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Alignment of the IEEE Industrial Agents Recommended Practice Standard With the Reference Architectures RAMI4.0, IIRA, and SGAM

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ABSTRACT Industrial cyber-physical systems (ICPS) are a key element that acts as the backbone infrastructure for realizing innovative systems compliant with the fourth industrial revolution vision and requirements to realize it. Several architectures, such as the reference architectural model industry 4.0 (RAMI4.0), the industrial Internet reference architecture (IIRA), and the smart grid architecture model (SGAM), have been proposed to develop and integrate ICPS, their services, and applications for different domains. In such architectures, the digitization of assets and interconnection to relevant industrial processes and business services is of paramount importance. Different technological solutions have been developed that overwhelmingly focus on the integration of the assets with their cyber counterpart. In this context, the adoption of standards is crucial to enable the compatibility and interoperability of these network-based systems. Since industrial agents are seen as an enabler in realizing ICPS, this work aims to provide insights related to the use and alignment of the recently established IEEE 2660.1 recommended practice to support ICPS developers and engineers to integrate assets in the context of each one of the three referred reference architectures. A critical discussion also points out some noteworthy aspects that emerge when using the IEEE 2660.1 in these architectures and discusses limitations and challenges ahead.

INDEX TERMS Standards, industrial agents, industrial cyber-physical systems (ICPS), industrial Internet of things (IIoT), reference architectural model industry 4.0 (RAMI4.0), industrial Internet reference architecture (IIRA), smart grid architecture model (SGAM).

I. INTRODUCTION

To realize the visions of intelligent, reliable, and collaborative future industrial infrastructures, a significant and widespread transformation needs to happen to the existing industrial systems, their services, the applications, the business processes, and even the involved personnel [1], [2]. The first step in this process is the digitization of the provided information, which enables the assets to capture the analog world, transform it, and make it available in a digital format [3]. The next step deals with the digitalization of information, which investigates how to best use the digitalized information in processes and enhance them [3]. The last step, which is the digital transformation [3], [4] is also the most complex and most encompassing one, as it deals with the creation of business innovations and models that capitalize on the digitalized information and services to generate knowledge and apply that knowledge at the enterprise level as well as in the interactions/collaborations at intra- and interenterprise levels.

Industrial cyber-physical systems (ICPS) [5], [6], [7], [8], coupled with innovative technologies [1], present a key concept within the efforts for the digital transformation [4] in the industry worldwide. ICPS have played a pivotal role in several domains like manufacturing and energy in Industry 4.0 [5] and are expected to be key enablers as we pave our way toward Industry 5.0 [9], where sustainable, social, collaborative [10], and human-focused [11] applications of new technologies across several sectors are envisioned and planned as the next societal evolutionary goal, for example, in Europe [12].

What principles to follow and how to implement Industry 4.0 is seen as challenging [13], [14]. Several reference architectures have been developed for different domains [15] that aim at the integration of cyber-physical systems (CPS), services, and applications, such as the reference architectural model industry 4.0 (RAMI4.0) [16], the industrial Internet reference architecture (IIRA) [17], and the smart grid architecture model (SGAM) [18], [19] to name a few. In this context, industrial agents technology can be seen as an enabler for Industry 4.0, which can instrumentally contribute toward realizing intelligent ICPS in a variety of domains, such as industrial automation, smart grids, logistics, and smart cities [14], [20], [21], [22].

While efforts are ongoing, the integration of ICPS that control the operational infrastructure is critical, and several technologies have been developed over the last years. Especially for those ICPS involved in the execution of low-level automation functions, it is paramount to utilize approaches that constitute best practices to minimize the risks (e.g., of security, reliability, and performance). To this end, standards are important to enable the compatibility and interoperability of these networked systems and develop innovations that are built on mature and widely agreed practices [23]. Several factors may affect the Industry 4.0 adoption, like software infrastructure, system flexibility, operational accuracy, and technology capabilities [24], hence it is important to be systematically assisted when technology-based decisions need to be made, something that the IEEE Industrial Agents Recommended Practice IEEE 2660.1 [25] attempts to enable.

The recently published IEEE 2660.1 standard [25], defines a technique for recommending the best interface practice for integrating software agents and physical assets. The focus is put on assets that execute low-level automation activities and is driven by feedback from experts who have used various interface practices in concrete scenarios. In this way, the IEEE 2660.1 standard improves the reuse, consistency, and transparency in integrating industrial agents and low-level control functions in ICPS environments by leveraging the best practices for designing industrial agents for specific automation control challenges. Note that the IEEE 2660.1 provides a methodological way to recommend the best practice for a specific application scenario, but it does not explicitly provide a particular interface standard [26]. Some research works, namely, [27] and [28], have already utilized the IEEE 2660.1 standard.

IEEE 2660.1 is not developed with a specific architecture in mind, such as RAMI4.0, IIRA, or SGAM, but it is interesting to see how its methodological proposals fit in the context of these architectures. Specifically of interest is how it can support the digitalization developments that are compliant with these architectures, as well as what the limitations might be. Therefore, this work aims to shed some light on these directions and provide insights that may be relevant to ICPS developers and engineers, as well as digital strategists that plan and execute the digital transition of assets and infrastructures along the context defined in each of these three architectures.

The rest of this article is organized as follows. Section II introduces the research questions and methodology for this work, and Section III presents the basic concepts related to IEEE 2660.1. Sections IV–VI describe how IEEE 2660.1 is aligned with RAMI4.0, IIRA, and SGAM, respectively, providing an illustrative example of using this standard for each case. Subsequently, Section VII discusses and analyses the alignment of the standard with the three analyzed reference architectures, as well as its limitations and boundaries. Finally, Section VIII concludes this article.

II. RESEARCH QUESTIONS AND METHODOLOGY

The issues raised concerning IEEE 2660.1 and its relation to the different reference architectures pose an interesting research direction. This is approached based on the following research questions (RQs):

- *RQ1:How can IEEE 2660.1 be used for scenarios that are based on the RAMI4.0, IIRA, and SGAM-based architectures?*
- *RQ2:What is the level of commonalities of IEEE 2660.1 scenario developments?*
- *RQ3:What are the lessons learned concerning the best way to develop applications driven by IEEE 2660.1 and compliant with RAMI4.0, IIRA, and SGAM architectures?*

RQ1 aims to investigate the relationship of IEEE 2660.1 with the three major architectures. Assuming that this can be realized, then one can link the process and context upon which scenarios stemming from different architectural approaches.

RQ2 takes as a prerequisite RQ1, i.e., that some scenarios can be realized (but does not specify the degree of fulfillment), and aims to investigate if there are commonalities along the utilization of IEEE 2660.1 in these three scenarios. To put it otherwise, at which level is there a common ground among all scenarios, implying that the utilization of the IEEE 2660.1 is architecture agnostic, and when do IEEE 2660.1 aspects flow in a strong manner in the scenario development?

RQ3 focuses on the gist from RQ1 and RQ2, i.e., on the best way and the limits of applying the methodology described in IEEE 2660.1 for each architecture. It could, for instance, be shown that up to a certain level, common best practice paths can be followed, and then from a point onward, the architecture-specific needs come into play and influence further development. Another alternative could be that one attempts to select development paths that are as much as possible compliant with both the architectures and the IEEE 2660.1, which could effectively ease the adoption in other domains.

The methodology followed is built along the three RQs. For this purpose, an application example was selected to stem the alignment of the use of IEEE 2660.1 to support the digitalization process of assets in each one of the three reference architectures. Subsequently, a scenario that adheres to IEEE 2660.1 was developed for each reference architecture to show how it is applied. Then, the three different approaches, as well as their commonalities, differences, and limitations, were compared and critically discussed.

III. OVERVIEW OF THE IEEE 2660.1 STANDARD

This section aims to briefly overview the IEEE 2660.1 [25] standard, particularly describing its scope of application, the clustering of the existing interface practices, and the recommendation method. For additional insights, it is suggested to get acquainted with the standard itself [25], and potentially also the works [26], [29], [30], [31], [32] that have focused on complementary aspects under consideration within the standard and may provide supplementary detailed insights.

A. SCOPE OF APPLICATION

The IEEE 2660.1 aims to recommend the most appropriate technological practices to interface software agents and assets, particularly low-level automation devices, along their lifecycle. For example, these interface practices can be used to interconnect software agents with a sensor (e.g., for monitoring a parameter), a robot controller (e.g., for starting/stopping the execution of a pick-and-place program), and a programmable logic controller (PLC) or an Industry PC (IPC) that controls a conveyor system (e.g., to read and write variables).

B. INTERFACE PATTERNS

The feedback from experts and the analysis of the literature substantiates the existence of different technological interface practices to interconnect software agents and low-level automation functions [26]. The identified interface practices can be clustered along three dimensions, namely, the *location*, the *interaction mode*, and the used *technology*, as illustrated in Fig. 1.

The interaction mode dimension is related to how the interaction between the agent and the asset is performed, for example, following a direct call under the client–server approach or using a publish–subscribe messaging pattern that enhances scalability. The location dimension is related to where the software agent is running, i.e., if it is running in the same computational platform of the physical asset (referred to as on-device) or in a remote one (referred to as hybrid). Lastly, the technology dimension considers the technological options

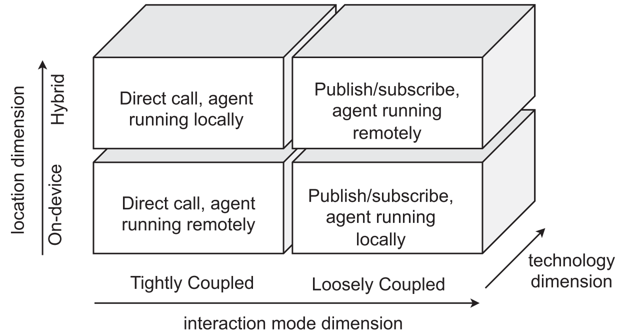

FIGURE 1. Types of interfacing patterns according to IEEE 2660.1 [26].

to implement the interface, for example, considering proprietary technologies or more standardized ones. According to the tuple *{location, interaction mode}*, different technologies solutions can be found, e.g., OPC Unified Architecture (OPC UA), Modbus, Representational State Transfer (REST), and sockets for the client-server approach, while for the publish-subscribe schema message queue telemetry transport (MQTT) and OPC UA may be used.

Due to the high variety of scenarios and requirements, no single interface practice is sufficiently adequate to cover all aspects, as each practice has its own set of strengths and weaknesses. The selection of the most fitting interface practice based on these strengths and weaknesses is not a straightforward task and depends on the case and what is valued more in a specific context. As such, IEEE 2660.1 proposes an approach that evaluates the existing practices according to the selected criteria to support the system integrator in making this decision.

C. RECOMMENDATION METHOD

The standard offers a method to recommend the best interface practice to interconnect software agents and physical automation devices. Based on a specific scenario and a selected recommendation algorithm, a recommendation engine proposes the best-suited recommended practices, according to the database of existing scored interface practices, as illustrated in Fig. 2.

The assessment and selection of the right software is a challenging engineering process [33]. The IEEE 2660.1 standard defines a methodology that strongly relies on the feedback provided by experts in implementing and using different technological interface practices and their assessment according to their experience. This requires the continuous update of interface practices in the repository, assessing each one according to a set of criteria that reflects the desired characteristics. Examples of quality criteria are supplied by the ISO/IEC 25010 standard [34], which originally provides quality characteristics for evaluating software systems. After an analysis of these quality criteria [29], [30], IEEE 2660.1 uses the response time, scalability, and reusability parameters.

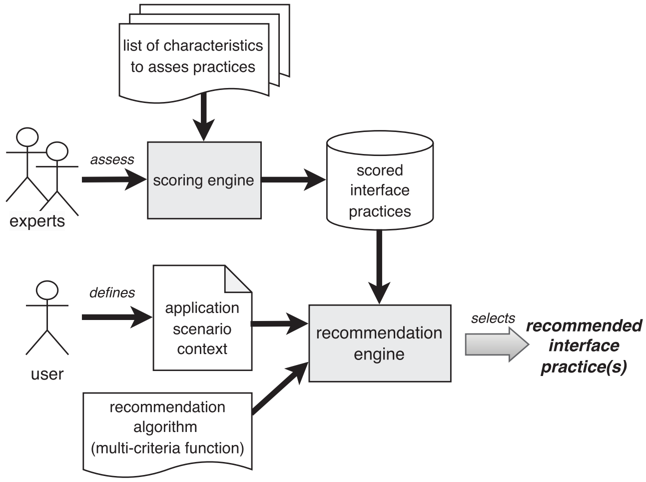

FIGURE 2. Recommendation method defined by IEEE 2660.1 [25].

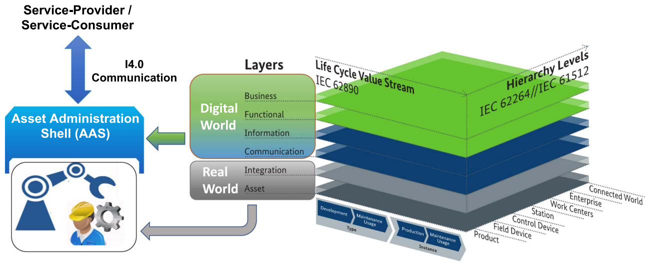

FIGURE 3. RAMI4.0 and the relationship to the AAS.

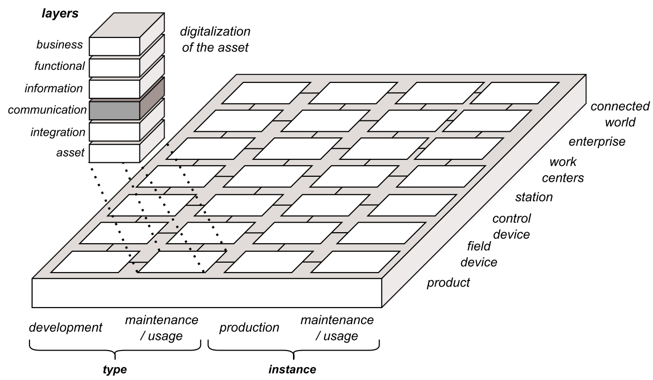

FIGURE 4. 2-D digitalization matrix of RAMI4.0.

The scoring engine supports the experts in performing their assessment of each interface practice, using a five-level Likert scale [35] to evaluate the different characteristics and performs the aggregation of entries from different experts for the same interface practice, for example, by performing the statistical average of the scoring values of each entry.

The recommendation engine evaluates the scored interface practices stored in the repository, aiming to select the one that better addresses the application scenario context defined by the user and that includes the function (e.g., monitoring, control, or simulation), application domain (e.g., factory automation, energy and power systems, and building automation), and technological constraints (e.g., capability to host agents in the asset controller).

After removing the interface practices that are not a good fit with the user-defined constraints, the remaining practices are evaluated according to one recommendation algorithm. The standard illustrates the application of the recommended method by using a multicriteria function that weights each criterion according to its relevance to the application scenario (also defined by the user). For example, the user can define that the response time is the most relevant parameter and should be weighted at 60%, and reusability is also important and should be weighted at 40%.

The recommendation engine, after applying the algorithm, provides the recommended interface practice and a list of alternatives sorted according to their evaluation scores.

IV. IEEE 2660.1 ALIGNMENT WITH RAMI4.0

This section overviews the RAMI4.0 reference architecture and tries to identify the alignment of the IEEE 2660.1 standard with it, providing an example scenario of its applicability.

A. OVERVIEW OF RAMI4.0

RAMI4.0 [16] is a 3-D architecture established by the *Plattform Industrie 4.0* [36] to serve as a reference for engineering Industry 4.0 systems. While at a high level, it has been defined almost a decade ago, associating industry standards with the specifications of its three dimensions, the development and implementation of different industrial digitalization and networking solutions are still ongoing. RAMI4.0 can be used by enterprises to guide them through a digital transformation roadmap [37]. There is a set of different approaches and technologies that allow specifying and effectively implementing RAMI4.0-compliant solutions. The details about the asset administration shell (AAS), and the different variations for real industrial applications, as shown in Fig. 3, are currently being specified [38], [39].

RAMI4.0 allows considering 2-tuple associated with any asset located within the hierarchy of an industrial infrastructure (following the levels specified by IEC 62264 and IEC 61512 and considering the phases of the value stream/life cycle of any of the assets according to the specifications given by the IEC 62890). The structure, and composition of the AAS, providing submodels based on digitalized data and information associated with different structural and functional specifications of the asset, is nowadays recognized as the basis of building digital twins [40] and easily integrating assets like robots in existing systems via the AAS [41].

From the 3-D model perspective, the digitalization process starts with a 2-D surface, illustrated in Fig. 4. This background matrix contains 28 cells, each being a 2-tuple that identifies the asset and its life cycle phases.

Applying a bottom-up digitalization engineering approach, each one of the 2-tuples, placed at the different cells of the 2-D matrix, needs to be digitalized following the vertical dimension (digitalization and networking layer dimension of RAMI4.0). The first step in the digitalization process is about access to the data and information that the 2-tuple can expose or consume when it will be digitalized and networked. This is specified by Layer 2 of the RAMI4.0, called "Integration." The concrete implementation of Layer 2, part of the AAS specification, requires the use of different technological interfaces according to the asset position within the hierarchical levels and the particularities and requirements of the data associated with the defined phases of the life cycle, depending on its position in the 2-D matrix represented in Fig. 4 and the application scenario.

Overall, modern solutions developed can be mapped to the different layers of RAMI4.0, offering transparency for the aspects they cover while architecturally and technologically also providing a better understanding of how different requirements and needs are addressed at each layer. For instance, an architecture that supports the integration of collaborative robots and couples it with a machine learning framework that eventually allows for advanced monitoring and analytics can be an example of such a mapping [10].

B. GENERAL CONSIDERATIONS

As explicitly highlighted in Fig. 4, the third layer, i.e., the communication layer, ensures the standardized communication between the physical (asset) and the cyber part, representing the digital world to transmit/receive data. In this sense, industrial agents constitute a suitable technological approach to implement a few structural and functional specifications of the cyber part of an asset, i.e., parts constituents of an AAS. The agent technology can extend the functionalities provided by AAS, mainly focused on passive submodels related to the asset technical and operational identification, the interconnection with the asset, and the storage of collected data. The introduction of agent technology into the AAS enhances proactivity and collaborative behaviors, based on, for example, intelligence capabilities of the digitalized and networked assets [20].

Since software agents can enable the digitalization of assets, they are particularly useful in realizing Layer 5, i.e., functional layer, which is an essential part of the AAS. In this sense, IEEE 2660.1 can contribute to supporting the selection of the most suitable integration interface for each asset according to the application scenario. In particular, the essence of IEEE 2660.1 to recommend the most appropriate technological interface practices fits well with the needs of RAMI4.0 to have different realizations of the communication layer based on the use of standards for the digitalization of the assets. This integration can be performed by using different communication standards and architecture styles, e.g., OPC UA, Modbus, and REST, and following different protocols, such as client–server (e.g., HTTP) or publish–subscribe (e.g., MQTT), and IEEE 2660.1 can strongly contribute to help in the decision to select the most appropriate practice.

Results						
Recomended interface practice						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HT-5	**Hybrid**	**Tightly coupled**	**Apache Milo**	**OPC-UA**		**4.00**
Details						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		4.00
HT-6	Hybrid	Tightly coupled	Java	Ethernet/IP		3.50
HT-7	Hybrid	Tightly coupled	Java	OPC UA		3.20
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		3.20
HL-1	Hybrid	Loosely coupled	Apache Paho	MQTT	Eclipse Mosquitto	3.20
HT-2	Hybrid	Tightly coupled	Java	Sockets		3.10
HT-3	Hybrid	Tightly coupled	Java	DPWS		2.80
HL-2	Hybrid	Loosely coupled	Java	OPC-UA		2.72
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		2.40
HL-3	Hybrid	Loosely coupled	C/C++/SQL	Sockets	DBMS	2.40
HT-1	Hybrid	Tightly coupled	Java	Modbus		1.92

FIGURE 5. Results of the recommended practice for the robot being produced (product level).

C. APPLICATION EXAMPLE

To illustrate the application of the IEEE 2660.1 to support the digitalization of assets within the RAMI4.0, consider that the objective is to digitize a manipulator robot that is being produced (i.e., an instance in the production phase of the lifecycle and value stream dimension) and placed at the hierarchical product level. For this purpose, an industrial agent may represent the AAS, and IEEE 2660.1 is used to recommend the best practice for its integration (communication layer). In such configuration, the expected functionality is monitoring its production, being the response time and reusability equally relevant to be considered (i.e., the response time, weighted as 50% and the reusability as 50%). At this stage, the robot asset cannot run agents locally.

Applying the IEEE 2660.1 recommendation method for this scenario and considering the dataset related to the feedback of experts included in the standard (that is only indicative and should be continuously updated), it is possible to get the results illustrated in Fig. 5. The output results provided by the recommendation method contain a list of ordered recommendation interface practices and their scores (one line for each), indicating their details, namely, the location of the software agent, the interaction mode, and the API client channel.

The recommended interface practice is a *tightly coupled* interface using OPC UA with the API client using Apache Milo (the second is similar but with the API client codified in Java). Since there is no possibility to host the agents directly running in the asset, the suggested practices rely on the *hybrid* location, which means that the client will be running remotely, and possibly the response time may be affected by the communication infrastructure. Note that the recommended practices may refer to similar technologies albeit different levels of specificity; as example, Java and Apache Milo (which is implemented in Java) do not conflict as one refers to an explicit software tool that is proposed to be used, while the other to a more general programming language.

Consider now that the same robot asset is positioned in a different cell of the 2-D matrix, see Fig. 4, for example, placed in a production line performing welding tasks (i.e.,

Results						
Recomended interface practice						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
OT-1	On-device	Tightly coupled	Java			3.77
Details						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
OT-1	On-device	Tightly coupled	Java			3.77
HT-7	Hybrid	Tightly coupled	Java	OPC UA		3.20
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		3.20
OT-2	On-device	Tightly coupled	C/C++	Sockets		3.09
HT-6	Hybrid	Tightly coupled	Java	Ethernet/IP		2.56
HT-3	Hybrid	Tightly coupled	Java	DPWS		2.56
OL-1	On-device	Loosely coupled	REST/JSON	MQTT	Eclipse Mosquitto	2.56
OL-2	On-device	Loosely coupled	C/C++/SQL	DBMS	DBMS	1.92
OT-3	On-device	Tightly coupled	C/C++/SQL	DBMS		1.92
HT-2	Hybrid	Tightly coupled	Java	Sockets		1.82
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		1.63
HL-1	Hybrid	Loosely coupled	Apache Paho	MQTT	Eclipse Mosquitto	1.63
HT-1	Hybrid	Tightly coupled	Java	Modbus		1.56
HL-2	Hybrid	Loosely coupled	Java	OPC-UA		1.45

FIGURE 6. Results of the recommended practice for the robot placed at production (control device level).

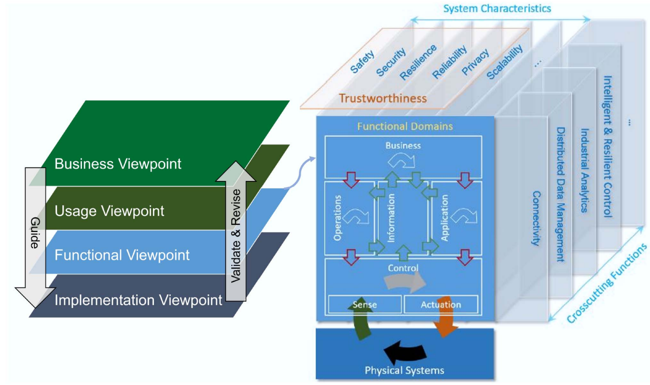

FIGURE 7. IIRA viewpoints and functional domains [17].

factory automation as application domain). At this stage, the robot controller can already run agents, and the functionality provided by the agent/AAS (functional layer) is the control of the asset, for example, to start or stop the execution of a robot program. The response time is the most important factor in such configuration, but also reusability is a valuable point to be considered (weighted as time response 80% and reusability 20%). The application of the IEEE 2660.1 recommendation method for this application scenario provides the results illustrated in Fig. 6.

Since there is the possibility to embed agents directly into the asset controller, the recommended practice is a *tightly coupled, on-device* approach, whereas the low-level automation functions and the agent are executed on the same platform. The demanding soft real-time tasks (associated with control functions) require the avoidance of running the agent remotely, which strongly impacts the expected response time. Other different coupling possibilities are possible, for example, *tightly coupled, hybrid* using OPC UA, or *tightly-coupled, on-device* using sockets, as shown in Fig. 6, but with lower scoring values.

These two examples clearly show the potential benefits of suggesting the best interface practice for two different application scenario contexts, even using the same asset but positioned at different stages of its life cycle.

V. IEEE 2660.1 ALIGNMENT WITH IIRA

CPSs and the Internet of Things may have differences [42], but they do share similar concerns concerning integration and interoperability. IIRA is a standards-based open architecture that provides guidance and assistance in the development, documentation, communication, and deployment of Industrial Internet of Things (IIoT) systems. It benefits the interoperability of the IIoT system by emphasizing the integration of crosscutting functions (e.g., connectivity, data management, analytics, and control) and by assisting in reaching a common understanding among diversified stakeholders. IIRA supports broad applications across industry sectors, such as manufacturing, energy systems, and logistics, and can be used by business managers, operators, planners, managers, and others who want to understand better the IIoT benefits.

A. OVERVIEW OF IIRA

IIRA classifies the common concerns in designing IIoT systems into four viewpoints, i.e., business, usage, functional, and implementation viewpoints, as illustrated in Fig. 7. The business viewpoint addresses the objectives of establishing an IIoT system and further identifies the system's capabilities to achieve the stated objectives. The usage viewpoint addresses how the system components are used to achieve the stated system capabilities. The functional viewpoint frames the functional components and how these components are connected and interacted in a system structure. This viewpoint is further decomposed into five functional domains, i.e., control, operation, information, application, and business domains, as shown in Fig. 7. Each domain owns several building blocks widely applicable to many industrial verticals. The implementation viewpoint defines the needed technologies to implement the functional components and the communication schemes to support the intended usage of the IIoT systems. The choice of technologies is also guided by the business viewpoint, e.g., cost, business objectives, and go-to-market time constraints. In Fig. 7, the requirements on a lower level viewpoint are guided and defined by a higher level viewpoint. Conversely, concerns from a higher viewpoint are validated and revised by the viewpoint below them.

As seen in Fig. 7, some functional blocks (e.g., information and business) have the same names as the digitalization layers defined by RAMI4.0 (see Fig. 3), while other blocks have different names, e.g., connectivity versus communication, although they describe similar aspects. IIRA and RAMI4.0 are complementary reference architectures for IIoT systems and can enhance each other. RAMI4.0 focuses on manufacturing, and IIRA emphasizes the integration of cross-cutting functional domains.

B. GENERAL CONSIDERATIONS

The three-tier architecture (i.e., edge tier, platform tier, and enterprise tier) is recommended for the IIoT implementation in IIRA. The edge tier [43] collects data from the sensors, actuators, and controllers through the proximity network. The platform tier analyzes and processes the data and provides data services (e.g., data analytics, data query, and storage) and management functions for assets and devices. The enterprise tier feeds back control commands to the platform and edge tiers using the decision support systems. This tier also provides the application interfaces to the users and other software systems. The implementation architecture deals with the needed technologies to implement the function domains from the functional viewpoint. The data and control flows among the elements in this architecture are coordinated by the activities of different users, departments, and organizations (usage viewpoint) to realize the system's capabilities (business viewpoint).

In the three-tier architecture, software agents enable a collection of functions in the operations domain, such as provisioning, monitoring, management, and optimization of a machine or process. Therefore, IEEE 2660.1 can contribute to selecting the most appropriate integration interfaces, placed in the network connectivity domain, that regulate the data, information, and control flows between the different functional domains. In particular, the IEEE 2660.1 approach can recommend the best communication protocol to support data transfer modes (e.g., event-based, asynchronous, and streaming) between the physical system and control domain and the functions in the operations domain, encapsulated by software agents. In addition, the data and control flows between the implementation tiers and the enterprise tier are often transmitted via public Internet or corporate networks, allowing enterprise-grade security.

C. APPLICATION EXAMPLE

This section demonstrates the application of IEEE 2660.1 to the spindle health monitoring and prognosis of computerized numerical control (CNC) machine fleets, as illustrated in Fig. 8.

The health condition of the machine tool spindle is of great significance in high-precision machining, aiming to: 1) estimate and predict the spindle health, including shaft imbalance, tool degradation, bearing failure, and abnormal machining processes, by analyzing the data from CNC controller and add-on sensors; and 2) enable an Internet-based service network for the maintenance planning and scheduling of geographically distributed CNC machine fleets.

For this purpose, a software agent is embedded in an edge to collect all the device-specific data extracted by the adapter that connects the CNC controller of a 5-axis machining and to transform the data into a computer-readable format for subsequent data analysis. This data are related to, e.g., spindle load profiles, *XYZ* tool coordinates, temperature, coolant

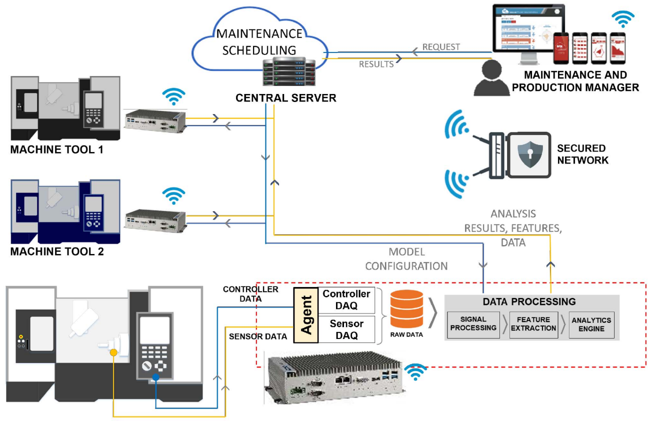

FIGURE 8. Platform for intelligent spindle health management for CNC machine.

Results						
Recomended interface practice						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		3.84
Details						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		3.84
HT-3	Hybrid	Tightly coupled	Java	DPWS		3.52
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		3.50
HT-2	Hybrid	Tightly coupled	Java	Sockets		3.28
HT-7	Hybrid	Tightly coupled	Java	OPC UA		3.20
HL-3	Hybrid	Loosely coupled	C/C++/SQL	Sockets	DBMS	3.04
HL-1	Hybrid	Loosely coupled	Apache Paho	MQTT	Eclipse Mosquitto	3.04
HL-2	Hybrid	Loosely coupled	Java	OPC-UA		2.97
HT-6	Hybrid	Tightly coupled	Java	Ethernet/IP		2.90
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		2.88
HT-1	Hybrid	Tightly coupled	Java	Modbus		1.84

FIGURE 9. Results of the recommended practice for monitoring the machine condition health (DAQ controller).

flow, electric power, spindle vibration, and three-phase motor current signals.

The collected data are used to extract important features, for example, statistical features, frequency domain features, signal patterns, and time-frequency distributions, by using pretrained machine learning models that will support the detection of abnormal machining processes and monitoring the spindle health. In this effort, both data from the CNC controller and add-on vibration sensors are collected.

For the controller data acquisition (DAQ), scalability and reusability are the most important factors for implementation, which are weighted as response time 10%, reusability 40%, and scalability 50%. Applying IEEE 2660.1 according to these assumptions, the recommended interface for the CNC controller DAQ is a tightly coupled interface using sockets with the API client using C/C++/SQL, as illustrated in Fig. 9.

Similar interface practices for client-server communications, such as the DPWS [44] with a Java-based API client and the OPC UA with Apache Milo client is also recommended by IEEE 2660.1 (second and third options, respectively, in Fig. 9). For all three recommendations, a tightly coupled

Results						
Recomended interface practice						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		3.70
Details						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		3.70
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		3.36
HT-7	Hybrid	Tightly coupled	Java	OPC UA		3.20
HT-2	Hybrid	Tightly coupled	Java	Sockets		3.18
HT-3	Hybrid	Tightly coupled	Java	DPWS		3.12
HT-6	Hybrid	Tightly coupled	Java	Ethernet/IP		3.00
HL-1	Hybrid	Loosely coupled	Apache Paho	MQTT	Eclipse Mosquitto	2.88
HL-2	Hybrid	Loosely coupled	Java	OPC-UA		2.79
HL-3	Hybrid	Loosely coupled	C/C++/SQL	Sockets	DBMS	2.56
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		2.52
HT-1	Hybrid	Tightly coupled	Java	Modbus		1.87

FIGURE 10. Results of the recommended practice for monitoring the machine's condition health (DAQ sensor).

connection between the agent and controller will be established, and the agent will run externally to the CNC controller without interfering with the low-level control activities. By comparing the first three recommendations, one can find that the use of a tightly coupled OPC UA client on a hybrid location has been widely studied and adopted for CNC machine monitoring in the recent literature [45], [46].

In comparison, the response time for the sensor DAQ is important in extracting useful features for data analysis, and thus, ensuring robust abnormal detection outcomes. Therefore, the three characteristics for sensor DAQ are weighted as response time 40%, reusability 30%, and scalability 30%. In this case, a tightly coupled OPC UA with Apache Milo Client is recommended by the IEEE 2660.1, as shown in Fig. 10.

This recommended interface provides sufficient time resolution for process abnormality detection and data trending. In addition, it holds excellent scalability and reusability. However, when a higher sampling rate ($\geq$ 1000 Hz) is intended for the frequency analysis, the recommended interface practice in Fig. 6 can be adopted. In this case, data acquisition hardware (embedded in an edge device) will be needed, and the software agent can be installed on the edge device.

VI. IEEE 2660.1 ALIGNMENT WITH SGAM

This section briefly introduces the SGAM reference architecture and discusses the alignment of the IEEE 2660.1 standard with this model. Also, a motivation example is provided for a better understanding.

A. OVERVIEW OF SGAM

The SGAM is a very well-known and nowadays widely accepted structured approach for modeling system architectures and corresponding use cases in the domain of power and energy systems that have been developed as an outcome (besides others) of the M/490 standardization mandate of the European Commission to CEN-CENELEC-ETSI. Initially developed to identify loopholes in smart grid standardization on the European level, it provides a layered concept for the aforementioned architecture development [18], [19]. As illustrated in Fig. 11, it introduces a 3-D framework consisting

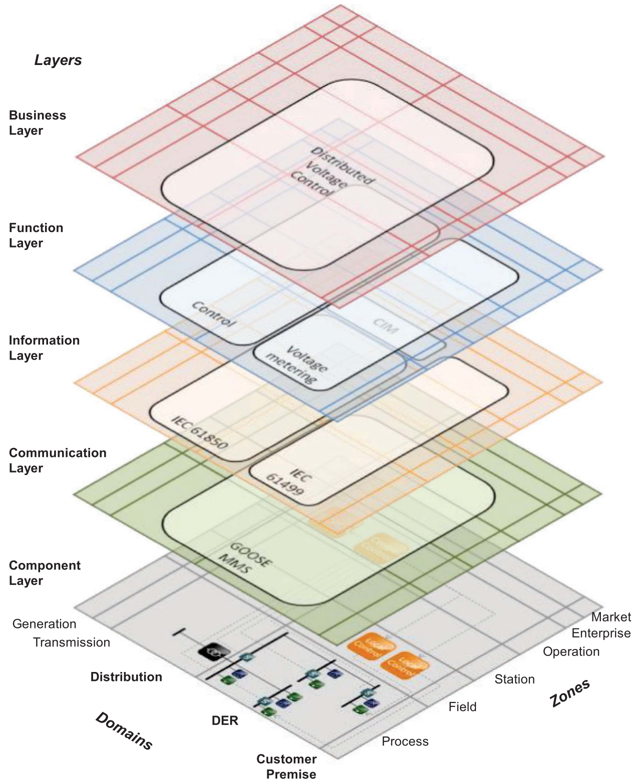

FIGURE 11. Overview of the SGAM architectural model (adopted from [18].).

of domains, zones, and (interoperability) layers. The domains represent the traditional layout of a power system infrastructure, including the generation, transmission, and distribution of electricity, besides the distributed energy resources (DER) and customer premises.

The typically hierarchical power system management is represented by the zones consisting of market, enterprise, operation, station, field, and process. These two axes of SGAM form the so-called component layer (also referred to as the SGAM plane) at the bottom, whereas four interoperability layers are put on top, representing the communication, information, function, and business-related services in a smart grid context. Due to positive experiences in various energy applications, SGAM also provided the basis for the development of RAMI4.0 and other related reference architectures in other domains, as discussed in [19].

Quite similar to RAMI4.0 (see Fig. 4), the digitalization process starts with a 2-D surface out of the 3-D-model perspective containing at least 30 cells, representing a specific component, as illustrated in Fig. 12.

By applying a bottom-up digitalization engineering approach, quite similar to the RAMI4.0, devices placed in the component layer (formed by the domains and zones) need to be digitalized following the vertical interoperability layers. The concrete implementation of the communication layer, as well as the corresponding information layer, requires the use

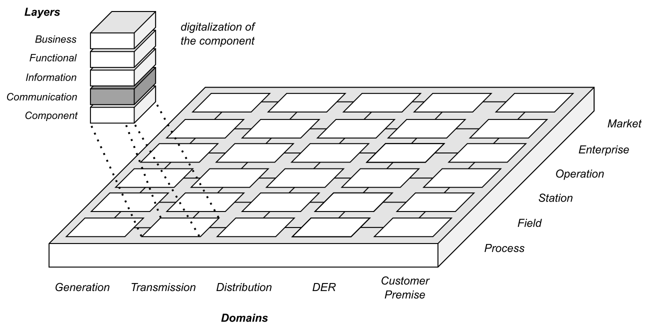

FIGURE 12. **2-D digitalization matrix of SGAM.**

Results						
Recomended interface practice						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		3.52
Details						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		3.52
HL-3	Hybrid	Loosely coupled	C/C++/SQL	Sockets	DBMS	2.72
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		2.64
HL-2	Hybrid	Loosely coupled	Java	OPC-UA		2.63
HT-2	Hybrid	Tightly coupled	Java	Sockets		2.40
HT-3	Hybrid	Tightly coupled	Java	DPWS		2.06
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		2.04
HT-7	Hybrid	Tightly coupled	Java	OPC UA		1.92
HT-6	Hybrid	Tightly coupled	Java	Ethernet/IP		1.50
HL-1	Hybrid	Loosely coupled	Apache Paho	MQTT	Eclipse Mosquitto	1.28

FIGURE 13. **Results of the recommended practice for streetlight switching without embedded agents.**

Results						
Recomended interface practice						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		3.52
Details						
Id practice	Location	Interaction mode	API client	Channel	Broker	Score
HL-4	Hybrid	Loosely coupled	Apache Paho	MQTT		3.52
HL-3	Hybrid	Loosely coupled	C/C++/SQL	Sockets	DBMS	2.72
HT-4	Hybrid	Tightly coupled	C/C++/SQL	Sockets		2.64
HL-2	Hybrid	Loosely coupled	Java	OPC-UA		2.63
HT-2	Hybrid	Tightly coupled	Java	Sockets		2.40
OL-1	On-device	Loosely coupled	REST/JSON	MQTT	Eclipse Mosquitto	2.40
HT-3	Hybrid	Tightly coupled	Java	DPWS		2.06
HT-5	Hybrid	Tightly coupled	Apache Milo	OPC-UA		2.04
OT-3	On-device	Tightly coupled	C/C++/SQL	DBMS		2.04
OL-3	On-device	Loosely coupled	Apache Paho	MQTT		1.98

FIGURE 14. **Results of the recommended practice for streetlight switching with embedded agents.**

of different technological device-level interfaces, communication protocols, and data/information models, depending on their position in the 2-D matrix and the associated application scenario and use case(s), as depicted in Fig. 4.

In summarizing, SGAM provides a structured approach where power and energy system applications and corresponding use cases can be mapped to the different interoperability layers for comparability and derivation of requirements as well as the identification of available communication protocols and information models as has been shown for example for a distributed, real-time control concept in a cell-based power system architecture [47].

B. GENERAL CONSIDERATIONS

Similar to other domains-like manufacturing and logistics, agent-based technologies can also be applied for the digitalization of solutions and devices in the power and energy systems domain. Therefore, the IEEE 2660.1 recommended practice provides a very good way to support automation engineers and ICT experts in selecting suitable communication interfaces and data models for each device/component concerning the corresponding application scenario and associated use case(s).

Such integration can be realized by the usage of different domain-specific communication approaches like IEC 61850, IEC 61400-25, IEC 60870-5/DNP3, IEC 60870-6, CIM (IEC 61970/61968), IEEE 2030.5, Modbus/SunSpec, OPC UA, OpenADR, and other approaches typically in a client–server, publish–subscribe, or producer–consumer way. Here, the IEEE 2660.1 recommendation method may help in finding the most appropriate solution for a given application scenario and related setup.

C. APPLICATION EXAMPLE

Simple but also quite complex monitoring and control actions, as well as diagnostics and (self-)reconfiguration tasks, are common for power and energy systems. In the following, the applicability of the IEEE 2660.1 methodology in the SGAM context is illustrated on a simple ON/OFFswitching of powering lights and signs along a street for energy savings.

In the first scenario, the involved simple switching relays cannot host the software agents due to computational resource constraints. Therefore, the higher level services (i.e., the control of the lighting and sign assets) that are provided by the agents are executed remotely on computing devices (typically PCs). Applying the IEEE 2660.1 method for this application, whereas the user evaluates the scalability with 60%, time response with 30%, and reusability with 10% leads to the results, as illustrated in Fig. 13.

Since the agents are constrained to run remotely due to the restrictions imposed by the user, only hybrid approaches are recommended, with the {Hybrid, Loosley Coupled} approach, implemented with Apache Paho as API client and MQTT as a communication channel, being the recommended interface practice for the above outlined application scenario. This is aligned with the objective of performing control tasks and having scalability as the most relevant criterion, since *loosley coupled* approaches typically scale better than *tightly coupled* ones.

In contrast to the first scenario, the second one uses instead of simple ON/OFF switching relays embedded control units that can host agent technology. By using the same evaluation criteria as for the first scenario (i.e., 60% for scalability, 30% for time response, and 10% for reusability) the results, as shown in Fig. 14, are being obtained.

Again, the {Hybrid, Loosley Coupled} approach with Apache Paho and MQTT as API client and communication channel are the most promising setup. On-device practices for this application scenario are not so relevant since the user rates the scalability as the most important criterion.

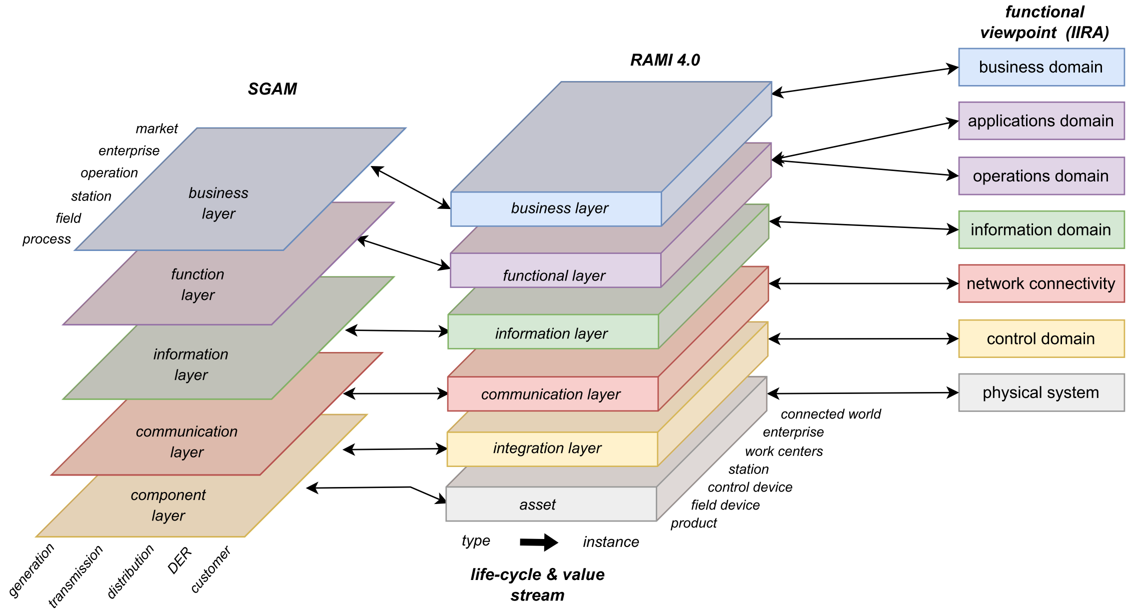

FIGURE 15. Mapping the three reference architectures considering the digital layers perspectives.

VII. DISCUSSION ON APPLYING IEEE 2660.1 TO REFERENCE MODELS

In the following, feasibility aspects, common themes as well as insights when applying the IEEE 2660.1 recommendation method is applied to RAMI4.0, IIRA, and SGAM are being discussed.

A. FEASIBILITY ASPECTS FOR UTILIZATION

In the effort to address the posed RQs, several aspects have emerged that can be discussed and critically viewed. RQ1 with the aim to demonstrate how IEEE 2660.1 can be used for scenarios that are based on the RAMI4.0, IIRA, and SGAM-based architectures, has so far been the core of the presentations in Sections IV–VI.

The three reference architectures address different application sectors, with RAMI4.0 focusing on smart digitalized and networked industrial production, SGAM focusing on smart grids, and IIRA focusing on more diverse sectors, including smart production, smart grids, and smart logistics. The presented examples provide an understanding of a potential path toward utilizing IEEE 2660.1 in conjunction with each architecture. Therefore, it is demonstrated that at some level, the generic workflow and the steps provided by IEEE 2660.1 can be beneficial when it comes to the design and development of ICPS approaches that also consider aspects of each of the three reference architectures.

B. COMMON THEMES

RQ2 attempts to investigate the underlying mechanics and focus on the commonalities, where IEEE 2660.1 could be utilized in all three approaches. This is a challenging question to answer, not only because of the complexities involved but also because the different presented scenarios have significant differences in their starting and ending points, as well as the aspects they consider in each architecture and how they integrate them.

One may hypothesize that some aspects are common along RAMI4.0, IIRA, and SGAM frameworks, and indeed their evolution has been partly coinfluenced, e.g., RAMI4.0 has been inspired by SGAM [48]. Therefore, they can be treated in a uniform way when it comes to the application of IEEE 2660.1 to solutions that are based on these standards. Indeed there have been efforts in the past to demonstrate a mapping among some of the architectures, although mainly bilaterally. A high-level mapping between the layers of the three investigated architectures is depicted in Fig. 15.

The RAMI4.0 and IIRA alignment, including differences and white spots, has been investigated [49]. It is pointed out that IIRA and RAMI4.0 are complementary, and assets play a pivotal role in both, while there are clear mappings between the functional domains and the RAMI4.0 layers [49], as also shown in Fig. 15. However, there are differences among them at conceptual and realization levels, as discussed in different studies [49], [50], [51], [52].

With respect to SGAM which focuses on the energy domain, Fig. 15 also depicts how its "Interoperability Layers" can be mapped into the "Digitalization and Networking Layers" of RAMI4.0. The mapping is straightforward since, conceptually, they share common ground for most layers, and also, the mapping to IIRA can be inferred via RAMI4.0 layers. Indeed, IIRA aims to cover several industries, including the energy one; hence such mappings among SGAM and IIRA might provide additional benefits for modeling and understanding smart grid infrastructures.

Related to the digitalization process that is required by the three reference architectures, several commonalities, and

TABLE 1. Characterization of Commonalities and Differences of Using IEEE 2660.1 in the Three Reference Architectures

Characteristics	Commonalities	Differences
Scope	Aim to support the development of smart and connected systems, processes, and products	Focus on different sectors: RAMI4.0 at smart production, SGAM at smart grids, and IIRA at a wider perspective, including smart logistics, smart health, and smart grids.
Role of software agents	Provide intelligence and collaboration models during the digitalization process of assets	The layer where they are placed is different, namely the function layer at SGAM, the functional layer at RAMI4.0, and the applications and operations domains' layers at IIRA.
Lifecycle coverage	All reference architectures address the lifecycle perspective	The dimensions/phases of the lifecycle are different; for example, RAMI4.0 focuses on the lifecycle of the assets, IIRA the different viewpoints, and SGAM the different domains.
Assets to be digitalized	A vertical dimension aiming for the digitalization of assets is considered in all reference architectures Assets can be physical hardware and software objects	The nature of the assets is related to the sector that the reference architecture is targeting, for example, automation-related assets in RAMI4.0, like robots, PLC, CNC machine, ERP and SCADA systems, energy-related assets in SGAM like a smart meter, smart transformers, DER, switchgear, loads, control system/IEDs/SCADA, and a diversity of assets related to the target sector in IIRA, like robot, PLC, sensor, load, and switch.
Contribution of IEEE 2660.1	Support the interface between the asset controller and the software agent	The layer the interface is covering is different, namely the communication layer at SGAM and RAMI4.0, and the network connectivity layer at IIRA.

differences can be identified, summarized in Table 1, as well as the need to have assets placed at different stages of the lifecycle/value-stream, and different levels of the management and control hierarchy.

The type of assets in each one of the domains covered by the discussed reference architectures is different, for example, mainly referring to robots, PLCs, and motors when considering production systems, while mainly referring to smart meters, smart transformers, DER, switchgear, loads, and control systems/IEDs/SCADA when considering smart grids. The digitalization of the assets requires the integration of the physical asset with the cyber part (e.g., an agent) and the Internet-based connectivity and interoperability. For this purpose, the three reference architectures provide a digitalization dimension in their proposed model that includes a specific layer that is responsible for this accomplishment; the integration layer complemented with the communication layer in RAMI4.0, the communication layer in the SGAM and the network connectivity (as part of the functional viewpoint) in IIRA, as illustrated in Fig. 15. This layer in each reference architecture provides different realizations toward the same objective.

The asset can be placed at different hierarchical levels and along different stages of its lifecycle, demanding different technological requirements for its integration. In the same manner, several standards are available to perform this integration, with the particularities of each scenario application imposing different technological solutions.

Overall there is a need to link the digital representation of an asset within the scope of a specific architecture. The IEEE 2660.1 standard contributes by simplifying the selection of the most appropriate technological interface practice according to the application requirements, providing recommendations related to the standard that should be used for each case. In particular, as illustrated in the previous sections, IEEE 2660.1 can be used during the digitalization process defined by the three reference architectures, providing the recommended technological interface practices for assets placed in different sectors (energy, industry, etc.) and at different stages of their lifecycle.

C. INSIGHTS ON UTILIZATION

The aim of RQ3 is to consolidate lessons learned from experiences in applying IEEE 2660.1 (related to RQ1) and investigating the commonalities and delimitations (RQ2). Some important lessons learned can be pointed out. However, it has to be considered that such lessons reflect only a fraction due to the limited application of the IEEE 2660.1; however, even if limited, they are still beneficiary for those considering undergoing similar efforts.

IEEE 2660.1 provides a workflow that enables the assessment of different technology combinations driven by community experiences. Hence, it is not a surprise that it can be applied to the particularities of each reference architecture focusing on the digitalization of assets, which strongly benefit from the technological recommendations provided by following the processes described in the IEEE 2660.1 standard.

Nevertheless, some limitations were observed. For example, the recommended method is strongly dependent on the feedback from experts and particularly pointing out the best interface practices for the diversity of sectors addressed by the several reference architectures. Several benchmarks for different technological combinations must be realized to have a harmonized and representative scoring for a specific practice.

However, such an exhaustive search is only sometimes the case. This bears the potential challenge that only a handful of approaches may exist and be proposed as best practices, while others may not, because they need to be sufficiently represented in the database (e.g., the experts did not submit an assessment and relevant scores).

New technologies and uncommon combinations entering the repository of best practices may need time to be trusted and demonstrate their benefits against other, more traditional approaches. It is strongly recommended to maintain an updated repository of scored interface practices accompanying the technology evolution in this area. In particular, it is important to have a collection of scored interface practices for each sector with sufficient representative cases and trusted assessments. In addition, such assessments need to be realized in a proper methodological manner that guarantees a common or similar baseline and trust in the mechanics behind the assessment. A potentially biased or poorly conducted assessment could lead to costly mistakes, especially if some efforts are scaled up within a domain, for example, to millions of smart meters in the energy domain.

Even if all processes and methodological steps are sufficiently fortified, there is a significant variance when it comes to the particularities of each use case, and what makes a good interface practice for one sector (or even use case) may not be the most obvious or best candidate for another sector or use case. Such specificities are attempted to be captured by IEEE 2660.1 behind the scores given and the algorithms for recommendations; however, to what extent these are sufficient needs to be further investigated.

In addition, the selection of the recommended practice may be dependent on additional criteria rather than response time, scalability, and reusability, which are defined in the standard. For instance, data volume and frequency of data exchange could be important criteria for the decision in the three reference architectures, which require need to be considered in the assessment of the collected interface practices and in the multicriteria function. Synchronization and data models regarding the exchanged data are not directly considered in the IEEE 2660.1 standard, which requires proper articulation with other standards related to these aspects. While potentially such aspects may be somehow captured in some of the metrics at some level, to what extent the impact of it is sufficiently represented in the composite score is not clear, and this might be decisive for a specific practice recommendation.

A big part of understanding the user's needs and proposing best-of-breed technologies means also understanding the operational context of the solution. While this standard makes some assumptions that all stakeholders have a good and similar understanding of such context and, for example, define performance in the same manner, this is expected to be challenging as solutions and application domains grow. Interoperability overall [53] is a key factor for Industry 4.0 and smart grid success. Especially semantic interoperability and even mapping across standards in the same or different domains would be needed to be taken into consideration by the recommendation engine proposed by IEEE 2660.1. Therefore efforts utilizing modern machine learning techniques that enable the creation of knowledge graphs and which could automatize the process could play an important role in finding semantic interoperability and potential conflicts in cross-domain standards [54].

VIII. CONCLUSION

The IEEE 2660.1 is a recently published standard that aims to suggest the best technological practice to integrate industrial agents and automation assets. In the context of digital transformation, using this standard can strongly contribute to supporting the digitalization process of assets by providing recommendations on the best interface practices for the asset and application requirements. This work discusses how the standard could be used within the three different reference architectures, namely, RAMI4.0, IIRA, and SGAM, based on exemplary application scenarios, particularly its applicability (RQ1), the commonalities, and differences (RQ2), and the limitations and challenges (RQ3).

It has to be considered that IEEE 2660.1 is a very young standard. Its usefulness will be judged over time by its usage in practice and evaluation of the benefits it attempts to deliver and how it can support the industry and the energy sectors, among others, in their digital transformation process. It should act as an enabler for the digital business models of the enterprise [2] while empowering engineers to select the best-of-breed technologies to realize the required smart applications and services efficiently. In the meantime, it is possible to reinforce that it offers a good way to set a base for best practice recommendations regarding technological aspects among different assessments. In addition, it has been shown that it is applicable and compatible at a high technical and functional level with existing approaches to design, develop, and operate ICPS, while at the same time showing that also links well to reference architectures, such as RAMI4.0, IIRA, and SGAM. However, such efforts are still at the beginning. They need to be investigated further in more detailed and elaborated scenarios to uncover further limitations or aspects that need to be clarified. Moreover, there is a need for further research identifying limitations that should conduct to potential enhancements of the standard or provide clear pathways for utilization of it in the different domains it attempts to cover. Future directions can be devoted to overcoming some of the identified limitations, namely, updating the catalog of assessed interface practices, particularly covering different application sectors, and including additional criteria that fit the needs of the three reference architectures.

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