Manufacturing Digital Twin Standards

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ABSTRACT

As a foundation of digital transformation, digital twins are critical for achieving smart manufacturing. Recent technology advancements, such as smart sensors, the Internet of Things (IoT), cloud computing, machine learning, and artificial intelligence (AI), have enabled digitalization in manufacturing and facilitated the development of digital twins in manufacturing. However, because of its interdisciplinary nature and complexity, guidance is still needed for the implementation of digital twins in manufacturing systems to ensure that the digital twin developed is trustworthy. This paper discusses manufacturing digital twin use cases, benefits, common challenges for implementing digital twins, relevant standards organizations, and industry consortia efforts, as well as ongoing efforts towards digital twin standards, focusing on the ISO standard, ISO 23247 - Digital Twin Framework for Manufacturing, and discusses digital twin standards development procedures.

CCS CONCEPTS

General and reference → **Document types** → General literature

KEYWORDS

Digital Twins, Standards, Manufacturing

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1 INTRODUCTION

Digital twin technology is a foundational element for digital transformation due to its ability to bridge the physical and digital spaces, providing a comprehensive and real-time representation of physical assets, processes, or systems. Digital twins can help achieve smart manufacturing by enhancing efficiency, productivity, and sustainability across various stages of a product lifecycle. Digital twins allow manufacturers to experiment with product designs, production methods, and new technologies in a virtual environment before implementing them on the factory floor. Their ability to simulate and test different scenarios in a virtual environment allows for agile responses to dynamic business requirements, which enables manufacturers to quickly adapt to changes in demand, market conditions, or product designs. Digital twins also enable collaboration among different functional units in an organization and stakeholders involved in the manufacturing process, even from a remote location. The shared digital representation enables better and easier communication, coordination, and decision-making across the entire enterprise. With the insights gained from digital twins, manufacturers can continuously improve their design, planning, and operation for products, processes, and systems; they can also implement data-driven strategies to improve overall performance and competitiveness.

1.1 Digital Twin Use Case Categories and Examples in Smart Manufacturing

Digital twins drive the transformation of traditional manufacturing systems into smart manufacturing systems that are more connected, intelligent, and adaptive. A few common digital twin use case categories and associated examples in smart manufacturing are briefly discussed as follows. More use case scenarios can be found in [1].

Real-Time Monitoring and Control: Digital twins provide real-time insights into the status, behavior, and performance of physical assets, equipment, systems, and processes on the manufacturing floor. This enables continuous monitoring and control, allowing immediate adjustments to optimize production and quickly make informed decisions. For example, in a Computer Numerical Control (CNC) milling operation, real-time monitoring and control digital twins constantly collect data on cutting forces, tool temperature, and tool wear. Based on these data, the digital twin dynamically adjusts cutting parameters such as feed rate and spindle speed to optimize the machining efficiency and maintain the part quality. If excessive tool wear is detected, the digital twin can automatically compensate by adjusting cutting parameters or commanding a tool change to ensure uninterrupted production.

Predictive Maintenance: By continuously collecting real-time data from sensors and historical data sources, digital twins can model and simulate potential scenarios and predict when equipment or machinery will likely fail. This enables predictive analytics, allowing manufacturers to anticipate issues and optimize resource allocation. This predictive maintenance capability minimizes unplanned downtime, reduces maintenance costs, and increases the productivity of manufacturing systems. Take the CNC milling process as an example; sensors can help continuously monitor spindle parameters such as temperature, vibration, and bearing conditions. The data are collected, processed, and inputted to the digital twin of the milling machine, in which machine learning algorithms may be used to predict spindle bearing failures. The digital twin can then direct the maintenance team when the spindle bearings are approaching failure, allowing them to schedule proactive maintenance activities, such as bearing replacement, during planned downtime.

Production Process Optimization: Digital twins can model and simulate manufacturing processes, enabling manufacturers to identify bottlenecks, optimize workflows, and improve overall production efficiency. This will result in better resource utilization and increased throughput. For instance, for a CNC machining process, real-time data from sensors on the machine and cutting tools can be collected and provided to the digital twin. The digital twin can then be used to simulate the machining process and optimize the toolpath, machining parameters, and tool selection to maximize quality and efficiency. Adaptive control strategies can help adjust machining parameters dynamically based on real-time feedback from the digital twin, ensuring optimal performance to minimize the production time.

Quality Assurance: Digital twins can help monitor and improve product quality by simulating and analyzing various production scenarios. Any deviations from quality standards can be detected early in the virtual environment to reduce defects. For example, CNC sensors can measure parameters such as tool position, spindle speed, feed rate, and cutting forces, while cameras can capture images of the machined parts. The real-time data from sensors and cameras are transmitted to the digital twin, where virtual inspections can be performed to compare the machined parts against the part digital twin. The digital twin analyzes the data to monitor key quality parameters, such as dimensional accuracy and surface finish, and generates reports for any deviations from specifications.

Energy Consumption Optimization: Smart manufacturing emphasizes sustainable and energy-efficient practices. Digital twins help identify opportunities to optimize energy consumption, reduce waste, and enhance overall sustainability in manufacturing operations. For example, in a CNC machining operation, meters and sensors can be used to measure electricity consumption, motor loads, and coolant system usage. Real-time data from these sensors are processed and transmitted to the digital twins, where energy consumption patterns can be analyzed and optimized. The digital twin provides insights into energy usage trends, recommends operational parameters or scheduling adjustments to optimize energy efficiency, and provides alerts for deviations from expected energy consumption levels.

Supply Chain Optimization: Digital twins can also support supply chain optimization. By modeling and simulating the entire supply chain, organizations can optimize logistics, reduce lead times, and improve overall supply chain efficiency. For example, to prepare a CNC machining operation, the supply chain digital twin integrates real-time data from suppliers (on raw material availability), production facilities (on production schedules), inventory systems, and transportation logistics providers and continuously analyzes the data to optimize production planning, inventory management, and order fulfillment. The digital twin provides insights into demand fluctuations, production capacity constraints, and supply chain risks, enabling proactive decision-making and optimization of supply chain processes.

1.2 Common Challenges for Manufacturers Adopting Digital Twins

While digital twins offer significant benefits for manufacturers, their implementations can be accompanied by various challenges at this time. In addition to issues such as extra cost for digitalization, specific expertise needed for digital twin development, and culture change, some common challenges that manufacturers may face when adopting digital twins include [2] [3] [4]:

- **Problem Complexity and System Integrations**: Developing and integrating digital twins into existing systems and processes can be complex. Compatibility issues and the need for interoperability with different technologies and legacy systems could be very costly.
- **Data Quality**: Digital twins rely on accurate and real-time data. Ensuring data quality, integrity, and security can be challenging, especially when dealing with data from various sources, including sensors, models, databases, systems, and human inputs.
- **Data Security**: Digital twins need to handle sensitive and critical data. Security issues related to data breaches, cyberattacks, and unauthorized access need to be addressed.
- **Scalability**: Scalability is a significant challenge because developing digital twins that can effectively scale to accommodate large and complex manufacturing operations is difficult.
- **Interoperability and Standardization**: Like the interactions among physical elements in the real world, digital twins of

these physical elements need to interoperate. Lack of standardized practices and interoperability between different digital twin implementations can hinder the development and integration of digital twins and collaboration across industries and value chains.
- **Validation and Verification**: Without verification and validation (V&V), digital twins could deviate from its intended use. However, ensuring that the digital twin accurately represents the physical system and performs reliably under various conditions is challenging.
- **Interdisciplinary Collaboration**: Developing a digital twin requires expertise from multiple disciplines such as engineering, information technology, and operations. Interdisciplinary collaboration is often needed to achieve a common goal. Coordinating this collaboration effectively can be difficult.

To address these challenges, manufacturers can leverage the experiences of other adopters, seek expert advice, and continuously establish, assess, and refine their digital twin strategies. Most importantly, manufacturers should advocate for industry standards, participate in relevant standardization development and adoption, and select technologies that adhere to existing standards.

1.3 Examples of Required Standards

During the development, implementation, and operation of manufacturing digital twins, standards can not only provide guidelines and a framework for implementing digital twins but also define common rules, specifications, protocols, data formats, and interfaces that ensure consistency and compatibility across different systems in achieving interoperability. Standards enable vendor neutrality, meaning the standards are not tied to proprietary technologies. Various vendors and solutions providers that comply with the same standards will guarantee compatibility and interchangeability of data, models, components, or systems, which in turn help reduce development and maintenance costs. Applying standards will contribute to the overall success and adoption of digital twin technologies. A few examples of different types of standards and their benefits are briefly discussed below.

- **Interoperability**: A digital twin involves highly complex collections of data and functional sub-systems, including data collection, data processing, data communication, data modeling, data analytics, data visualization, modeling and simulation, optimization, and control. In addition, digital twins need to interact with many other devices, systems, and software applications to achieve their goals. Some of these systems could be distributed. There are significant challenges to seamlessly integrate these systems with data in various formats, e.g., sensor data, human inputs, 3D models, and simulation results. Standards can provide a common framework and language, ensuring that different components from various vendors in different formats interoperate effectively. This interoperability is essential not only for creating a cohesive and integrated digital twin ecosystem but also for supporting the development and adoption of digital twins.
- **Consistency**: Standards help ensure consistency in the design, development, and implementation of digital twins. This consistency is vital for achieving reliability, predictability, uniformity, and reusability in digital twins developed and operated across various applications and industry domains.
- **Data Sharing and Data Integration**: Digital twins rely on data from various sources, including sensors, databases, models, systems, and human users. Standards for data formats, protocols, and communication enable efficient exchange and integration of data. This, in turn, supports the accurate representation and validation of the physical element/system/process by the digital twin and enhances the overall performance of the digital twin.
- **Digital Twin Security**: Digital twins often deal with sensitive and critical data; security is paramount. Digital twin security standards can help establish best practices for securing data, communications, and access control, reducing vulnerabilities, and ensuring that cybersecurity is emphasized.
- **Scalability**: Standards facilitate the scalability of digital twin implementations. As the complexity and scale of digital twin projects increase, applying standards can allow for better and easier expansion and integration of new components or functionalities without compromising the overall system integrity.

In section 2, the paper discusses major Standards Development Organizations (SDOs) and industry consortia that work on the topics of digital twins and highlights their relevant efforts. Section 3 focuses on an ISO digital twin framework standard, ISO 23247, provides an introduction of the four parts including the reference architecture and the functional entities, and summarizes some lessons learned from applications of the standard. Section 4 discusses the importance of existing standards that can be leveraged for developing manufacturing digital twin use cases. Section 5 discusses typical standards development procedures. Finally, section 6 presents the conclusions and discusses future work.

2 STANDARDS DEVELOPMENT ORGANIZATIONS AND INDUSTRY CONSORTIA WORKING ON DIGITAL TWINS

The development of digital twin standards has only started recently. It is an ongoing process, and a number of SDOs are establishing guidelines and standards for implementing digital twins. A few standardization efforts have contributed to the advancement of digital twins in various industries. Some key organizations involved in digital twin standardization include:

- **ISO (International Organization for Standardization)**: ISO is an independent, non-governmental, international SDO composed of representatives from the national standards organizations of member countries. ISO develops and publishes international standards in technical and non-technical fields, ranging from manufactured products and technology to food safety, transport, information technology, agriculture, and healthcare. ISO has been actively working on standards related to digital twins. ISO/TC184/SC4 is the technical committee responsible for Industrial Data and has published ISO 23247 [5], a digital twin framework standard for manufacturing, which provides a comprehensive framework to support manufacturers for building their digital twins.

- **IEC (International Electrotechnical Commission)**: IEC is an international standards organization that prepares and publishes international standards for all electrical, electronic, and related technologies. ISO/IEC/JTC1/SC41 works on standards in the area of Internet of Things (IoT) and Digital Twin. Recently published two digital twin standards: ISO/IEC 30173 - Concepts and terminology [6] and ISO/IEC TR 30172 - Use cases [7]. IEC/TC65 is working on Industrial-process measurement, control, and automation. A recently published standard by IEC/TC65, IEC 63278-1:2023, defines the structure of a standardized digital representation of an asset, called Asset Administration Shell (AAS) [8], which supports the implementation of manufacturing digital twin applications.
- **IEEE (Institute of Electrical and Electronics Engineers)**: IEEE is a professional association for electronics engineering, electrical engineering, and other related disciplines. The IEEE Standards Association (IEEE SA) is an operating unit within IEEE that develops global standards in a broad range of industries, including power and energy, artificial intelligence systems, internet of things, consumer technology and consumer electronics, biomedical and health care, learning technology, information technology and robotics, telecommunication, automotive, transportation, home automation, nanotechnology, information assurance, emerging technologies, and many more. IEEE P2806, System Architecture of Digital Representation for Physical Objects in Factory Environments, is one of the standards supporting the development of digital factories/digital twins. It describes the objective, components, data sources required, and procedure of digital representation in factory environments [9].
- **OMG (Object Management Group)**: The OMG SDO is a global, open-membership, non-profit consortium. They create technological standards for a diverse range of vertical industries. As an industrial consortium under OMG, the Industry IoT Consortium (IIC) focuses on driving deployments of innovative technology solutions that digitally transform businesses. IIC and the Plattform Industrie 4.0 worked together to align their reference architectures, i.e., the Plattform Industrie 4.0's RAMI 4.0 and the IIC's Industrial Internet Reference Architecture (IIRA) [10]. The IIC Digital Twin Interoperability Task Group (DTITG) has published a technical report on "Digital Twin Core Conceptual Models and Services [11]." Digital Twin Consortium (DTC) is another industry consortium under OMG that promotes the development, adoption, and standardization of digital twin technologies. DTC unifies industry, academia, and government to advance digital twin technology and brings together organizations from various sectors, including manufacturing, healthcare, transportation, and energy, to collaborate on advancing digital twin standards and best practices. The consortium's activities support cross-domain standardization efforts, creating a common foundation for interoperability and knowledge sharing. DTC focuses on defining the vocabulary, taxonomies, guidelines, and frameworks for digital twin technology. A DTC white paper on the "System-of-Systems Model Enabling Interoperability for Value Creation" will be published soon. The white paper introduces the System of Systems (SoS) concept, discusses SoS applications to digital twin systems, and emphasizes SoS composability and interoperability for value creation.
- **ASME (American Society of Mechanical Engineers)**: ASME is an American professional association that promotes the art, science, and practice of multidisciplinary engineering and allied sciences around the globe via continuing education, training and professional development, codes and standards, research, conferences and publications, and government relations. ASME is thus an engineering society, a standards organization, a research and development organization, and an advocacy organization. ASME has established a Digital Twin Task Group under the ASME Technical and Strategic Advisory Board. The group is tasked with identifying and evaluating industry needs and developing guidance materials to effectively implement digital twin applications [12]. In addition, the ASME VV50 Subcommittee, Verification and Validation of Computational Modeling in Advanced Manufacturing is creating a guideline for Computational Model Verification, Validation, and Uncertainty Quantification (VVUQ). Once completed, the guideline of VVUQ interaction with model lifecycle will help manufacturers better manage the validity and credibility of their models for advanced manufacturing applications. The guideline will also support the VVUQ interaction of digital twins, even though digital twins involve more than just computational models. For example, VVUQ with changes in the physical element, data measurement, data collection, data transmission, result interpretation, and controls must also be continuously performed [13].
- **The Open Platform Communications (OPC) Foundation**: The OPC Foundation develops and maintains the OPC Unified Architecture (OPC UA) standards, which are crucial for secure and reliable data exchange in digital twin implementations [14]. The OPC standards are widely used in industrial automation systems and applications to support interoperability, scalability, security, and reliability. Some of the main standards developed by the OPC Foundation include: (1) OPC Classic, including specifications for data access (OPC DA), alarms and events (OPC A&E), historical data access (OPC HDA), OPC Batch, and OPC Security; (2) OPC Unified Architecture (OPC UA), including specifications for data access (OPC UA Data Access), alarms and events (OPC UA Alarms and Conditions), OPC UA Historical Access, OPC UA Programs, OPC UA Safety; (3) OPC UA PubSub, a communication model that supports publish-subscribe messaging patterns in addition to the traditional client-server model; and (4) OPC UA Companion Specifications, A series of specifications are developed in collaboration with industry organizations to define how OPC UA should be used within specific industries (e.g., robotics, machine tools, energy systems), for example, the MTConnect-OPC UA Companion Specification, is to ensure interoperability and consistency between MTConnect specifications and the OPC UA specifications, and devices and software that implement those standards. The specifications are developed jointly by the MTConnect Institute and OPC Foundation [15].
- **Industrial Digital Twin Association (IDTA)**: IDTA focuses on advancing the concept of the digital twin in industrial

settings. As part of its mission, the IDTA collaborates with various stakeholders to develop standards and guidelines that promote the use of digital twins in industry [16]. A major contribution to digital twin standards by IDTA is the AAS standard, which is a crucial component of the Industry 4.0 initiative, enables the digital representation and consistent data exchange of an asset, forming the basis for interoperability between digital twins. Industry 4.0 promises to create value through the cross-manufacturer exchange of information with industry-neutral standards for communication, services, and semantics. An asset is an object that is to be integrated into the information world of Industry 4.0. There is a large range of possible assets - from machines and their components, supply materials, products, and software to documents such as plans, contracts, or purchase/service orders. A digital twin contains all the information that defines the characteristics and behavior of its corresponding asset. AAS consists of a series of submodels that describe all the data and functions of a particular asset, such as characteristics, properties, states, parameters, measurement data and capabilities. These AAS modeling capabilities facilitate digital twin development for Industry 4.0 to provide full interoperability and simplify data management for non-intelligent and intelligent devices alike. AAS makes it possible to use different communication channels and applications and connects objects to the networked, digital and decentralized world. AAS also allows a cross-manufacturer exchange of information with industry-neutral standards and accompanies the entire life cycle of devices, machines, and plants.

3 ISO DIGITAL TWIN FRAMEWORK STANDARD

This section introduces the digital twin framework standard, ISO 23247 - Digital Twin Manufacturing Framework. The standard guides and supports the development of digital twins in manufacturing by providing a generic development framework that can be instantiated for case-specific implementations of digital twins in manufacturing. The standard defines a “Digital Twin in Manufacturing” as “A fit-for-purpose digital representation of an observable manufacturing element (OME) with synchronization between the manufacturing element and its digital representation.” An OME could be any physical artifact, process, or behavior on the manufacturing floor (e.g., personnel, equipment, materials, processes, facilities, assets, and systems) [5].

The standard includes four parts: (1) Overview and general principles, (2) Reference architecture, (3) Digital representation of physical manufacturing elements, and (4) Information exchange. The standard provides guidelines, methods, and approaches for analyzing modeling requirements, defining scope and objectives, promoting the use of common terminology, and providing a generic reference architecture for implementing manufacturing digital twins. The standard also helps facilitate the composability of digital twins and interoperability among various domains and entities by applying existing relevant standards. It provides examples of data collection, modeling and simulation, communication, integration, visualization, and control. Figure 1 shows the functional view of the digital twin framework for manufacturing [17].

This framework reference architecture consists of multiple functional entities in each domain, i.e., User domain, Digital Twin domain, and Data Collection and Device Control domain. Each functional entity (FE) performs specific tasks. For example, as one of the functional entities within the Application and Service sub-entity in the Digital Twin Entity, Simulation FE is responsible for simulating the OME according to the scope and context of the application. Applications of the framework do not necessarily need to implement all the possible functional entities; only those relevant to the use case need to be selected and implemented. Therefore, it is possible that a digital twin may not even have the simulation functionality. The methods and tools chosen to model a digital twin depend on the purpose of the digital twin [4]. Shao et al. [18] performed an extensive analysis of the digital twin framework standard.

Ferko et al. [19] studied that, to what extent, the current digital twin architectures documented in literature are aligned with the reference architecture presented in the ISO 23247 standard. 29 digital twin architectures in manufacturing from 140 peer-reviewed papers were analyzed against the ISO 23247 reference architecture and misalignment report was generated. They also performed a survey with 33 respondents and conducted four semi-structured, in-depth expert interviews. The study found that several multinational companies have used the ISO 23247, although its adoption is still in its early stages. The study also reported that the current digital twin architectures mostly focus on functional aspects, neglecting non-functional entities related to, e.g., security and maintainability. None of the analyzed cases implements the Plug-and-Play Support, Peer Interface, and Data Assurance FEs, while only one case implemented the Access Control FE. Reasons for that could be the different maturity levels of the current digital twin applications and the challenges associated with implementing certain FEs. They also identified that two functionalities (i.e., Data Storage and Digital Twin Versioning) found in use cases are not supported by the ISO 23247 reference architecture. Participated survey respondents and experts believe that aligning with the ISO 23247 reference architecture is pivotal for tackling challenges, such as interoperability and evolvability, but the standard needs to be extended with additional FEs to address new manufacturing requirements. A new part will address some of these issues.

Wallner et al. [20] applied ISO 23247 for digital twin applications in flexible manufacturing cells to reduce the implementation effort for system installation and update. The main OMEs were machine tools, robots, peripheral devices such as autonomous mobile robots, manufacturing utilities such as tools, and processes. Various information systems depend on or interact with these manufacturing cells. They identified some additional requirements for improving ISO 23247 in order to address their needs: (1) the standard needs to provide mappings for basic use cases such as CAD/CAM to the functional entities in the user domain; (2) the characteristics of each life cycle stage of the digital twin itself are needed to support the change analyses within the

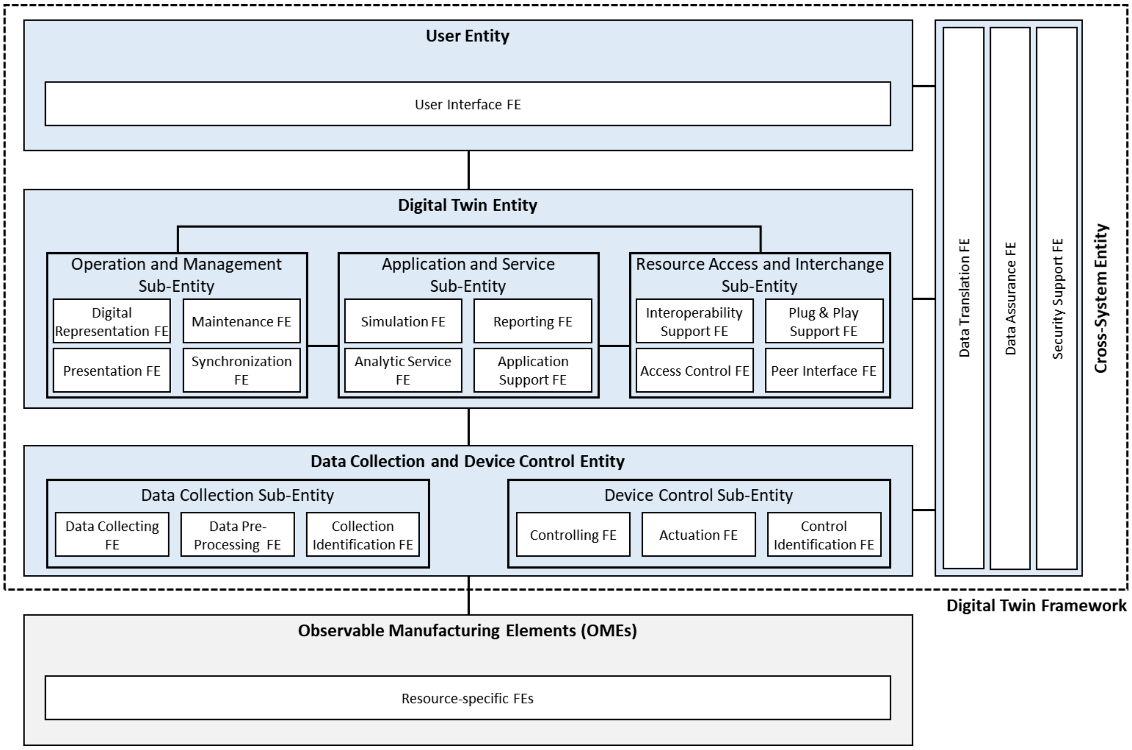

Figure 1: Functional view of the digital twin framework for manufacturing [17].

digital twin, a life cycle meta layer could help for the reconfiguration of flexible manufacturing cells; and (3) as one of the three core aspects in the transition into Industry 5.0, human-centric should be considered in future revisions of the standard.

4 LEVERAGING EXISTING STANDARDS

Since the development of digital twin standards only started a few years ago, fewer standards have been specifically completed for digital twins. However, existing standards for data collection, data security, information modeling, simulation, visualization, and networking can be leveraged when developing digital twin components and systems. With these relevant standards from various functional categories, users can select those applicable to their digital twin implementations. For example, to create a digital twin of a CNC machining process, ISO 23247 can be used as a guideline for defining digital twin requirements, applying the standard reference architecture, and designing components of the digital twin. AAS can be used to digitally represent assets such as machine spindles, cutting tools, and parts [8]. STEP (Standard for the Exchange of Product model data) [21] can be used to represent the part, the tools, and the machine designs, the MTConnect [22] protocol can be used for collecting the real-time operational status data of the machine tool when cutting the part, OPC-UA [23] can also be used to communicate data and control commands between the machine and its digital twin, and QIF (Quality Information Framework) [24] can be used to represent the product inspection result. These existing standards, as examples, are briefly discussed as follows.

- **STEP**: ISO 10303, Automation Systems and Integration - Product Data Representation and Exchange, also known as STandard for the Exchange of Product model data (STEP), supports the computer-interpretable representation and exchange of product manufacturing information. It can represent 3D objects in Computer-aided design (CAD) and related information, which can be used to model 3D parts/products and equipment [21]. For example, the STEP standard will help create a comprehensive digital representation of a CNC machine, including geometry, kinematics, and control parameters.
- **Asset Administration Shell (AAS)**: AAS is the central concept of Platform Industry 4.0 to enable interoperability [10], enabling more intelligent, connected, and autonomous industrial systems. AAS provide a structured framework for representing digital twins of industrial assets. The AAS submodels represent specific aspects or domains of the asset, such as operational data, maintenance, or configuration parameters. Each submodel contains a set of properties and operations relevant to its domain. For example, using AAS to represent a CNC machine and its components can encapsulate all relevant information, functionalities, and services associated with the assets and enable the digital twin to be easily integrated into an Industry 4.0 framework.
- **MTConnect**: MTConnect is a domain-specific semantic vocabulary for manufacturing equipment. It provides

structured, contextualized data with no proprietary format. MTConnect data sources include equipment such as machine tools, robots, coordinate measuring machines, sensor packages, and other factory floor hardware [22]. It supports digital twin interoperability by providing operational data for real-time equipment, e.g., real-time machining status. Digital twin applications using MTConnect data provide more efficient communication, interoperation, and real-time data and model exchange.

- **OPC Unified Architecture (OPC UA)**: OPC UA is a machine-to-machine communication protocol used for industrial automation and developed by the OPC Foundation [23]. The OPC UA is a platform-independent service-oriented architecture that integrates individual OPC Classic specifications into an extensible framework, provides a standardized framework for secure and reliable communication, and allows digital twins to integrate with diverse devices, components, and systems. When applied to a CNC digital twin, OPC UA can facilitate data integration and data exchange between the digital twin and the CNC machine, the supervisory system, and other relevant manufacturing applications.
- **Quality Information Framework (QIF)**: QIF is an ISO standard for creating digital threads. It is a CAD-neutral file format for downstream interoperability and traceability throughout the entire product lifecycle, especially in computer-aided processes and engineering applications. QIF is built on the Extensible Markup Language (XML) framework for easy integration and interoperability with other systems, web/internet applications, and other formal standards. It applies to product design, manufacturing, and quality inspection [24]. In a CNC digital twin application, QIF can represent the measurement result of a produced part and compare it with the part design data to identify issues with the machining process.

5 DIGITAL TWIN STANDARDS PROCEDURE

As digital twins become more prevalent in a wide range of industries for various purposes, more efforts from academia, industry consortia, and government agencies are focusing on identifying research directions and supporting industrial needs for digital twin development. These findings, in turn, will be the foundation of standardization efforts that facilitate the implementation of digital twins. SDOs will prioritize the identified topics and develop corresponding standards according to their focus subject areas and the industries they serve. Although different SDOs may have their own standards development practice, a general step-by-step procedure for the development of digital twin standards is as follows:

1. Identifying Standardization Requirements: The first step is identifying the requirements for digital twin standards across industries and applications through consortia efforts, industry workshops, surveys, and use case collection.
2. Creating and Reviewing Draft Document: SDO committees draft the initial standards, which will undergo multiple review cycles involving industry domain experts, solution providers, stakeholders, and the public.
3. Piloting Implementations: Industry participants may implement the draft standards on a pilot basis to test the applicability, feasibility, and effectiveness of the draft standards in their use cases.
4. Revisioning and Improving: Based on the feedback from pilot implementations and the advancement of technology, the draft standards are iteratively refined and updated for improvement.
5. Promoting Wider Adoption: As standards mature, the SDOs, industry consortia, and stakeholders will work together to promote the adoption of the standards. Manufacturers globally should start applying the standards, ensuring a consistent approach to digital twin implementation.
6. Evolving and Growing New Standards: The digital twin landscape is dynamic, and standards need to evolve to accommodate new technologies, use cases, and industry requirements. New standards need to be introduced to address specific aspects of digital twin implementation.

This is a general guideline; specific standard work items may follow a varying procedure depending on the focus of the SDO and the industry sector. For example, there are a few ongoing standardization efforts on digital twins, including new additions of ISO 23247 (Part 5: digital thread for digital twins and Part 6: digital twin composition), ISO/IEC JTC1 efforts on digital twin reference architecture, maturity models, guidelines for IoT and digital twin use cases, measure of digital twins, and data extraction and transactions.

Shao et al. [18] discussed potential new parts of ISO 23247, Digital Twin Framework for Manufacturing. Ferko et al. [19] and Wallner et al. [20] also proposed some future work based on their studies. National Academies recently published a report on Future Directions for Digital Twins [25]. To address these needs, a few potential standardization topics for manufacturing are briefly discussed as follows.

- common data models that capture the essential information (e.g., data ID, properties, format) and relationships within digital twins, the standards will promote consistency, reusability, and integration across diverse digital twin ecosystems.
- interoperability frameworks that define common interfaces, protocols, and integration patterns for digital twins; these kinds of standards can facilitate communication and collaboration between different systems.
- semantic models through standardized ontologies for effective communication and understanding of concepts, relationships, and context.
- data security standards for digital twins to enable authentication, access control, data encryption, and secure communication protocols that support data confidentiality, data integrity, and data privacy to enhance trust and confidence in digital twins.
- standardized testing and validation methods for digital twins to ensure their reliability, accuracy, and performance and enhance their credibility and trustworthiness. These methods should cover data quality assessment, model validation, conformance testing, and performance evaluation.
- frameworks and guidelines for managing the entire lifecycle of digital twins (i.e., requirements, design, development,

deployment, operation, maintenance, and retirement) to promote consistency, traceability, and scalability of digital twins. This end-to-end visibility enables organizations to optimize processes at every stage of the lifecycle.

SDOs, industry consortia, research institutions, and stakeholders can work towards creating a unified ecosystem that fosters interoperability, scalability, reusability, and innovation. Harmonization efforts should leverage and bridge existing standards, frameworks, and initiatives to avoid fragmentation and duplication of efforts. Collaboration promotes knowledge sharing, cross-domain interoperability, and the development of holistic solutions for digital twins. All the efforts together will enable the widespread adoption and effective implementation of digital twins across industries and help manufacturers build, manage, and deploy their digital twins better, faster, and cheaper.

6 CONCLUSION

Because digital twins are still in their relatively early stage, the ecosystem of digital twins has yet to be well established. Manufacturers need help in implementing their digital twins efficiently and effectively. Current implementations are mainly using ad-hoc approaches [26]. Standards must go beyond expensive, custom solutions to an affordable marketplace of products and tools for digital twins. Standards will facilitate the composition and integration of digital twins by providing guidelines, methodologies, frameworks, common terminologies, architectures, and interface specifications. They help create, integrate, update, validate, and secure digital twins more accurately and consistently, enabling interoperability between them and supporting software and hardware from different vendors. This can, in turn, significantly reduce the development time and effort required to create and use digital twins.

In the near future, potential specific digital twin standards may include work that supports the development and validation of digital twins. For example, (1) digital thread for digital twins, (2) digital twin composition, (3) building digital twins from reusable components, (4) verification, validation, and uncertainty quantification of digital twins, (5) guidelines for building cognitive digital twins, (6) digital twins and the metaverse, (7) plug and play digital twins, and (8) update the ISO 23247 reference architecture to add more details for current FEs and new functionalities, such as data storage and digital twin versioning. In addition, more research will be conducted to prove the effectiveness and adaptability of these standards in real world applications.

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