Chapter 5.2)[18]
- The upcoming AAS SMT *Characteristic Curves* shall describe specified component behaviors, which can be used to model a component with the "native elements" in a simulation tool if no *FMI* is provided by the manufacturer of the component
- Also, in the Catena-X context there are currently further models under development such as for Software-in-the-loop model exchange, thermal modeling simulation and Co-Simulation

Table 9: AAS SMTs relevant for simulation & virtual commissioning

AAS SMT	Vers.	Name	Description	Links[19]	Use in MX projects
All AAS SMTs from the basic set – listed in Table 1 – are relevant in the simulation & virtual commissioning phase as this is the final step before the physical commissioning the whole mechatronic system. Again, *Generic Frame for **Technical Data** for Industrial Equipment in Manufacturing* provides all the technical basic information needed for simulating and virtual commissioning the whole system or at least critical parts of it.					
The AAS SMT *Hierarchical Structure enabling **Bills of Material*** – listed in Table 2 – is important again to represent the hierarchical structure of the entire mechatronic system and the relationship elements needed for simulating and/or virtual commissioning (at least) critical parts of the system.[20]					
The AAS SMT *Provision of **3D Models*** gives the necessary metadata for the 3D model files which are needed in the simulation and/or virtual commissioning phase.					
IDTA # 02005	1.0	Provision of **Simulation Models**	This SMT allows the interoperable provision of simulation model files for an asset via AAS for a wide range of simulation model types and simulation purposes. It contains information about the type of model, how to use the model, and the areas of application	Pdf - GitHub	Factory-X, Robot-X, DIAMOND

In the following, the usage of the AAS SMT *Provision of simulation models* and the *FMI* standard in the context of virtual commissioning is described in more detail.

The *Functional Mock-up Interface standard* (FMI, https://fmi-standard.org/) is a free standard that defines a container and an interface to exchange executable dynamic simulation models. It provides an open, tool-independent interface for coupling simulation and simulation environment. *FMI* avoids vendor lock-in, increasing flexibility in tool selection and migration. Most virtual commissioning and other simulation environments support the *FMI* standard already today.

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18 Alternative to the wrapper approach, selected information from the file could also be integrated in the submodel to enable references from other submodels for a complete system AAS. To transfer the acquired engineering data into an executable simulation model, an integration and generation step is necessary.

19 Compare also the AAS SMT Repository under https://smt-repo.admin-shell-io.com/

20 Depending on the various domains and data requirements, different data models could complement or replace the AAS *SMT Hierarchical Structure enabling Bills of Material*, such as the new AAS SMTs *Automation Engineering*, *Interface Connectors* or the data model *AutomationML* (see also chapter 5.1).

The AAS SMT *Provision of simulation models* can be used with an *FMU* (*Functional Mock-up Unit*) to create a behavioural model for a specific production component, e.g. a frequency converter for a turntable. Instead of utilizing a component from a proprietary virtual commissioning behaviour library, the *FMU* serves as a replacement, containing the internal behaviour of the component along with corresponding inputs and outputs. These inputs and outputs are linked to the PLC inputs and outputs to verify the control logic's correctness during the virtual commissioning process. To achieve this, first, an *FMU* must be created that models the frequency converter's internal behaviour and includes the required input and output variables. These variables should correspond to the PLC inputs and outputs for seamless integration. Component manufacturers can embed their specific know-how directly into the models. Next, the AAS SMT *Provision of simulation models* can be used to incorporate the FMU in an AAS for the turntable's frequency converter. This allows for a digital representation of the component's behaviour within the production system context, enabling the virtual commissioning process to test the control logic's correctness without requiring the physical frequency converter. Additionally, the SMT provides the possibility to describe additional properties of the simulation models' purpose and required environment which makes it easy to integrate the component within the virtual commissioning model without lots of manual effort.

This example of the usage of *FMI* and AAS in combination offers advantages in terms of flexibility, time, and cost efficiency during the virtual commissioning process.[21] Beyond virtual commissioning, *FMUs* open new opportunities, e.g. to support energy optimization or predictive maintenance. In the future, AI methods could support automated *FMU* generation

4.4 Recommendations for AAS usage in a nutshell

Based on the findings presented above, the following recommendations for using the AAS in collaborative engineering within digital ecosystems can be summarized (see Figure 10): Building on a basic set of AAS elements, additional AAS Submodel Templates are relevant during the course of the engineering process, from initial requirements engineering & concept design to discipline-specific design and engineering to the final simulation and virtual commissioning phase.

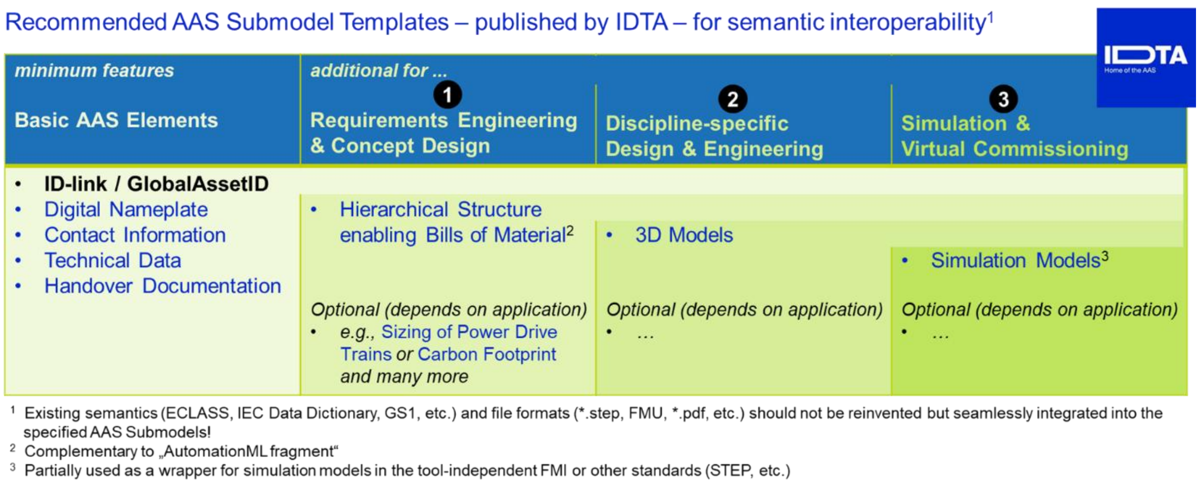

Figure 10: Recommended AAS elements for collaborative engineering in digital ecosystems

As collaborative engineering based on AAS is a dynamic field of development in which several solutions are still in progress, it is advised to use the relevant information channels of the IDTA or to consult the IDTA AAS repository regularly.[22]

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[21] The guideline developed within the DIAMOND research project (see [12] and [13]) describes best practices for applying the FMI Standard in virtual commissioning including topics such as model scope and integration aspects.

[22] Overview of all IDTA registered AAS Submodel Templates: https://industrialdigitaltwin.org/en/content-hub/submodels and https://smt-repo.admin-shell-io.com/

5 Complementary standards & activities

As shown in the previous section for some aspects, it may be reasonable to use or integrate complementary solutions or established standards in collaborative engineering of complex systems. This chapter presents some examples of complementary activities.

5.1 Common data models in plant engineering

The engineering of production plants requires component information but the transition between component provider and plant engineering (executed by e.g. the plant operator) often causes re-modeling of information instead of data model transfer. To overcome this gap, the DIAMOND project combined two established standards: *AutomationML (AML)* as a lightweight XML-based exchange format for engineering data and *Asset Administration Shell (AAS)* as a technology-neutral information model for lifecycle-wide provisioning of asset data [14]. Components are modelled with AAS, and plants are modelled with AutomationML. Thus, the AAS models need to be integrated with the AutomationML (AML) models (AML model consisting also of cross-components information like controlling logic) for the plant lifecycle (see Figure 11).

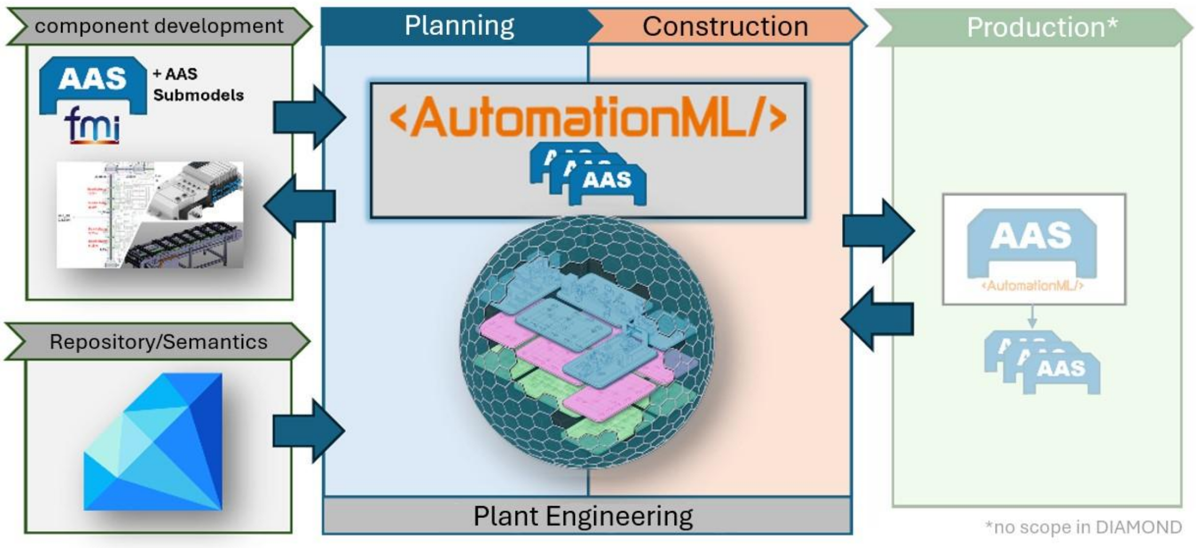

Figure 11: Application fields of AML and AAS in the DIAMOND context [15]

Instead of a 1:1 translation and transferring all information from one “world” to another, DIAMOND strives for meaningful integration in the form of references. Depending on the information, life cycle phase, and use case, this can be done at the model level, element level, or attribute level. Component data models therefore need to fulfill the requirement of having a unique GlobalAssetID to be integrated as mandatory attribute into the engineering data model. Furthermore, the AAS of the components should be designed to facilitate integration and interlinking of existing information, rather than requiring re-modeling, to support a smooth transition between component development and plant engineering.

Interoperability between AML and AAS is especially important for following two key transition points:

1. **From planning to engineering (AAS → AML)**: Abstract planning objects are linked to concrete components in the AML model. Through GlobalAssetID and AASInternalConnector, detailed information from the AAS can be dynamically integrated.
2. **From engineering to operation (AML → AAS)**: After engineering is completed, the AML project is referenced as a file in a plant-level AAS. Additionally, selected attributes and structures can be explicitly published as AAS elements.

5.2 STEP, FMI and others in the context of AAS

Standards for the interoperable exchange of product model data have already existing before the development of the AAS as cross-vendor standard for the digital representation of physical assets.

STEP, formally standardized in the ISO 10303 standard, is such an example which describes the physical and functional aspects of a product. This standard is mainly used in product data management and especially in product development to **exchange 3D models** between different computer systems. The AAS SMT *Provisioning of 3D models* explicitly refers to this standard and enables the integration of STEP files into the AAS context. The AAS does not want to reinvent the wheel but rather integrate existing formats and standards. So, there is no need to redo anything from scratch.

This is also true for the **FMI** standard, which has been developed for the exchange and co-simulation of dynamic models between different software tools. The AAS SMT *Provisioning of Simulation Model* can be used to integrate **FMU**s – concrete **simulation models** packaged according to the FMI standard – and thus to provide simulation models in the widely used standard in the broader context of the AAS as digital representation of industrial physical assets.

Also, other standards, which are for example widely used in specific sectors such as the **IFC** standard in the construction sector, could principally be integrated into the AAS context – whenever it is recognized as beneficial.

6 Conclusion and outlook

This publication focuses on the major phases of engineering complex mechatronic systems from initial requirements engineering to virtual commissioning. Later phases of continuous engineering, e.g. product and process optimization based on operating data, were not considered.

In these later phases, where the digital twins originally created in the early engineering phases are used throughout the entire life cycle as a kind of **digital thread**, **security and life cycle management** become critical – especially when third-party digital twins are used in the multi-stakeholder context of digital data ecosystems [16]. A key question to be answered is how to organize and govern the versioning and update of the digital twins, including responsibility and accountability across the entire life cycle. Thus, maintenance aspects must be considered from the very beginning.

As collaborative engineering in digital ecosystems is a **dynamic field of development**, much is still in flux and numerous AAS-based solutions are work-in-progress. Several AAS SMTs are in development, driven by a lively AAS community in a kind of bottom-up approach, leading to the risk of ending up with a multitude of overlapping semantic data models in confusion. In this context, the IDTA as the AAS user organization must balance the advantages of a bottom-up, community-driven approach with the requirements of a coherent and aligned overall strategy, including appropriate quality standards.

With the increasing spread of the AAS, driven e.g. by the integration into widely used engineering tools, and the provisioning of AAS-based infrastructure services[23], entirely **new performance leaps in collaborative engineering within digital ecosystems will be possible**.

[23] See for example AAS-based Asset Data eXchange Hub operated by IDTA GmbH: https://adx-hub.com

7 Glossary

AAS – **A**sset **A**dministration **S**hell	A standardized digital representation of an asset, such as a machine or a product, that serves as a digital twin for Industrie 4.0.
AAS SMC – **A**sset **A**dministration **S**hell **S**ub**m**odelElement**C**ollection	A structural element within an Asset Administration Shell that acts as a container to logically group multiple submodel elements (properties, values, or other collections) together. It functions as a structured container, allowing complex data to be organized semantically.
AAS SMT – **A**sset **A**dministration **S**hell **S**ub**m**odel **T**emplate	A standardized, reusable blueprint for structuring specific, semantic data about an industrial asset's lifecycle, such as its nameplate, technical data, or documentation. These templates ensure interoperability between different IT systems by using uniform data models (often via dictionaries like ECLASS) and defining mandatory submodel elements.
AASX	A standardized file format (AASX Package File Format) designed for the exchange of Asset Administration Shells (AAS). It is a ZIP archive that organizes all technical data, documentation, and properties of an asset (such as a machine or product) into a structured, machine-readable format.
API – **A**pplication **P**rogramming **I**nterface	A defined set of rules and interfaces that allows different software components to communicate and interact with each other. Most APIs use HTTP to handle requests and responses between different software components.
AML / AutomationML – **A**utomation **M**arkup **L**anguage	A neutral data format based on XML for the storage and exchange of plant engineering information, provided as an open standard.
Authoritative Source of Truth	A trusted source of information that is considered the most accurate, reliable, and up to date for a specific dataset or piece of information. In digital engineering it is the reference point for models and data across the system life cycle, providing traceability as the system evolves, capturing historical knowledge and connecting configuration-controlled versions of models and data.
CAD – **C**omputer-**a**ided **d**esign	The use of computer software to create, modify, analyze, and optimize 2D drawings or 3D models of physical objects.
CAE – **C**omputer-**a**ided **E**ngineering	The use of computer software to simulate, analyze, and optimize engineering designs and processes. CAE tools help engineers predict how products will behave in the real world, reduce physical prototyping, shorten development time, and improve performance and reliability.
CAM – **C**omputer-**a**ided **M**anufacturing	The use of software and computer-controlled machinery to plan, manage, and automate manufacturing processes. CAM converts design data (often from CAD systems) into instructions that control machines such as CNC mills, lathes, routers, laser cutters, plasma cutters, and 3D printers.

CMMS – **C**omputerized **M**aintenance **M**anagement **S**ystem	A software used to plan, track, schedule and optimize maintenance activities for physical assets (machines, equipment, facilities). A CMMS helps organizations move from reactive, paper-based maintenance to proactive, documented, and data-driven maintenance management.
DPP4.0 – **D**igital **P**roduct **P**assport **4.0**	An industry-ready, digital, and standardized record of a product's entire life cycle, tracking data from raw materials to disposal. It utilizes the Asset Administration Shell (AAS) to create machine-readable digital twins, enabling cross-company transparency, enhanced sustainability, and circular economy compliance.
Digital Thread	An integrated, traceable flow of product-related data and relationships that links all digital artifacts and lifecycle activities for a product – from requirements and design through manufacturing, service and end-of-life. It creates a continuous, bidirectional connection between engineering, manufacturing, supply chain and business systems so every decision can be made using the same authoritative information.
Digital Twin	A digital replica of a physical asset, system, process, or product that mirrors its structure, behavior and state across time. It combines data, models and connectivity so stakeholders can observe, analyze, simulate and optimize the real-world counterpart throughout its lifecycle.
ECAD – **E**lectronic **C**omputer-**A**ided **D**esign	ECAD refers to the software tools, methods and workflows used to design, simulate, document and prepare electronic circuits, printed circuit boards, and associated wiring/harnesses for manufacturing and integration.
ECLASS	A leading international, ISO/IEC-compliant standard for the classification and unique description of products and services, acting as a universal language for Industrie 4.0 and digital master data management. It enables cross-industry, borderless, and language-independent data exchange, covering roughly 45,000 product classes and 19,000 properties.
ERP – **E**nterprise **R**esource **P**lanning	A suite of integrated software applications that manage and automate core business processes across an organization – typically including finance, procurement, inventory, manufacturing, sales order processing, human resources, and supply chain operations. ERP systems provide a single source of truth for transactional data and support cross-functional workflows to improve efficiency, visibility and decision-making.
FMI – **F**unctional **M**ock-up **I**nterface	An open standard for exchanging and co-simulating dynamic models between different software tools.
FMU – **F**unctional **M**ock-up **U**nit	A standardized software component that contains a simulation model based on the Functional Mock-up Interface (FMI) standard.

GlobalAssetID – Global Asset Identifier	A unique, persistent identifier assigned to a physical asset (or a logical asset instance) so it can be unambiguously referenced across systems, organizations and over the asset's lifecycle. It enables consistent tracking, integration and traceability of asset data across PLM/PDM, ERP, MES, CMMS, IoT platforms and third-party systems.
HiL – **H**ardware-**i**n-the-**L**oop	A real-time testing methodology where one or more physical hardware components are connected to a simulated environment that emulates the rest of the system. The goal is to test hardware behaviour, control software, and their interactions under realistic, repeatable, and safe conditions before or in parallel with full system integration.
HTTP – **H**yper**t**ext **T**ransfer **P**rotocol	An application-layer protocol used for transmitting hypermedia and other resources across the World Wide Web. It defines how clients (usually web browsers or other HTTP clients) request resources and how servers respond.
IEC CDD – **C**ommon **D**ata **D**ictionary of the **I**nternational **E**lectrotechnical **C**ommission	An international, standardized, online repository for classifying and describing products across industrial and technical domains. Maintained by IEC, it provides unique, machine-understandable identifiers and definitions for, properties, and data types, fostering interoperability in Smart Manufacturing and Industrie 4.0.
IFC – **I**ndustry **F**oundation **C**lasses	An open, international standard for exchanging digital data in the construction industry, primarily for building information modeling.
IoT – **I**nternet **o**f **T**hings	A network of physical devices, vehicles, machines, sensors, actuators and other "things" that are connected to the internet (or local networks) so they can collect, exchange and act on data. IoT extends digital connectivity beyond traditional computers and phones to everyday objects, enabling new monitoring, automation and analytics capabilities.
IRDI – **I**nternational **R**egistration **D**ata **I**dentifier	A standardized identifier scheme used to reference semantic concepts, data elements, or data specifications in a globally unique and machine-interpretable way. It is commonly used in standardization efforts (for example in IEC and ISO contexts) and in digital modeling approaches such as the AAS to unambiguously point to a concept from a registry or classification.
MCAD – **M**echanical **C**omputer-**A**ided **D**esign	MCAD refers to software tools, methods and workflows used to create, analyze and document the mechanical aspects of products and systems — primarily geometry, assemblies, parts, tolerances, materials and manufacturing information.
MES – **M**anufacturing **E**xecution **S**ystem	Software that manages, monitors and controls manufacturing operations on the shop floor in real time. MES fills the gap between high-level planning in ERP and engineering/product definitions in PLM by executing production orders, collecting operational data, and ensuring products are produced correctly and efficiently.

MX-Port – Manufacturing-X Port	A concept for an open and flexible framework, empowering companies of all sizes to collaborate and create value within digital ecosystems. The MX-Port shall enable seamless, secure, and scalable data sharing across industries based on five distinct layers, focusing on key qualities such as interoperability, trust, scalability, and data sovereignty.
PDM – **P**roduct **D**ata **M**anagement	A system and set of practices used to organize, control, and share product-related information throughout the product lifecycle. PDM helps engineering, manufacturing, and other teams keep a single, authoritative source of product data so work is coordinated, traceable, and auditable.
PLM – **P**roduct **L**ifecycle **M**anagement	A strategic discipline and set of software tools that manage all information, processes and people involved in a product's lifecycle – from initial concept and requirements, through design and manufacturing, to service, maintenance and end-of-life. PLM creates a single, consistent "digital thread" linking engineering, manufacturing, procurement, quality, and business systems so decisions are made using the same controlled information.
REST API – **Re**presentational **S**tate **T**ransfer **A**pplication **P**rogramming **I**nterface	A style of Web Application Programming Interface that lets clients and servers communicate over HTTP using a set of simple, standard operations. It is an architectural approach rather than a strict protocol, using standard HTTP methods to perform actions on resources and promoting a uniform, consistent interface so different clients can interact with the server in a predictable way.
SAMM – **S**emantic **A**spect **M**eta **M**odel	A meta-model that defines how semantic information about assets, properties and their relationships is represented, organized and exchanged. It is used e.g. in the Catena-X context.
SiL – **S**oftware-**i**n-the-**L**oop	A development and testing approach where control software (algorithm code, model-based controller, or embedded application) is executed in a simulated software environment that emulates the target runtime and the rest of the system.
SSOT – **S**ingle **S**ource of **T**ruth	A practice where data is stored in one central, reliable location, ensuring that everyone uses the same, up-to-date information.
SSP – **S**ystem **S**tructure and **P**arameterization	An open standard and data-exchange format that describes the architecture (structure), component relationships, interfaces, and configuration (parameterization) of cyber-physical systems — especially for model-based engineering, simulation, and tool interoperability in domains such as automotive, industrial automation and mechatronics.
STEP – **S**tandard for **t**he **E**xchange of **P**roduct model data	An international standard, known as ISO 10303, for describing and exchanging product data throughout a product's lifecycle, typically used in the CAD context.
URL – **U**niform **R**esource **L**ocator	A standardized, unique address used to identify and locate resources on the Internet. It is also used for identification and addressing of product-related information in industrial digital ecosystems (e.g. persistent identifiers and access mechanisms for product data)

VC – **V**irtual **C**ommissioning	The process of developing, testing, validating, and optimizing control system software and automation logic in a virtual environment that accurately represents the physical system (machinery, robots, conveyors, sensors, actuators and their interactions) before commissioning on the real hardware.

8 List of figures, tables and annexes

Figures

Tables

Annexes

9 References

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10 List of websites for further information

Websites of involved projects:

- Catena-X: https://catena-x.net/
- Construct-X: https://construct-x.org/
- DAVID: https://www.ifak.eu/de/projekte/david
- Decide4ECO: https://www.decide4eco.de/
- DIAMOND: https://diamond-project.de/
- Factory-X: https://factory-x.org/de/
- Fluid 4.0: https://fluid40.de/
- Process-X: https://www.namur.net/en/work-areas-and-project-groups/focus-topics/process-x.html
- Robot-X: https://www.ifak.eu/de/projekte/robot-x
- VWS4LS: https://arena2036.de/vws4ls/ueberblick/

Further relevant websites:

- Manufacturing-X Initiative: https://www.plattform-i40.de/IP/Navigation/DE/Manufacturing-X/Initiative/initiative-manufacturing-x.html
- Manufacturing-X Guidance Board: https://mx-guidanceboard.org/
- International Manufacturing-X Council: https://imxc.org/
- Industrial Digital Twin Association: https://industrialdigitaltwin.org/
- Open Industry 4.0 Alliance: https://openindustry4.com/

11 Annexes

Annex 1: Three engineering phases from the perspective of different projects

	Requirements Engineering & Concept Design	Discipline-specific Design & Engineering	Simulation & Virtual Commissioning
Catena-X	Customers and suppliers align their sets of requirements in the form of acceptance, clarification, or declination. This phase is iterated until an agreed-upon form is achieved by both parties. (Further Input in the Requirements KIT)	System design, component selection and integration, selection of specific product properties such as the materials included. Master data for the product is created, which will be used across all instances of the product. A discipline-specific use case is the geometric design of the components and their integration.	Simulations to check how supplier components can be integrated into OEM systems, and to check interrelated components, e.g., for thermal analysis or software in control units. Relevant components might be distributed across different stakeholders in the product ecosystem, and therefore co-simulations are often required
DIAMOND	Design of a discrete manufacturing plant.	Engineering of discrete manufacturing plants and exchange of information between the different disciplines in context of engineering, e.g. mechanical design and layout planning.	Simulation and virtual commissioning of discrete manufacturing plants and exchange of information between different disciplines in context of engineering, e.g. layout planning and virtual commissioning.
Factory-X	Search for automation solutions in accordance with requirements across different (component) suppliers; Initial design of the automation solution as a mechatronic system (e.g. machine or part of a machine) that may contain components from different suppliers	Detailed and integrated engineering of a machine or machine part (e.g. control cabinet) such as electrical design, etc. in a collaborative way between different engineering disciplines and even different companies (e.g. machine builder and control cabinet manufacturer)	Simulation of mechatronic system that may contain components from different suppliers
Fluid4.0	Design the hydraulic or pneumatic drive system according to requirements and search for suitable components (based on any calculation or through accompanying 1D-system-simulation) within the dataspace. Represent the system structure in the AAS and get Asset IDs for suitable components		Automatically generate and parametrize 1D-system-simulation models based on the AAS. Parametrize the application software automatically based on the AAS of the used components.

Process-X	In the **Conceptual Engineering** phase, concepts for the plant's automation are developed based on the process structure of the plant. As a basis for further development, at the end, a first definition of the execution concept takes place and a cost estimate (±25-30 %) is carried out.	At the beginning of **Basic Engineering** the concepts previously developed for the automation of the plant are finalized in cooperation with the other disciplines. In **Detail Engineering**, the PCT field devices, DCS, SPLC/ PLC, and electrotechnical components are fully specified for ordering.	There is no Simulation & Virtual Commissioning in the process industry. Instead, "cold commissioning", in which the individual functions of the plant units / sections and the functioning of the whole plant are tested. It is followed by a preliminary test-run with testing mediums (e.g. water), functionally testing the whole plant with all its automated components but without chemical reactions, and the first setting of regulatory control functions is performed.
Robot-X	Design robotic systems based on application-specific requirements and identify suitable hardware, software, and engineering models from a cross-industry dataspace ecosystem. Represent requirements, functional relations, and system architecture in the AAS to establish a standardized basis for model-based development.	Engineer domain-specific robotic components and digital artifacts, such as 3D CAD models, gripper models, object models, and simulation models, using assets from shared component catalogues. Enable collaborative, AAS-based exchange between project partners to support integration, reuse, and refinement across disciplines.	Automatically retrieve supplier-provided AAS-based simulation assets and integrate them into robotics workflow interfaces and simulation tools. Use these interoperable models for rapid validation and virtual commissioning to reduce engineering effort and accelerate deployment of customized robotic solutions.

Annex 2: Four different roles from the X-projects perspective

	Customer / User	Manufacturer / Supplier	Subsystem / Part Solution Supplier	Component Product Supplier
Catena-X	Person or company owning a vehicle. All components in this product can be seen as subcomponents, even though they can be distributed into other industries as well (batteries,...)	Usually, an OEM producing a complete vehicle. Components of suppliers are integrated and tested as complete system	Suppliers of vehicle components, such as gearboxes, powertrains, and batteries. They develop sub-systems which are integrated as a complete set into the final vehicle.	Producers of components like bolts, gears, bearings, or battery cells, that do not add a function on their own but when integrated into a subsystem
DIAMOND	Factory operator	Factory (equipment) builder		Provider of components
Factory-X	Factory operator & owner who order & use complex automation solutions and machines	Equipment / machine manufacturer; mechanical engineer who integrates configured systems and components and	Supplier of configured sub-systems - e.g. control cabinet or automation system with integrated components	Supplier of automation components such as actuators, controllers, sensors, …
Fluid4.0	Factory operator; Construction company	Manufacturers of conveyors, press, injection molding, etc., construction machines like excavators, wheel loaders, dumpers, agricultural, forest, municipal, machines, etc.	Industrial hydraulic system provider (aggregate, tanks, valve blocks); Mobile hydraulic system provider (steering, driving, braking, working)	Component manufacturer (pumps / motors, valves, cylinders, filters, hoses, pipes, oil compressors, tanks)
Process-X	Owner operator accountable for the production process	Engineering Contractor (EPC, EPCM, …)	Sub-Contractor of EPCM or EPCM-Contractor; Package Unit Vendor	Provider of auto-mation components like actuators, controllers, sensors, etc.
Robot-X	Industrial end user or SME operating customized robotic systems, robot cells, or automation lines	Robot manufacturer, system integrator, or automation builder engineering and supplying complete robotic solutions supplying complete robotic solutions	Supplier of configurable robotic subsystems, e.g. grippers, safety systems, object models, and simulation-ready software modules	Supplier of standard robotic components and digital assets like robots, sensors, controllers, end-effectors, CAD data, simulation models, and AAS-based component descriptions

Annex 3: Summary of relevant AAS aspects (AAS specifications from Part 1 to Part 5)[24]

Aspect	Description	Key Features/Examples	Source
Part 1: Metamodel	Defines the structure and semantics of the Asset Administration Shell (AAS).	Submodels for specific aspects Attributes and relationships Based on DIN SPEC 91345, IEC 61360	https://industrialdigitaltwin.org/content-hub/aasspecifications/part1_metamodel
Part 2: Application Programming Interfaces	Specifies HTTP/REST-based interfaces for accessing the AAS.	Read/write submodels Query data Standardized interoperability	https://industrialdigitaltwin.org/content-hub/aasspecifications/specification-of-the-asset-administration-shell-part-2-application-programming-interfaces-idta-number-01002-3-0-3
Part 3a: Data Specification – IEC 61360	Defines formats for storing and exchanging AAS data.	Serialization Formats: JSON, XML, RDF IEC61360 Data Type Mapping	https://industrialdigitaltwin.org/content-hub/aasspecifications/specification-of-the-asset-administration-shell-part-3a-data-specification-iec-61360-idta-number-01003-a-3-0-2
Part 3a: Data Specification – IEC 61360	Defines formats for storing and exchanging AAS data.	Serialization Formats: JSON, XML, RDF IEC61360 Data Type Mapping	https://industrialdigitaltwin.org/content-hub/aasspecifications/specification-of-the-asset-administration-shell-part-3a-data-specification-iec-61360-idta-number-01003-a-3-0-2
Security Aspects TF Part 4 Security	Ensures secure access and communication.	Authentication (OAuth2, Token-based) Authorization models Encryption and secure transport (TLS)	industrialdigitaltwin.org/en/wp-content/uploads/sites/2/2025/08/IDTA-01004-3-0-1_AAS-Specification_Part4_Security.pdf
Part 5: Package File Format (AASX)	AASX format	zip & co.	https://industrialdigitaltwin.org/content-hub/aasspecifications/idta-01005-3-0-1_package_file_format_aasx

[24] See also https://industrialdigitaltwin.org/content-hub/aasspecifications