Digitalized Cross-organizational Interoperability in Industrial Business Ecosystems: Implications and Models for Process Industry

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Abstract: Interoperability between industrial organizations is a persistent challenge, particularly as the goal is to enable digitalized communications between information and communications technology (ICT) systems operated by different parties. This paper studies how the current interoperability tools and models support the foundations of digitalized business-to-business communication. While the focus area is plant lifecycle information in process industry, covering investment projects as well as operations and maintenance (O&M), the problems can be generalized to all manufacturing. The results of this study suggest that the current interoperability models and standards offer little support for building cross-organizational interoperability with digitalized tools. Thus, there should be consortia that span the enterprises in process industry, aiming to develop the architecture of collaborative business networks that fulfil sustainable interoperability and the related governance. To accomplish this goal, this paper shows what elements exist and what are lacking, mapping these to European Interoperability Framework (EIF).

1 INTRODUCTION

The everyday operation of industrial enterprises should improve in sustainability, but this progress is hindered by interoperability issues between organizations and their systems of information and communications technology (ICT). In their operation, the enterprises execute collaborative business processes with multiple business partners involved. The processes are often complex, but they also evolve and change over time, which necessitates adaptation (Agostinho et al., 2016). The processes should exploit ICT in information exchange to improve efficiency, reliability, and automation. From the functional viewpoint, the information exchange could occur via direct ICT system integrations in the point-to-point manner, but this is economical only if the number of business partners is low and the data volumes are high (Kannisto et al., 2020). Such integrations are rigid and expensive. Instead, the integration should be loosely coupled, which is what interoperability refers to (Vernadat, 2010). In general, interoperability issues and other technical factors were identified as an obstacle to data sharing by 73 % of respondents in a recent study (Scaria et al., 2018, p. 75).

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Interoperability has been a goal in both generic ICT and industrial production for long, resulting in interoperability models and technologies, but the goal remains unreachable. Despite accomplishments to a certain extent, such as communication protocols and some information models, industrial enterprises still communicate largely manually. It can be argued that the low-hanging fruits have been collected, i.e., the easiest problems have been solved especially if these are generalizable enough to provide a solid return of investment. For example, invoicing is a relevant activity for any enterprise, and as invoices share a general format regardless of the industry, e-invoicing has expanded rapidly (Koch, 2019). However, the narrower the field of application and the greater the heterogeneity, the less tempting it is to seek for a solution.

Regarding interoperability, process industry provides an example about a great potential in business-to-business ICT interoperability but modest results this far. Process industry is asset intensive, and the business processes that require the exchange of plant lifecycle information necessitate masses of data to be communicated regarding engineering and equipment. Concretely, such lifecycle processes are related to investment projects or operations and maintenance (O&M). Unfortunately, the practitioners still rely on data exchange with manual tools, such as spread-

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sheets, in the absence of a digitalized medium. This study considers that ”digitalized” refers to machine readable rather than digitally accessible as defined by (Hendler and Pardo, 2012).

To contribute to the development of ICT interoperability between organizations, this paper outlines the current obstacles, tools, and models, and discusses what is still lacking. The research question is:

> How do interoperability models and existing standards support digital interoperability in the exchange of lifecycle information in the business ecosystems of process industry, and what are the future directions?

Although the viewpoint is lifecycle information in process industry, the problems are analogous with manufacturing and the related business.

The research method is constructive, starting with a background survey in Section 2. For the basis of the construct, Section 3 considers the practical business needs of the exchange of lifecycle information. Then, Section 4 outlines interoperability models and standards that could and should contribute to digital ecosystems regarding lifecycle information in process industry. These provide the components to show which aspects of interoperability already exist and which are still missing, indicating a research gap. Finally, Section 5 concludes the paper.

2 BACKGROUND

The ecosystem view of lifecycle information has rarely been studied. The closest related research fields are organizational interoperability in general and the technical view of lifecycle information.

Enterprise modeling is a potential approach for organizational interoperability. Model-driven methods would enable enterprises that adapt to changes in a dynamic way, leading to sustainable interoperability (Agostinho et al., 2016). Organizations should constantly manage their enterprise models, making these models a top priority and enabling the sensing, smart, and sustainable (Sˆ3) enterprise (Weichhart et al., 2016). Furthermore, enterprise modeling can, combined with knowledge representation, contribute to organizational interoperability by enabling reusable enterprise models (Weichhart et al., 2018).

Regarding the interaction of enterprises, the concept ”digital business ecosystem” refers to a community of business actors with digital information exchange. The concept is analogous to the biological ecosystem, including the ”co-evolution” of the business and the digital representations (Nachira et al., 2007, p. 5). A business ecosystem involves a high modularity and necessitates coordination, which is more demanding than an open market or hierarchical supply chain (Pidun et al., 2019). The formation of the ecosystem can contain both bottom-up and top-down elements, as the former contributes to co-evolution and the latter to interoperability (Lenkenhoff et al., 2018). To transform the production equipment business from an open market to an ecosystem, an ecosystem architecture has been proposed, but this remains abstract and focuses on technology rather than interoperability models (Kannisto et al., 2020). Another study argues that systematically applied ontologies can lead to an ecosystem, but this requires coordination (Ameri et al., 2022). The ecosystem can even span multiple domains. These can, as assumed in Industry Commons Ecosystem (ICE), co-operate in a cross-domain manner by exploiting ”breakthrough innovations”, which is enabled by seven layers that include factors, such as societal values, ethics, environment, contracts and legislation, intellectual property, finance and payment systems, and data interoperability (Magas and Kiritsis, 2022).

Data-driven solutions have arisen in industrial systems recently, leading to goals for data sovereignty and data autonomy. Data sovereignty refers to acting according to the laws of the data origin, whereas data autonomy means that the owner can determine who can access its data and how to use it. Europe is leading this development, as European Commission has announced ”a European strategy for data” that covers multiple data spaces, including industrial manufacturing, agriculture, green deal, and health, among others (COM(2020) 66, 2020). The development has resulted in a pursuit for platforms that aim to facilitate data sharing. In this effort, the initiative Gaia-X aims to provide an appropriate infrastructure, whereas International Data Spaces (IDS) target at controlling data usage (Braud et al., 2021). Software is already being developed for IDS, such as (Nast et al., 2020).

Multiple authors have studied semantic interoperability. In data exchange, standardized properties for the items can form the basis (Epple et al., 2017). Regarding the exchange of engineering data, there is a need for consortia to reach and govern interoperability (Fillinger et al., 2019). The application of the standard ISO 15926 has been studied for semantic interoperability (Kim et al., 2020). One study showed that a fast data exchange solution may be tempting over a slower standards-based one (Papakonstantinou et al., 2019). The standards related to semantic interoperability are referred to in Section 4.2.

To summarize, it appears that there is a research gap between the domain-specific technology and general interoperability research. This leaves the organizational aspects of process industry neglected.

3 BUSINESS NEEDS

3.1 Information Exchange

The lifecycle-related collaboration of process industry has multiple challenges, resulting from the need for interoperability. Earlier, these have been discussed in (Hästbacka and Mätäsniemi, 2009) and (Kannisto et al., 2020). Furthermore, this outline has been contributed to by discussions with practitioners in Finnish process industry although the issues are generally similar all over the world.

The lifecycle processes in process industry, including investment projects and O&M, are characterized by a large number of heterogeneous business actors. This complexity has led to a situation where many aspects remain insufficiently covered by standardization despite a number of standards and the large capital investment. Figure 1 illustrates the actors involved in the lifecycle of a plant, including plant operators, equipment suppliers and manufacturers, engineering agencies (investment projects only), and maintance service providers (maintenance only). For each actor but the operator, the figure presents the most important types of lifecycle information delivered. The operator, on the other hand, needs data of all of these types. Each actor and their tasks regarding data delivery are explained in the following sections.

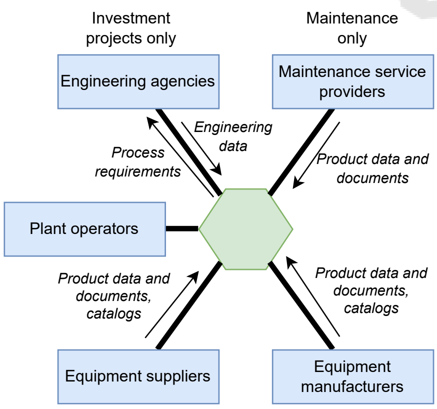

Figure 1: The stakeholders generally involved in investment projects and maintenance service as well as the data and documents exchanged with plant operators.

The information exchanged between the actors is inherently complex. This results from the complexity of the processes and equipment. There are standards for the data, but these have a modest rate of adoption and often require customization. The following subsections explain the role of each actor, whereas Section 3.2 explains the issues of data handover.

Plant Operators. Plant operators utilize the production equipment to make the end product. Regardless of the end product (e.g., food, chemicals, or metals), the industries process materials and must therefore measures, such as temperature, chemical concentration, pressure, and mass. The processing requires equipment, such as storages, pipes, valves, pumps, and measurement equipment. For operation, the operators need to manage various types of information that should become available during the lifecycle of the plant. The operators must manage the requirements of their production processes so that appropriate systems can be designed and built. During operation, the operator needs information about the products so that appropriate spare parts can be found and any updates in the engineering design can be performed.

Equipment Manufacturers and Suppliers. Equipment manufacturers and suppliers provide the production devices. The manufacturers build the equipment, providing a selection with varying characteristics and capabilities. Respectively, the suppliers sell the equipment, but even the manufacturer can sell directly without a dedicated supplier. The supplier provides a catalog to potential buyers about the selection.

Upon selling equipment, the manufacturer or supplier should provide the related data and documents. The operator needs these for the subsequent maintenance and engineering activities. Unfortunately, the structure of the equipment data is heterogeneous and specific to each equipment type, such as pumps, valves, and measurement devices. Furthermore, a set of attachment documents must follow, including but not limited to bills of materials and certificates.

Engineering Agencies. Engineering agencies sell services to the operator as the operator has specialized in process control rather engineering. The agency must receive process requirements from the operator. Based on these, the engineers design an implementation, choosing equipment from a supplier. Once the design is complete, the agency should hand over its design data to the operator. The complexity of this data is similar to the equipment data as engineering determines the equipment properties.

Maintenance Service Provider. Maintenance service providers take care of equipment replacements

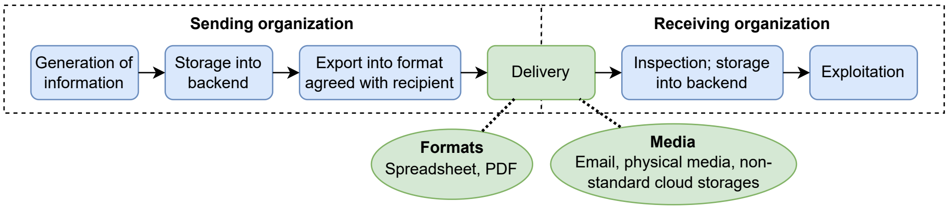

Figure 2: Within the scope of lifecycle information, the stages required to deliver data between organizations, along with the current delivery with a low automation degree. The stages are loosely based on (CFIHOS, 2021).

and the installation of spare parts as appropriate. The service provider can have a storage to provide the most commonly used products. The data delivery differs from an investment project due to its low volume as the maintenance usally applies only to one piece of equipment. Thus, to reduce the burden of data exchange, the service provider typically collects a data batch to be delivered only every few months.

3.2 Issues in Data Delivery

Figure 2 illustrates the various stages required to deliver information from one organization to another along with the manual delivery media. These stages involve the generation of information, its storage locally, its export to a format suitable for communication, the actual delivery, inspection and storage in the receiving end, and exploitation. These stages are loosely based on (CFIHOS, 2021).

The state-of-art delivery occurs with tools that are digitally accessible (spreadsheets and Portable Document Format PDF) and use a medium with a low automation degree, i.e., email, cloud storages with no support for standard data structures, or even physical media (Kannisto et al., 2020). This is because there are no tools to deliver the data in a format agreed by all parties in the ecosystem. There are standards, but their adoption rate is low and local customizations are often necessary. Usually, the plant operator requests to receive the technical data, such as equipment properties and engineering design, in its preferred spreadsheet format. PDFs are applied for human-readable documents, such as certificates and bills of material.

The manual spreadsheet-based process causes issues in data quality and availability. Although spreadsheets enable some automation, they are error-prone and inefficient by leaving too much freedom to the user. The actual content of the data fields often varies after the preferences of the creator. Besides, the manual process can cause a delay of months before the equipment supplier or maintenance service provider delivers the up-to-date equipment data after collecting a batch after one-by-one replacements. Meanwhile, the updates remain inaccessible to the operator.

The manual practices persist because there is no ecosystem-wide governance. The plant operators, as the ultimate customer, have the power regarding which data formats are used, but these are operator-specific. Even these processes could use a machine-readable format, but the volume of data delivery has been too low for a proper incentive. Besides, the operators lack knowledge about ICT solutions and standards. A sufficient governance could change this.

4 MODELS AND STANDARDS

4.1 Interoperability Models

Interoperability models enable practitioners to form common concepts and structures to facilitate discussion and the development of concrete solutions. This section outlines models relevant in ICT and production systems, the selection criteria being: either involved in industrial research (1), designed for production systems (2), or stems from a technological background (3). Thus, the selected models are European Interoperability Framework (EIF), the data federation pyramid, and Reference Architectural Model Industrie 4.0 (RAMI 4.0). EIF is domain agnostic but included as there are studies for production systems (criterion 1), e.g., (Panetto et al., 2019). The data federation pyramid is domain agnostic as well but stems from a technical motivation similar to this study (criterion 3). Finally, RAMI 4.0 was created explicitly for industrial systems (criteria 1–3). It remains future work to include more of interoperability models especially from other domains for more of material.

4.1.1 EIF

EIF is a conceptual model about the elements of interoperability, published by European Commission (EIF, 2017). Figure 3 illustrates the elements. In the core, there are interoperability layers called technical, semantic, organizational, and legal. The element *interoperability governance* spans over each layer, referring to the decisions, structures, and arrangements required to reach and maintain interoperability. Another governance element, *integrated public service governance*, refers to involving or introducing the public services necessary for persistent interoperability. This covers security and privacy, information services, and catalogs. Although EIF has been meant for public services, its abstract, generic nature provides an analogy with the industrial production operated by enterprises.

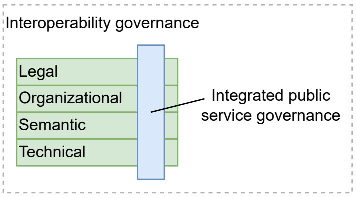

Figure 3: The elements of EIF. Modified, re-drawn based on (EIF, 2017).

EIF is domain agnostic, but there is an extension modeled for cyber-physical manufacturing systems. This extends the layers of EIF with related elements. The two lowest levels, technical and semantic interoperability, form the cyber world, whereas organizational and legal interoperability are the physical world including people. The cyber world must enable the interoperability of models, whereas the physical world must enable knowledge transfer, resilience, and sustainability. (Panetto et al., 2019)

4.1.2 Data Federation Pyramid

The data federation pyramid provides a layered interoperability model that builds upon a technical viewpoint but places business needs as well as trust on top of technology (see Figure 4). It shows how the ICT domain initially struggled with interoperability problems even regarding hardware and operating systems. Later however, the interoperability of software, networks, and data representation has been accomplished. In the present days, the community works on semantics and pragmatics. Pragmatics refers to understanding what kind of requirements arise from the interoperability effort, whereas trust refers to the reliability of the data. (Bergman, 2018, pp. 69-71)

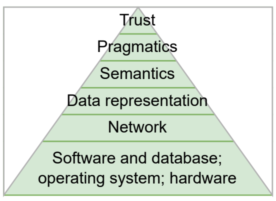

Figure 4: The data federation pyramid. Modified, re-drawn based on (Bergman, 2018, p. 71).

In the data federation pyramid, the two topmost layers, pragmatics and trust, involve organizational complexity whereas the others have a clear technical emphasis. Pragmatics is not to be confused with pragmatic interoperability, which has no commonly agreed definition (Asuncion and van Sinderen, 2010). However, the concept resembles what is called organizational interoperability in EIF, although organizational interoperability must be wider as it includes more of aspects than only the pragmatic consequences of aiming at interoperability. In the context of cross-organizational interactions, pragmatics will result in all of the collaborative effort required to reach interoperability. Bergman's definition of trust is restricted as it considers only reliability and thus lacks trust in the data usage of collaborators in the spirit of data autonomy.

4.1.3 RAMI 4.0

RAMI 4.0 provides a three-dimensional model for interoperability as shown in Figure 5. The three dimensions are layers, hierarchy levels, and lifecycle and value stream. From interoperability viewpoint, the layers are most relevant, covering the physical asset, its connectivity with a communication protocol, the information, functionality, and business. Compared to EIF, this focuses more on devices and less on business, containing no explicit element for governance. The lifecycle dimension focuses on devices and is therefore more restricted than the lifecycle of entire plants. (Adolphs et al., 2015)

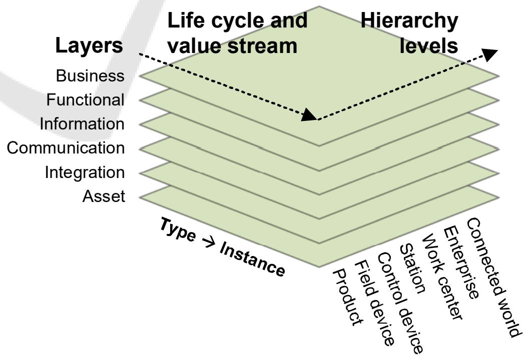

Figure 5: RAMI 4.0 reference architecture. Modified, re-drawn from (Kannisto et al., 2022), based on (Adolphs et al., 2015).

RAMI 4.0 appears to be inspired by Smart Grid Reference Architecture (SGAM). SGAM provides a three-dimensional reference architecture for power systems (SGAM, 2012). The most remarkable difference is that RAMI 4.0 replaced the power distribution hierarchy with the lifecycle dimension.

4.1.4 Models Compared

Interoperability models are often layered and vary in the level of detail depending on the domain. Commonly, the layers include technology or infrastructure on the bottom, followed by semantics, business, and legal, although not all models cover these aspects, as indicated by a comparison of EIF, SGAM, and two other interoperability models GridWise and eHealth (Reif and Meeus, 2020). Still, some models introduce more of aspects, as RAMI 4.0 has two additional domain-specific dimensions and EIF provides an abstract model for governance.

Although RAMI 4.0 stems from industrial domain, EIF appears best from the viewpoint of organizational coverage. EIF stresses the importance of governance, whereas RAMI 4.0 focuses on what appears solely technical from EIF viewpoint. The data federation pyramid is even more technical, providing little elaboration about the two topmost layers that cover organizational issues.

4.2 Standards

Several standards contribute to exchanging lifecycle information in process industry. ISO 15926 consists of multiple parts that aim for interoperability for lifecycle information (ISO 15926, 2004). The parts include, for instance, a data model and reference data library, providing generic concepts that enable application-specific extensions. From this foundation, Data Exchange in Process Industry (DEXPI, nd) has been created for the exchange of piping and instrumentation diagrams. Capital Facilities Information Handover Specification (CFIHOS, 2021) aims to provide a "common language" for the delivery of lifecycle information. CFIHOS specifies properties and equipment classes as the basis of common data information modeling. IEC 61987 series, such as (IEC 61987-10, 2009) for valve data, specifies structures to deliver both equipment and engineering information, among others. This list of standards is not exhaustive but provides an overview with examples.

Asset Administration Shell (AAS) is an initiative and standard to provide interoperability within the value chain. AAS provides abstract information models, associating these to data models and communication protocols. Introduced along with RAMI 4.0, AAS enables a standardized interface for assets to provide their data (Adolphs et al., 2015). AAS is being standardized (AAS Pt. 1, 2022). Regarding AAS, Digital Twin is a related concept, referring to the digital representation of a concrete object or process. One aim of the concept is to facilitate the exchange of engineering information (Sierla et al., 2020). Still, this communication requires a concrete medium, which is lacking from process industry at least. This study regards Digital Twin as a container of data and models that still requires concrete standards for the interfaces that enable interoperability, thus providing no actual interoperability tools.

Additionally, there is a group of competing domain-agnostic standards to deliver business documents or messages in a standardized format as reviewed by (Chituc, 2017). This field is, therefore, covered better than most of process-industry-specific communication. Such business documents include, for example, request for quotation, order, and invoice. The standards reviewed by Chituc include, e.g., Universal Business Language (UBL), Open Application Group Integration Specification (OAGIS), RosettaNet, and Electronic Business using Extensible Markup Language (ebXML). However, the standards provide no help in exchanging lifecycle information.

Open Platform Communications Unified Architecture (OPC UA, 2017) provides standards for communication in industrial plants but lacks a focus on both cross-organizational communication schemes and lifecycle information. Although the newer OPC UA "PubSub" specification (part 14) introduces data models enabling cloud storage, there is no standard medium for multi-actor schemes. Besides, OPC UA lacks an information model for process requirements, product and engineering data, and catalogs.

Despite a number of existing standards, their adoption and influence on plant-lifecycle-related business processes is limited. The reasons not to adopt standards stem from the business environment, the organizations, and the standards themselves (Braaksma et al., 2011). Clearly, the complexity of the environment and information structures hamper digital interoperability efforts. Consequently, the business practices remain heterogeneous, and there are neither common information models nor appropriate data platforms.

4.3 Future Directions

Despite the challenges, there are initiatives to change the situation. In Sweden and Finland, research institutes and companies organized an initiative called Nordic Interoperability Cooperation (NIC) to recognize new potential business models, Norway has been involved in the discussions, and there are Europe-wide efforts as well (SEIIA, 2022).

AAS aims to enable interoperability within the value chain. It has gained the attention of scholars, inspiring an entire workshop in 2022, e.g., (Jacoby et al., 2022). Currently, AAS has a scope different from lifecycle information where information and data models as well as semantics are essential. To be applicable for lifecycle data, AAS still necessitates a related information model as well as some medium and organization to maintain interoperability. It remains to be seen if AAS will either extend its applicability or at least inspire the development of lifecycle information processing.

The themes data sovereignty and data autonomy have gained interest, which can contribute to lifecycle information as well. As these are domain-agnostic topics, they again lack a direct contribution to semantic interoperability and the related governance for lifecycle information. However, the dataspaces Gaia-X and IDS are penetrating even to industrial setups, contributing to communication and data autonomy (Usländer et al., 2022).

Inspired from existing standards and frameworks, Figure 6 illustrates how the current and future contributions can enable interoperability for lifecycle information. EIF is was chosen for the foundation due to its emphasis on interoperability governance. The figure illustrates the four layers as well as the pervasive governance. Each layer is explained in the following paragraphs.

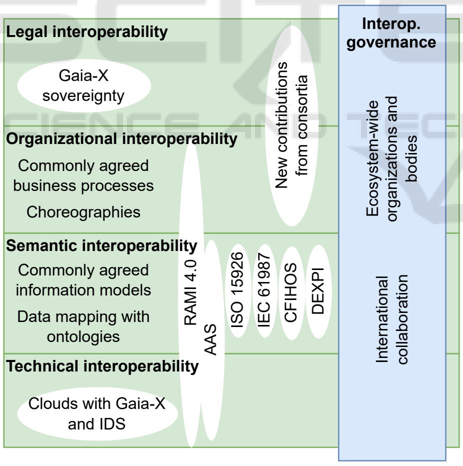

Figure 6: Standards and contributions regarding lifecycle information in process industry; built upon (EIF, 2017).

The bottom layer covers technology, including platforms, that enables data exchange in an autonomous manner. Gaia-X and IDS provide the infrastructure and dataspaces. Furthermore, RAMI 4.0 and AAS provide communication interfaces.

The second layer is semantics, which is a persistently challenging issue in lifecycle information. Multiple standards contribute to this layer, at least RAMI 4.0, AAS, ISO 15926, IEC 61987, CFIHOS, and DEXPI. Of these, some provide static information models, whereas others map these into ontologies. Ontologies help in various production-system-related information management tasks (Batres, 2017).

The third layer refers to business processes, including any common agreements for business-to-business interaction. This is where new consortia are necessary as there is currently no sufficient coordination regarding the application of information models and the required technical platforms. Although RAMI 4.0 covers this area, it provides no concrete tools to manage organizational interoperability. The consortia can arise from existing national organizations or the ones already developing the standards. In forming such consortia, a rulebook from Sitra helps to create a fair ecosystem (Rulebook for a Fair Data Economy, 2021).

The topmost layer, legal interoperability, is implemented with Gaia-X that has data sovereignty as a core goal. The layer still requires more of consideration in an open consortium to guarantee suitability for the specifics of process industry. The earlier mentioned Sitra rulebook helps here as well (Rulebook for a Fair Data Economy, 2021).

4.4 Discussion

The proposed model, mapping standards and activities to EIF, is a potential approach for interoperability regarding lifecycle information exchange in process industry. Because the business is currently an open market, the way for an interoperable ecosystem is to increase coordination (Pidun et al., 2019). For the concrete data exchange platform, there is no guarantee if Gaia-X is the solution, but at least its ideas should be followed to reach data autonomy, which is desirable to industrial actors to protect their property.

The model could still be more concrete requiring the organizations of process industry. It could map the concrete consortia of process industry into the figure and show their relationships with the non-domain-specific items, such as Gaia-X and AAS. Clearly, suitability to process industry can realize only if the domain demands a recognition for its requirements. Additionally, the model could be seek for acceptance within the business actors, such as operators and equipment suppliers. This would increase credibility and potentially introduce new elements as well as encourage discussion within the domain.

As a limitation, this study only considers lifecycle information in process industry, excluding the explicit needs of other domains and activities. Still, engineering, equipment, and maintenance are equally important in manufacturing, and the respective interoperability governance is necessary in any cross-organizational communication that faces evolution regardless of the domain.

5 CONCLUSIONS

This paper studied the support from models and standards for organizational interoperability in process industry, finally suggesting future directions. The authors argue that the complex, heterogeneous nature of enterprises and collaborative tasks effectively slows down the progress towards common practices. Although such practices would increase efficiency, it will take a considerable effort from any enterprise. Regarding interoperability models, it was discovered that while some models mention organizational issues, there is little concrete support, and others exclude organizational factors altogether. Of the examined interoperability models, EIF provides the best foundation by stressing interoperability governance, a core element in sustainable interoperability. EIF is, however, abstract and oriented to public services rather than industrial production, lacking any concrete concepts for an ecosystem. Fortunately, ongoing projects and proposal can relieve the interoperability problems but only if the enterprises are ready to collaborate and participate in the bodies that govern standardization. Additionally, more work is necessary for the data infrastructures, such as Gaia-X and IDS.

Considering the data federation pyramid suggested by (Bergman, 2018, pp. 69-71), the challenges of semantics and pragmatics still dominate the field of interoperability. Semantic interoperability is currently partially reached as some information models are available and others not. Pragmatics is what causes the most tangible interoperability issues as this covers the actual realization of interoperability in the everyday tasks.

For future work, there are multiple topics. First, there could be contributions towards a concrete ecosystem for lifecycle information, along with the required coordination and governance, with both bottom-up and top-down elements for both co-evolution and interoperability (Lenkenhoff et al., 2018). Second, the scope of the study could be extended to cross-domain scenarios. This could include, e.g., energy management and building information modeling (BIM) as these should be considered in daily industrial operation to reach the green transition. Third, the application of platforms, such as Gaia-X, could be studied for interoperability and data autonomy.

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