Semantic Integration Patterns for Industry 4.0

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Abstract: In the manufacturing industry, digital twins have emerged as a key technological concept for the creation and use of digital representations of assets and their associated processes. In emerging networked manufacturing systems, digital twins of machines or components do not reside within one specific application, platform or edge node, but they ideally consume and deliver information (e.g. sensor data, master data) to all connected applications in the operational systems. This results in complex integration requirements for both, the assets and the applications. Starting from an overview of industrial information models, the paper describes a recent research approach towards semantic **interoperability concepts for data-driven digital twin in manufacturing systems.** It gives an architectural overview of a **platform** for the integration of operational management systems and connected assets based on **semantic integration patterns. The paper describes the initial concepts of the underlying research project "i-Twin".**

1 INTRODUCTION

Digitalization is currently one of the main drivers for improvements in productivity and resource efficiency within industrial manufacturing. Initiatives started in the last decade, such as the "Plattform Industrie 4.0" (https://bit.ly/3J4zxfT) and the "Industry IoT Consortium" (https://bit.ly/2yvG9U7), turned almost every newly designed machine into a smart, connected asset. This shaped the ecosystem on shop floors from classical hierarchical production-line processes based on the "automation pyramid" (Åkerman, 2018) to flexible connected production networks. These networks induce communication and interoperability requirements related to the production assets.

To address this challenge, industrial data models for engineering and operation have been developed, partly independently by manufactures and partly in standardization organisations. Compatibility between these models is still limited, as industry standards emerge slowly and are often shaped for special branches or domains. Interoperability concepts therefore tend to use domain-specific, proprietary, closed approaches for creating, transforming, importing, exporting, and synchronizing data sets and messages.

Recently, digital twins - digital replica of physical assets - emerged as a key technological concept for machines and infrastructure components in the manufacturing industry. Information models for data-driven digital twins aim to describe:

- the master data of the manufacturing plant and equipment,
- the configuration parameters for operating the plant and its components, and
- the dynamic sensor data acquired from plant equipment, which are then used for a variety of accompanying processes such as monitoring, analytics, forecasting, and optimization (e.g. KPI determination, maintenance planning, increase of equipment availability).

Digital twins ideally consume and deliver information to all connected applications in the operational manufacturing systems. Therefore, digital twins and related information models find themselves naturally in the centre of interoperability considerations, and solutions to provide open, standard-based, self-describing (semantic) interfaces between the participants of a manufacturing eco-

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system bear a high potential to reduce integration efforts.

This is where a research project entitled "i-Twin" (https://srfg.at/i-twin) enters the scene: Starting in 2022, the project investigates interoperability concepts for data-driven digital twins in the manufacturing industry. The project propagates an open-source middleware for the integration of operational management systems and connected assets based on a concept called "semantic integration patterns". It aims at reducing the integration effort and allowing secure and reliable exchange of master data and operational data in manufacturing networks.

In our paper, we describe the architectural concepts forming the foundation of the semantic integration patterns for Industry 4.0, which are by design rooted in the RAMI4.0/AAS (DIN SPEC 91345, 2016) information model and apply the model not only to connected assets, but also to (software) applications in the manufacturing system.

The remainder of the paper is organized as follows: Section 2 gives an overview of the state of the art in industrial information modelling and highlights the relationship of digital twins with models in the digital factory. Section 3 describes the architectural approach towards semantic integration patterns in the digital factory. Finally, section 4 shows the potential of the chosen approach for semantic integration of operational systems and assets in the manufacturing industry, followed by an example for the industrial uptake and exploitation and an outlook of the future work.

2 INDUSTRIAL INFORMATION MODELS

In this section, we give an overview of industrial information models (digital twins, assets, digital factory) with a focus on models supporting machine-readable semantic modelling schemes. The overview of the state of the art in this area also includes a survey and known challenges in the field of middleware for manufacturing software integration.

2.1 Digital Twins and the Digital Factory

Introducing the concept of Digital Twins (Kritzinger, Karner, Traar, Henjes, & Sihn, 2018) as a digital replica of physical assets is widely adopted approach to self-describe the physical properties of assets and provide digital communication interfaces to the outside world. The currently developed "Digital Twin Framework for Manufacturing" (ISO/DIS 23247-1, 2021) is a standardisation approach towards a context-dependent implementation and the promotion of reusability and composability of digital twins (Lu, Liu, Wang, Huang, & Xu, 2020). Further standardization activities w.r.t Digital Twins (ISO/IEC AWI 30172, 2020; ISO/IEC AWI 30173, 2020) have just been started. The recently released standard series "Digital Factory Framework" (IEC 62832-1, 2020) goes one step further and connects digital twins of multiple assets into a "Digital Factory". The recent foundation of the "Industrial Digital Twin Association" (IDTA, https://industrialdigitaltwin.org/) reflects und underlines the importance and necessity of standardization of information models for digital twins in the industry.

2.2 RAMI4.0 and the Asset Administration Shell

To address compatibility issues in industrial horizontal and vertical integration scenarios, the "Reference Architecture Model Industrie 4.0 (RAMI4.0)" (DIN SPEC 91345, 2016) includes a meta-model standard for the digital description of physical assets (with properties and capabilities) called "Asset Administration Shell (AAS)". AAS integrates multiple underlying semantic standards for cross-domain aspects, such as security, identification, configuration, and domain-specific aspects, e.g. for manufacturing or food & beverage.

The term Asset Administration Shell (AAS) was coined in combination with its functional counterpart, the "I4.0 component", which need to be (1) uniquely identifiable, and (2) able to communicate with other I4.0 components. The current specification provides comprehensive information on the structure of the AAS (AAS Part 1, 2022), and the specification of the interoperability at runtime (AAS Part 2, 2021) for I4.0 components. This specification now provides full understanding on how to implement and use the AAS and provides mappings to XML, JSON, RDF, OPC UA (IEC 62541, 2020), and AutomationML (IEC 62714, 2022) as well as a package file format for AAS (AASX) to share I4.0-compliant information.

Furthermore, an AAS supports data interoperability based on semantic integration by providing references to standardized and corporate ontologies as a fundamental part of the AAS data model.

As shown in Section 3, AAS and its information model form the basis for the implementation of the semantic integration patterns.

2.3 Semantic Information Models and Domain Knowledge

According to the World Wide Web Consortium, RDF, RDF Schema (RDFS) and OWL are base technologies for expressing knowledge (W3C, 2022). While RDF represents the formal language for describing structured information, RDFS contributes the data-modelling vocabulary for RDF data. As an extension of RDF, it provides mechanisms for describing groups of related resources and the relationship between them. In addition, the Web Ontology Language (OWL) allows for representing rich and complex knowledge about things. The Simple Knowledge Organisation System (SKOS) finally is used for defining classification schemes or taxonomies.

A recent European study underlined the impact of semantic technologies and semantic enrichment on improved data quality (EC DIGIT, 2019). In the manufacturing domain, the representation of self-contained knowledge about assets is supported by the RDF data model for the Asset Administration Shell.

The digital exchange format IEC 61360 (CDD, 2017) for commonly shared concepts represents the industrial counterpart of the semantic web technology for vocabularies and is an integral part of the AAS. It allows for the definition of hierarchical concept classes, their properties and unit of measures. It also supports the assignment of predefined value lists to properties in a general manner or when used in combination with distinct concept classes.

ECLASS (https://eclass.eu/) is a well-known "common data dictionary" based on the mentioned IEC 61360 format and provides a cross-sector standard for classification of products and services. Using such standardized reference data is a key when exchanging data with other companies, or with other business domains. The thirty-nine subject areas covered by ECLASS include electrical engineering, construction, logistics, food, medicine optics, automotive and others.

The Industrial Ontologies Foundry (IOF, 2021) provides reference ontologies to support manufacturing and industry needs. The work is conducted in different working groups, addressing topics such as maintenance, supply chain, production planning.

With OPC UA, the OPC Foundation developed an open standard for the exchange of machine information via internet protocols (TCP/IP, HTTP). In addition to the transport of measured and controlled variables from and to the machines, OPC UA supports sector-specific extensions ("Profiles") of the information models based on companion specifications (CS). Notable among others are OPC UA for Machinery, Robotics and Machine Vision (OPC UA Information Models, 2021). Well-established standards in specific manufacturing domains, such as ISA-95, Weihenstephan Standards (WS, 2022) and EUROMAP (EUROMAP, 2021), are currently mapped into OPC UA companion specifications. Based on OPC UA, "universal machine technology interface" (UMATI, 2021) currently develops a CS for machine tools. In 2019, semantic descriptions of OPC UA information models ("OPC UA NodeSet ontologies") were proposed to represent semantic digital twins of manufacturing resources (Perzylo, Profanter, Rickert, & Knoll, 2019).

2.4 Middleware for Manufacturing Software Integration

To our current knowledge, there are no ongoing activities or a roadmap for standardisation of interfaces for the rising number of factory software applications in Digital Factories, such as CMMS (computerized maintenance management system), MES (machine execution system) or ERP (enterprise resource planning) systems, to foster their interoperability. The European research project PERFoRM (H2020) identified the architecture requirements for an industrial manufacturing middleware (Gosewehr, Wermann, Borsych, & Colombo, 2017). However, the project was only few years too early to fully integrate the emerging Industry 4.0 standards (e.g. RAMI4.0).

On a high level, the architectural approach to interoperability and data integration issues, as suggested by the stakeholders in the design and development of the emerging approaches for European data ecosystems (e.g. GAIA-X, International Data Space), is clearly relying on semantic interoperability and interface descriptions. Especially with the rise of the Industry 4.0 paradigm, this led to the definition of a new series of standards (e.g. RAMI4.0/AAS, OPC UA CS, and frameworks for digital twins and digital factories) that are just starting to get industrial adoption. These new standards have enormous potential for application integration in the industry.

Available commercial solutions of OT software platforms, such as Forcam MES, zenon, PS7, PI Asset Framework, and even larger approaches, such as Siemens MindSphere or SAP AIN) preferably build on existing OT and IT information models. Moreover, interoperability between the manufacturing applications is usually accomplished by proprietary interfaces. On the one hand, this is due to the lack of existing interoperability standards at the time when these systems were developed; on the other hand, the use of proprietary interfaces creates a strong bond between manufacturers and their IT system providers and integrators (“vendor lock-in”).

With the strong digitalization trend in the manufacturing industry and the emerging Industry 4.0 standards integrating semantic interoperability concepts by design (e.g. RAMI 4.0, OPC UA CS, and Digital Factory), we see a good chance for claiming a solution for a semantic interoperability middleware for the small and medium sized companies (SMEs) in the European manufacturing and IT industry. However, for SMEs, these standards bear another difficulty: Since they usually do not have the resources necessary to build a customized data ecosystem for their operational systems, and since extensive commercial solutions are not available for them at an affordable price, they often rely on the availability of a middleware solution supported by their system providers.

Therefore, we propose the semantic integration of those solutions with the semantic descriptions for the assets by also using the concept of the AAS. This approach is based on an idea of a highly influencing IEEE article, where AASs were added also to logical components that are managing physical assets on higher layers, such as for OPC UA gateways and web applications (Ye & Hong, 2019). They come up with the recommendation that “practitioners should use standard technologies to implement AASs because unification and standardization can expedite the convergence of heterogeneous technical, syntactic, and semantic specifications existing in the market. In this way, proprietary I4.0 Components will be interoperable and available to the public in future I4.0 networks.”

3 SEMANTIC INTEGRATION PATTERNS

As pointed out in the previous section, the RAMI4.0 set an architectural standard for the digitally connected industry. Subsequently a set of standards provided the conceptual framework for a new generation of IT systems and opened the floor for semantic interoperability in the “Digital Factory”.

Yet, apart from solutions designed for the large and very large industry, there is a lack in a middleware layer for semantic interoperability that fits the requirements (and the budget) of SMEs. On the other hand, developers of the IT systems for such manufacturers are urgently looking for lightweight interfaces for the exchange of (semantically enriched) data between machines and the applications or between different operational applications.

Typical scenarios exemplifying these interoperability problems are:

- Different IT systems managing asset information (e.g. ERP, CMMS, edge nodes) want to make sure they are “talking” about the same machine and at the same time avoid duplicate and outdated information.
- An edge controller requests the recent maintenance history of a specific asset in order to inform operating staff about recent maintenance activities.
- A management dashboard requests the reasons for downtimes in order to calculate the overall equipment efficiency (OEE).
- An analytics service wants to use selected machine data to develop machine-learning models depending on the material used at production time. Regular updates of the trained models to edge nodes for real-time analysis is required.

To master this communication requirements and to overcome the mentioned integration hurdles, we propose to activate not only the production environment as I4.0 components. All applications required in a manufacturing environment can be equipped with an AAS in order to establish the runtime connectivity for other participants. Furthermore, we propose the definition and implementation of semantic integration patterns for assets on the one hand, and for manufacturing applications on the other hand. For this, the Asset Administration Shell (defined in RAMI4.0) serves as the basic concept for the development of semantic integration patterns.
outlines the functional aspects in a networked manufacturing environment in which IT systems (“application layer”) receive information from the production equipment (“edge layer”) but also exchange (higher level) information between each other. The proposed data integration layer a) acts as the abstraction layer between the connected applications, b) provides the data distribution mechanisms for data producers and data consumers and c) distributes security settings across the system and finally d) connects with active I4.0 components, e.g., activated AAS instances. The active I4.0 component finally serves as the runtime environment for the proposed semantic integration efforts.

3.1 Innovative Architectural Design for the Digital Factory

The data integration layer including generic connectors is the enabler of the proposed semantic interoperability between manufacturing applications and assets in an operational environment. The

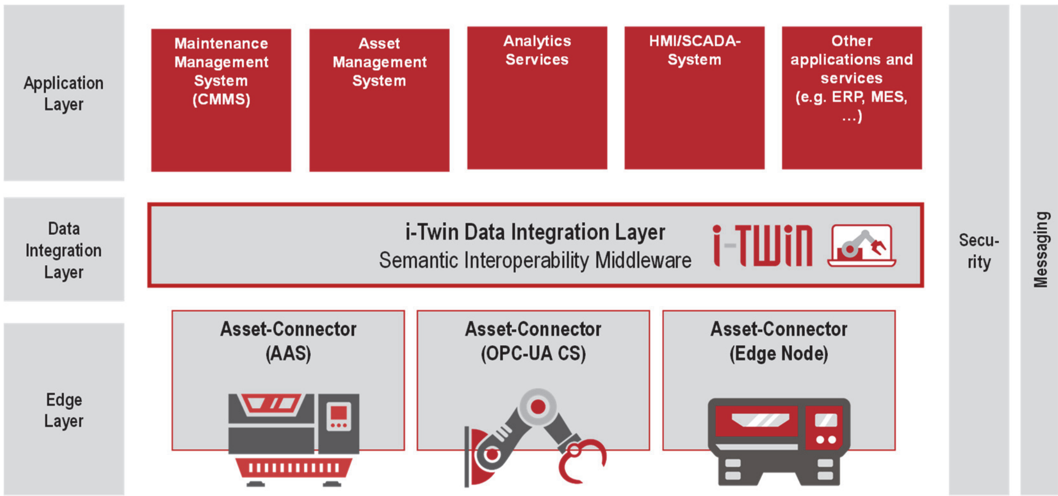

Figure 1: Semantic interoperability middleware – functional aspects.

solution is based on the following design principles:

- Digital Factory: The IEC 62832 standard defines as set of model elements and rules for modelling production systems.
- Semantic Integration Patterns (for details see section 3.2) for minimally invasive integration of manufacturing applications (e.g. CMMS) and OT software platforms, as well as for analytics services based on available standards for the exchange of machine learning and KI models.
- A messaging system for semantically described data streams.
- A security and identity management service to protect data processed in the middleware.

From a technological perspective, the proposed solution builds on the following design criteria:

- Canonical meta-data format: The use of Asset Administration Shell (AAS) as a meta-model for describing assets, their properties and capabilities in a consistent format, and subsequently allows the use of semantic markup.
- Semantic markup: The IEC 61360 (CDD) standard is applied for semantic enrichment of asset properties. ECLASS already provides a data set of approx. 46.000 concepts for products and services from different application areas. In addition, the administration and provision of corporate and domain specific concepts (e.g. a maintenance ontology) must be supported.
- Identity management: A central identity and rights management based on state of the art security mechanisms ensures that data packages are accessible only for authorized participants and applications with valid access tokens.

Figure 2 gives an overview of the building blocks of our three-tier approach for a semantically enriched middleware and connected I4.0 components. This approach also contains the asset connectors and application connectors. We refer to both types of connectors as “semantic connectors” and describe the underlying design principles in the subsequent section 3.2.

The application layer provides connectors for factory applications (e.g., analytics service, ERP system) according to semantic integration patterns.

On the edge layer, asset connectors realize the integration of assets and their related asset data, again based on semantic integration patterns. Connectors expose the applications or the assets data and functionality in standardized interfaces to the I4.0 world, hiding the proprietary details of the applications or assets, but adhering to security settings. They connect with the semantic integration middleware consisting of the following basic components. For better understanding, we also provide some implementation options of them:

Asset Repository: Manages the static information (“master data”) required for data exchange from the applications and assets involved. This can be separate, but also based on existing asset information systems in the companies, if available.

Distribution Network: Allows loose coupling of factory applications, represents the data hub enabling applications to access real time asset data by means of stream processing. Instead of direct updates in a central database, generated events ("management/ control information") are exchanged between applications, or sensor data ("real-time data") are exchanged between machines and applications. It integrates message brokers such as Apache Kafka or MQTT implementations into the system. Main advantages of the stream processing approach are higher read/write performance, scalability, flexibility, agility and traceability in case of errors.

Semantic Lookup: Extends the elements and properties used in the Asset Repository with global and corporate classification schemes, dictionaries according to formats like IEC 61360 (e.g. ECLASS), and RDF/OWL.

Security & Identity Management: Manages security mechanisms such as encryption, user & role management, authentication and access control (e.g. implemented using OAuth2 mechanisms, https://oauth.net/2/). Security is applied to the data integration layer as well as the connectors (application/edge layer).

3.2 Semantic Connectors

Asset Connectors expose a standard compliant I4.0 interface, providing secure access to real-time data but also accepting method invocation requests. Internally, they interact directly with the asset's control device or facilitate OPC UA or similar methods to obtain the asset's details, for example to obtain or update the value of a property or to invoke a control command. Likewise, Application Connectors expose a standard compliant interface in the exactly same way as asset connectors. Effectively, they transform both the applications methods and the exchanged data into the standardized I4.0 world. The aim is to enable method invocation requests to the standardized I4.0 world, of course by applying security settings.

Both types of connectors require an AAS determining the runtime API (AAS Part 2, 2021) and more important, the structure of the exchanged data (AAS Part 1, 2022). An asset or application exposing its information in this way is referred to as an active I4.0 component, providing standardized access and data. The AAS specification provides the model elements for describing properties of an asset and its communication capabilities.

Our proposed approach to go beyond the state of the art of current enterprise integration patterns (EIP, https://www.enterpriseintegrationpatterns.com/) for software is the design of Semantic Integration Patterns extending the traditional EIP concepts by making the exchanged operational data or message payload explicitly known to all of the participants finally participating in a communication. As an example, active I4.0 components representing an asset want to retrieve its maintenance history from a CMMS. For a successful management of this request, the I4.0 needs to know a) how to interact with the CMMS, b) the exact method name including required request parameters and c) the structure of the maintenance history records returned by the CMMS. In a traditional way, this results in massive integration efforts for each required functionality. Moreover, whenever a connected application changes, the integration effort must be repeated.

To reduce this integration hurdles, a semantic integration pattern may be seen as a potential communication between two participants. First, the AAS meta model is used to define the commonly used functionality provided by application types. As indicated in the example, the provision of the maintenance history may be considered as a functionality provided by most (or all) CMMS. When modelling the application type for CMMS, it is obvious to foresee this method. By using model inheritance with AAS meta-model, the generic definitions are redefined and finally instantiated by a

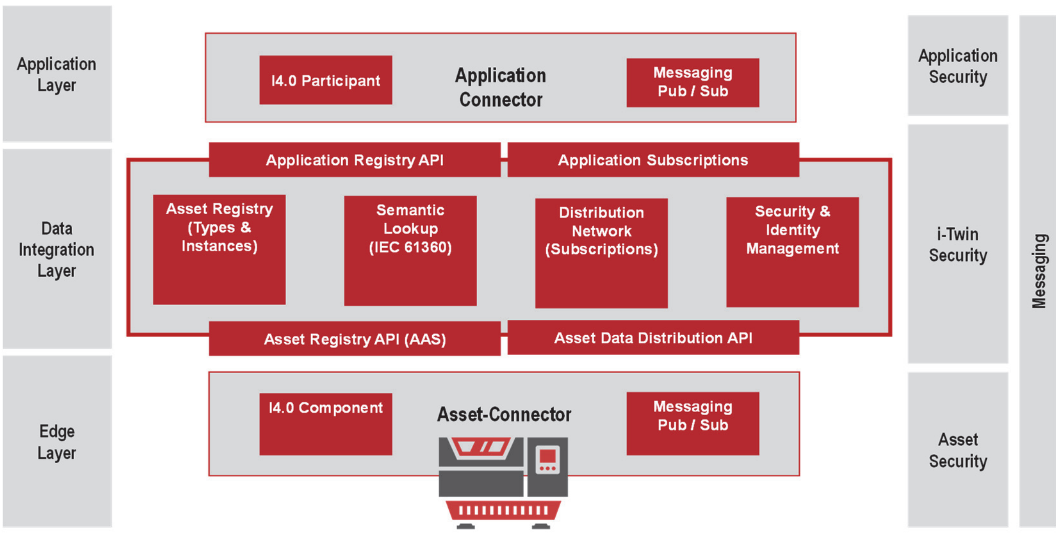

Figure 2: Building blocks of the semantically enriched middleware and connected I4.0 components.

concrete CMMS.This holds for both, the AAS model elements and the linked semantic information model.

Hence, the following design principles apply to the semantic integration patterns:

- Extensive use of model inheritance
- Extensive use of type/instance relationships
- Mandatory use of semantic references to semantic information models

As a result, the I4.0 component simply needs to know the semantic identifier of the requested method. It may ask the Asset Repository whether the method is enabled, e.g., a concrete CMMS system is integrated with the system and offers this requested method. In case a CMMS is present, the I4.0 component receives the full details of the methods request parameters and also the response data structures. It is then possible to create and invoke the request by means of the Asset Repository component. The I4.0 component does not need to know which CMMS system is in use or where it can be reached. Due to the semantic definition of each exchanged data object, the structure of the method's response is also available in a standardized, I4.0 compliant structure. The semantic connector finally transforms exchanged data into application specific, type safe data objects.

Application connectors bring semantic integration patterns to life. They take the structural settings obtained from the Asset Repository and instantiate the respective AAS models. Application Connectors use the semantic identifiers obtained in the instantiated AAS model structure and facilitate the Semantic Lookup to gain insights into the requested data structures in order to validate the data and to transform the data from/to proprietary interfaces. This transparent exchange of structural data definitions works for method invocations and asynchronous data streams. Thus, the following design principles w.r.t to networking are met:

- Applicability in networked manufacturing environments
- Compliance with existing and emerging industry standards (esp. RAMI4.0), w.r.t data exchange.
- Support for data-driven digital twins integrating distributed data sources ("micro data ecosystem" for assets)

4 CONCLUSIONS

In this paper, we presented a conceptual approach towards the development of a semantic interoperability middleware platform acting as mediation layer between manufacturing applications in the office floor (IT) and industrial assets in the shop floor (OT). We introduced the concept of semantic integration patterns as a means to provide semantically enriched and secure exchange of information between the participants of a manufacturing IT eco-system. In the concluding section, we describe the potential of the proposed solution, provide an example for the industrial exploitation and give an outlook of the future work in the underlying i-Twin project.

4.1 Potential of the Chosen Approach

As key beneficiaries of the proposed semantic integration middleware layer, we identified manufacturers (including equipment manufacturers), application developers, system integrators, service providers, and edge developers. Subsequently we describe the potential and the benefits for these stakeholder groups:

Manufacturers and equipment manufacturers benefit from:

- Transparency of data produced and consumed by assets and applications;
- Secure access to and distribution of data between manufacturing applications;
- Availability of searchable asset libraries in a vendor independent standardised format;
- Established workflows for the integration of analytics services with established secure data provision in the training phase;
- Integration of asset descriptions from equipment manufacturers in a standardized format with semantically described data points.
- Generally semantic data integration is a driver for acceleration, automation and cost optimization of production processes.

Application developers, system integrators and service providers benefit from:

- Reduction of integration effort of own system with other systems by semantic integration patterns for application types (access to type-based application profiles);
- Reduction of integration effort for asset data with own system by semantic integration patterns for asset types (access to type/instance-based asset libraries);
- Automated data modelling and data-exchange from edge to application.

Edge developers benefit from:

- Availability of a library of semantic integration patterns for applications and assets for speeding up the commissioning phase;
- Speeding up of the integration design phase (data point engineering, asset master data) through methodological support.

4.2 Industrial Exploitation by Example

As an example of how the developed concepts will be applied and drive the product and process innovation at an Austrian OT software development company, we highlight some of the strategic potentials identified by their head of research.

The semantic integration patterns will expand the existing competence in the field of OT data modelling and data analytics towards semantic integration of OT systems with manufacturing IT systems (e.g. computer-based maintenance management systems). Especially on edge components or services a certain level of semantic information enrichment for existing software solutions will be necessary. It will be a mandatory "feature" to properly prepare the data locally before the data exchange to "higher level" application scenarios for example predictive analytics can be executed.

Actual architecture concepts will be extended or validated against the conceptual design of the semantic interoperability middleware. This concerns especially the area of abstract model descriptions and the necessary secure data exchange over different operational levels. Existing platform solutions, which are actually solely handling industrial data, will be enriched with new services and especially connectivity capabilities. These connectivity add-ons will not only handle the raw (secure) data transmission but also if necessary a semantic transformation between different standardized models of the various Industries.

Typical processes in relevant customer segments (process industry, pharmaceutical, critical infrastructure and food & beverage) will be validated against the challenges of modern Industry 4.0 applications. Industry independent solutions, which are targeting all these industries, must show a high flexibility in terms of semantic data modelling, as we already see today that each Industry are striving to develop their specific standards. This further on will lead to the generation of new services and which will allow for designing generic rules for transformation of semantic information between the different standards.

4.3 Outlook

The underlying project, in which the concepts presented here are developed (i-Twin), continues to provide a conceptual system design of the semantic interoperability platform (parts of the ongoing work in this field were described in the previous sections). Such a platform will allow the implementation of data-driven digital twins integrating distributed data sources (e.g. a micro data ecosystem for industrial assets).

Based on the architectural design, a proof-of-concept implementation of a cloud-based, secure, multi-tenant, and multi-sided platform will be developed, characterized by open interfaces and open source permissive license.

Further research will be dedicated to the design and publication of semantic integration patterns for assets, applications, and analytic services, covering the support of type/instance relationships; the applicability in networked manufacturing environments, and the compliance with existing and emerging domain standards (esp. RAMI4.0/AAS).

A validation process in an industrial asset management scenario and in a lab environment will accompany the research.

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