Abstract: To enable interoperable communication between enterprise software and industrial assets, the Internet of Production reference model suggests a single platform for routing and data access. This Middleware+ must not only act as a central message broker but also meet the challenge of incompatible data models. However, its exact capabilities remain blurred. We first compile relevant technologies and standards to integrate. Definition of requirements and a software architecture proposal follow. Considering the heterogeneous degree of connectivity within producing companies, we then sketch the path to implementation based on maturity levels. The result is a distributed information system architecture ensuring the rigorous use of semantic information models throughout the entire lifecycle of a product.

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Keywords: Internet of things, flexible and reconfigurable manufacturing systems, modeling of manufacturing operations, enterprise integration, systems interoperability, protocols and information communication

1 INTRODUCTION

With advent of digital manufacturing, academic discourse reference (Papazoglou et al., 2015), standardization bodies (Lin and Simmon, 2019) and industrial initiatives (DIN SPEC 91345) have elaborated on reference architectures to provide companies with a common approach to digitalize their factories. Still, none has gained enough traction to be considered an industry standard applicable for companies of all sizes.

The Internet of Production (IoP) reference model was established to present producing companies a novel approach for enterprise information flow (Pennekamp et al., 2019). Data from all enterprise software systems are interconnected with continuous streams of data from the shop floor to enable the focused distribution of information and decision-support. Successful use of industrial data has been hindered by the heterogeneity of systems’ interfaces. The IoP requires a platform to serve as a single access point for data providers and clients alike. This platform needs to understand and convert all incoming data formats for mutual communication. This so-called middleware enables massive system-to-system communication with reduced implementation efforts, resolving the so-called $n^2$-Problem. The dampened growth of interfaces with regard to communication participants significantly reduces complexity (Travis and Ozkan, 2002).

In addition to routing messages between all participants, the IoP tasks its middleware with contextualizing all incoming data, enhancing it to a Middleware+. Rich meta-data and the rigorous use of semantic information models shall deliver interoperable communication to pave the way for flexible, adaptive production management (Molitor et al., 2019).

Middleware+ serves as central platform for communication in the IoP. Previous work outlines its basic functionality, acting as a broker between agents. Yet, there are no precise requirements defined to ensure effective procurement or implementation for this type of software – especially with regard to semantic modelling. Thus a bottom-up approach discussing existing semantic standards shall lay the foundation for requirements elicitation. Motivated by challenges of production engineering, the IoP considers data sources from product development up to the product usage phase and leaves end of life out of scope. Still, the necessary integration between enterprise software and cyber-physical production systems poses significant technological challenges. In addition, an organisation’s migration path towards middleware-centric industrial communication remains unclear. Considering companies’ varying achievement in the field of enterprise integration and industrial communication, the method for introducing a Middleware+ must be differentiated with regard to maturity level of digitalization in the enterprise.
DATA AND INFORMATION MODEL STANDARDS

Standardization efforts have addressed the challenge of interoperability between systems in a variety of domains (Velasquez Villagran et al., 2019). In the context of this work, interoperability shall be described as “a measure of the degree to which diverse systems [...] are able to work together to achieve a common goal.” Semantic interoperability (representing a shared meaning between systems) builds on syntactic and technical interoperability that lay the foundation of compatible messaging (Jacob et al., 2017). A shared context and disambiguating identification enables digital shadows that provide digital twins with live data (Kiesel et al., 2020). Digital shadows are understood as task-specific views on a data source depending on the information requirements of the consumer. All its information flows must abide to the FAIR guiding principles of findability, accessibility, interoperability and reuse of digital assets (Liebenberg and Jarke, 2020). As enterprise software systems each only cover a part of the product lifecycle, interoperable data exchange has shifted into focus. Some enterprise software systems have well-established standards for technical, syntactic and semantic cooperation. Others lack them entirely. This chapter provides an overview of relevant standards being used for data exchange modelling within the product lifecycle. Finally, compatibility and mapping methods for semantic standards are discussed.

2.1 Development Cycle

The development cycle describes all processes that span from inception of a product idea to the start of production for delivery. Product Data Management (PDM) systems are most relevant to administrate product design data. Their functionality is standardized in VDI 2219 and aims to describe all data sources relevant to the product design process. PDM manages its data in close cooperation with the authoring systems such as CAD or simulation software. It uses meta-data to structure files and documents in databases. Interconnecting all data sources and identifying instances across system boundaries remains a central challenge, especially due to the inherent complexity of the development cycle: CAD drawings can be used in a variety of simulation runs which in turn may investigate the interaction between multitudes of subsystems. PDM systems mirror these dependencies. The standard demands that all documents and their content shall be classified according to their source for simplified search.

Despite the wide range of CAD software providers, the use of standards for data exchange has proliferated. The STEP series of standards (ISO 10303) first defines the EXPRESS description language and builds a variety of application-specific extensions upon it. These so-called “Application Protocols” (AP) are specified to fulfill the requirements of relevant applications. AP 203 and AP 214 specify the well-known file format for the exchange of geometric data. AP 242 even provides a data framework relevant to PDM systems including i.e. identification, validity, structure and configuration. Using a STEP standard significantly reduces the necessity of import and export functionality in authoring systems that operate with proprietary formats internally (Vajna et al., 2018).

| System | Function                  | Description       | Meta Model    |
|--------|---------------------------|-------------------|---------------|
| CAD    | Draft and design          | ISO 10303 (STEP)  | EXPRESS       |
| ERP/   | Enterprise planning       | MESA B2MML        | ISA-95 (IEC   |
| MES    |                           |                   | 62264)        |
|        | Production planning       | VDI 5600 (UMCM)   | RDF/OWL       |
| OPC UA | Data transport            | IEC 62541         | OPC UA        |
|        |                           |                   | Meta-Model    |

Despite these modeling standards in the development and production cycle, summarized in Table 1, the problem remains that data from machines may not always be semantically structured from source. This may be due to the age of an asset or due to design priorities. MQTT for example is applied in the industrial context despite delivering an unstructured payload. This was mitigated by the Sparkplug B extension (Nipper, 2016).

2.2 Production Cycle

The production cycle is largely dependent on enterprise decisions. Management plans production according to orders and business constraints. To model these processes, the Business-to-Manufacturing-ML was introduced based on the ISA-95 standard (IEC 62264). The need for unified modelling as a prerequisite for communication among industrial assets is widely accepted (Wortmann et al., 2020). As such, AutomationML (IEC 62714) uses the standard CAEX for modelling to streamline the design and setup process of industrial assets. During plant operation, the AutomationML model gives definitive information on the structure of a plant (Kovalenko et al., 2015). However, it does not specify the mechanisms for flow of live data. This shortcoming holds true for interfaces to Manufacturing Execution Systems (MES). While there are standards like “Universal Machine connectivity for MES” (UMCM) as well. Specified in VDI 5600-3, it defines an ontology tailored to the field information requirements of an MES. All data are structured within categories such as product, job or process, serialized as an OWL-ontology. The academic community has suggested ontological approaches for introducing semantic models into the manufacturing domain such as base ontologies (Borgo and Leitão, 2004) and hierarchical systems of ontologies with ongoing working efforts to expand into vertical industries (Palmer et al., 2018). The challenge of combining modelling conventions with live data information flow is addressed by OPC UA (IEC 62541). This comprehensive standard models assets as nodes with references and specifies integration with a variety of bidirectional communication mechanisms, flanked by a robust security architecture. Industry-specific extensions called “companion specifications” standardize nodes and relations between them. In this context, basic building blocks for information modelling in the fields of machinery, robotics or commercial kitchen equipment were agreed upon. The standard continuously adapts to new developments to ensure performant and secure communication.
2.3 Usage Cycle

Data from the usage cycle are used for several goals. By feeding it back into the development and production cycle, products are optimized based on customer behaviour (Gussen et al., 2020). Furthermore, customer data are monetarized and used to develop new customer services (Kagermann and Riemensperger, 2015). Depending on the product, the requirements for communication capability vary greatly. Thus, a detailed analysis of existing standards would go beyond the scope of this paper. In addition, development and production data are more important for Middleware+ structure.

2.4 Model Mapping

After having explored the existing modelling standards and their industry-specific applications, the question arises to what degree they are compatible with each other. When analysing the structure of underlying meta models, the solution space as to how interoperability between them can work opens a spectrum of approaches – from a common core to individual mapping between each (Jacoby et al., 2017).

A common core is introduced by (Pfrommer et al., 2016). This core could significantly reduce implementation cost for a middleware. However, it requires compatibility with all adapting standards. Examples show a mapping from OWL/RDF, HTTP/HTML and AutomationML to the new core. RDF has been suggested as the central data model for industrial data as well (Grangel-Gonzalez and Halilaj, 2016), citing its URI-system, simple data format and coherence as unique strengths.

For the sake of simplicity, mapping to an already existing standard would avoid the introduction of a new meta model. OPC UA positions itself as such by introducing a set of companion specifications that specify one-to-one mappings to existing standards. This initiative has provided the public with mappings to the information models of ISA-95 (OPC-10030) and AutomationML (OPC-30040) among others. As such, the AutomationML-class SystemUnitClass is depicted as a UA-ObjectType AMLSystemUnitClass that can represent objects with the same semantic expressiveness as in the original representation. In addition to the mapping, OPC UA leverages these standards by combining them with the communication mechanisms at the heart of the OPC UA specification. It operationalizes the standards in the industrial context such that they transcend their initial purpose as design tools and become powerful components for data transmission management (Henßen and Schleipen, 2014).

3 CONCEPTIONALIZATION OF MIDDLEWARE+

After having outlined the core role of Middleware+ in the IoP and consequently discussing relevant standards as well as existing work, this chapter attempts to transfer existing technologies to apply them towards a structure for a Middleware+. This demands the development of formal requirements that have been established in related works. A structural blueprint is derived from them while remaining technology-agnostic.

3.1 Approaches to Semantic Middleware

Drawing inspiration from the legacy of the Enterprise Service Bus (ESB), researchers have identified that a central message hub can create loosely-coupled information distribution systems while controlling for the complexity of the system itself (Fuchs et al., 2019). Heterogeneous data models remain a problem that solutions are still being developed for. Recalling the design choice necessary for semantic integration (Chapter 2.4), an approach that chose a common core information model is the “Virtual Automation Bus” implementation of the Eclipse Basyx Project. It uses the semantic structure of the asset administration shell at its core and demands compliance from the field level. Thus, contextualization of inherently non-semantic data is necessary by the means of gateways or edge devices and cannot be done inside the broker (Kuhn et al., 2020).

3.2 Functional Requirements of a Middleware+

Table 2 summarizes the functional requirements (FR) of Middleware (M+). They were derived from existing academic works, each covering aspects of what a Middleware+ needs to be capable of managing.

| FR   | Description                                                                 |
|------|-----------------------------------------------------------------------------|
| 1    | M+ ingests data from all field devices in all relevant formats and uses function calls for bidirectional communication flows. (Rojas and Ruiz Garcia, 2020) |
| 2    | M+ mediates between data sources and consumers. All devices are uniquely identifiable under a data governance regime that implements user management as well. (Otto et al., 2016) |
| 3    | M+ converts data and methods to an inherently semantic, searchable data format and offers it via a single interface. (Song et al., 2009) |
| 4    | If no data model is specified, the user builds it from standard components and saved for administration. All data and information models are stored. (Kefalakis et al., 2019) |
| 5    | M+ offers tools for data processing and synthetic variables. (Liebenberg and Jarke, 2020) |
| 6    | M+ executes CRUD queries on all available databases of the organisation with respect to the database type. (Curry, 2020, p. 57) |
| 7    | M+ differentiates data flows according to their importance and urgency to provide optimal reliability and availability. (Anderl et al., 2020) |

A method for detailing the list below with company-specific non-functional requirements was established by (Fuchs and Hartner, 2019). It focuses on constraints of existing IT-infrastructure and discusses the role of availability and the subsequent usage of cloud infrastructures in particular.
3.3 Structure of a Middleware+ 

The structure of resulting software system derived from the requirements is sketched in Fig 1. Extending from the layered approach of (Molitor et al., 2019), it details the components with special respect to interface types and semantic capabilities. Field devices (data layer) vary with respect to type, age and connectivity interfaces. This, in consequence, may require modification to partake in interoperable communication. 

A common syntax lays the basis for communication. Appropriate data transport mechanisms must be ensured by design, gateways in the middle, wrappers around the device’s native interface or adapters as an extension of the Middleware+. Gateways even allow transformation to semantic standards if the inner structure of the field device is known. On the network layer, the broker is responsible for distribution of industrial data. Devices already using the correct semantic standards are registered, pass access control and retain their information models depending on their heritage. Different semantic standards (Chapter 2.2) shall be mapped (Chapter 2.4) to the one chosen for the single interface. 

For handling of uncontextualized data, we introduce the “semantic annotation engine” that serves to enhance the expressive power of data. It maps all incoming variables and documents to a semantic protocol by configuration. The user interface accesses a repository of building blocks encouraging the reuse of existing semantic structures. Only by consequent mapping to a semantic standard, the single interface is provided with a guarantee that semantic data is delivered to the higher layers. 

In the database layer, a central DBMS-tool administrates relevant databases that provide information especially from the development (Chapter 2.1) and usage cycle (Chapter 2.3). (Liebenberg and Jarke, 2020) have discussed why the concept of “views” plays a significant role for databases in the IoP. Combining this approach with a two-step access mechanism could prove fruitful where the first step is a query to a graph-based meta-representation and the second step is query-translation depending on the database type. 

4 APPLICATION OF MIDDLEWARE+ 

Since the focus on semantic modelling and central data processing in a Middleware+ as part of the IoP represents a fundamental shift in industrial communication, careful consideration of company-specific circumstances is required. 

4.1 Digital Maturity 

While size, production paradigms and industry are relevant factors when introducing a Middleware+, the experience with digital manufacturing technology is the deciding factor. Hence, (Schuh et al., 2020) have developed a benchmarking methodology defining maturity from computerization (level 1) to adaptability (level 6). It ranks companies according to measurable standards in the categories of resources, information systems, organisational structure and culture.
As the latter two are not relevant for technical discussion around a communication architecture, they are neglected. The category resources examines digital capability of a company’s assets that lay the foundation for connectivity as well as the degree to which the subsequent communication is structured. The category information systems takes advancement in information processing and system integration into account.

4.2 Transformation Paths

In acknowledgement that not all requirements (Chapter 3.1) will be met immediately, we propose a differentiated approach. Industrial companies mostly reside on the first three maturity levels, named computerization, visibility and transparency. Thus, a demand for transformation paths to middleware-centric communication for an archetype of each arises. Companies with the maturity level of computerization have no digital infrastructure in the field that allows them to exercise meaningful analysis of production processes. Connectivity and administration are prerequisites for subsequent advancements and themselves already realize the use-cases of condition monitoring, alarms and events. A SCADA-system implements the aggregating functions and could serve as a central middleware-like platform. Already at this stage, important decisions about tools must be made – especially with regard to a security concept and communication protocols selection. Else, transition to higher maturity levels will cause dysfunction. Having ascended to the connectivity level, companies will now use middleware as a broker with a single interface for all live data and services. It is enriched by read-queries for broad database access and a data governance regime. The broker offers data processing tools. The SCADA-software from the first stage can access its required data from the broker and maintain its functionality without redundancy. The newly gained qualities allow use cases like OEE-monitoring, track-and-trace and automated quality inspection unlocking the maturity level visibility. A Middleware+ as specified in Fig 1 builds on top of this by requiring the consequent use of semantic data formats and semantic search as well as bidirectional access to databases and high convergence between edge, on premise and cloud computing. Only then, adaptive flexible production and dynamic reconfiguring can be achieved at scale.

5 CONCLUSION

The IoP requires a Middleware+ that leverages legacy equipment to contemporary industrial communication. Informed selection of semantic standards and appropriate communication infrastructure represent a sizable integration effort that must combine technological (Chapter 2, 3) as well as organizational considerations (Chapter 4). This work presented an approach capable of meeting the challenge and laid out a path for semantic and non-semantic data to cooperate in an industrial architecture.

In future research, the special role of the OPC UA PubSub profile could be investigated – especially in its implementation over MQTT (that has a broker at the core of its communication mechanism). Extending its functionality could be an approach to realize the semantic annotation engine.

The Information Model DB suggested by the “UA for Cloud” Working Group of the OPC Foundation could lay foundational work towards the common data and information model repository.

6 ACKNOWLEDGEMENTS

This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy—EXC-2023 Internet of Production—390621612.

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