Proceedings of the ASME 2023
Manufacturing Science and Engineering Conference
MSEC2023
June 12-16, 2023, New Brunswick, NJ, USA

MSEC2023-101127

AN ANALYSIS OF THE NEW ISO 23247 SERIES OF STANDARDS ON DIGITAL TWIN FRAMEWORK FOR MANUFACTURING

Guodong Shao, Simon Frechette, Vijay Srinivasan

National Institute of Standards and Technology, Gaithersburg, Maryland, USA

ABSTRACT

ISO has recently issued a series of standards (ISO 23247) that deals with a digital twin framework for manufacturing. It is a generic framework that can be specialized to enterprises engaged in different manufacturing processes, such as discrete, batch, or continuous. This paper presents an analysis of this series of standards with two main objectives: (1) to inform the manufacturing community at large and (2) to examine this series of standards for applications in emerging industry sectors (e.g., biomanufacturing) and with novel manufacturing technologies (e.g., additive manufacturing). It takes a bottom-up approach, dealing with key terms and concepts first and gradually building up the framework. It includes interpretations and analyses to guide an appreciation of what the ISO 23247 series standardizes and the space it opens up for further development and industrial application.

Keywords: ISO, standards, digital twin, manufacturing, analysis, framework

1. INTRODUCTION

In the manufacturing industry sector, one encounters physical artifacts, processes, and behaviors that are often abstracted as mathematical models. Computable representations of these mathematical models have evolved and given rise to various computer-aided software systems over the past fifty years. A recent manifestation of this evolution is the rise of the notion of a digital twin in manufacturing [1- 4].

A digital twin is a digital model that is created to accurately reflect an existing physical object. The physical object is fitted with sensors that produce data about different aspects of the object's attributes and performance. This data is then relayed to an information processing system that applies it to a digital model. This digital model, also called a digital twin, can then be used to run simulations or other analytical models, study current performance, and generate potential improvements that can then be applied back to the actual physical object.

A digital twin can also be created for processes, allowing simulations to be run based on real-time data. The data used by digital twins is usually collected from network-enabled sensing devices, allowing for the capture of required information that can then be integrated into the digital twin.

A digital twin is, in effect, a virtual environment where ideas can be tested with few limitations. With an IoT (Internet of Things) platform, the model becomes an integrated, closed-loop digital twin that can be used to inform and drive strategy across a business. For example, a digital twin can replicate what is happening to an actual product in the real world and offer real-time feedback. The designer can then see if it is working as intended and determine if any improvements are needed based on actual data. This approach can also be translated to other situations, such as for a manufacturing process, which can be assessed with real-time data to react to changing demands, requirements, or business conditions.

Because of the interdisciplinary nature of a digital twin and the technologies involved, developing digital twins in manufacturing presents significant challenges to manufacturers, and a need for standardized definitions of terms, concepts, and reference models has risen. The ISO standards community that deals with industrial data for automation and integration has responded to this need with a new ISO 23247 series of standards [1-4] in the form of a generic framework that can be specialized to enterprises that are engaged in different manufacturing processes (such as discrete, batch, or continuous). This paper presents an analysis of this series of standards to inform and educate the manufacturing audience. It also examines the application of the standardized framework to emerging industry sectors (such as biomanufacturing) and novel manufacturing technologies (such as additive manufacturing). The analysis presented in this paper adopts a bottom-up approach, starting with the standardized definition of a *digital twin*.

In the context of manufacturing, a digital twin is defined as a 'fit for purpose digital representation of an observable manufacturing element with synchronization between the element and its digital representation' [1]. Three key phrases and words in this definition are worthy of some elaboration. They are: (1) *observable manufacturing element (OME)*, addressed in Section 2, (2) *fit for purpose*, addressed in Section 3, and (3) *synchronization*, addressed in Section 4, of this paper.

The rest of the paper is devoted to a discussion of domains and entities that make up the standardized framework in Section 5, looking ahead in Section 6, and drawing some conclusions in Section 7.

2. OBSERVABLE MANUFACTURING ELEMENTS

It is generally acknowledged that there are physical artifacts, processes, and behaviors observed in manufacturing that have computable counterparts in the form of digital representations. For example, an inherently three-dimensional physical part can be twinned with its three-dimensional representation in a CAD (Computer Aided Design) system; in fact, manufacturing of that part often starts with a three-dimensional digital representation of it in a CAD system (alternatively, with a two-dimensional drawing).

A major contribution of the ISO 23247 series of standards is the definition of eight types of Observable Manufacturing Elements (OMEs) and seven types of attributes for the digital representation of each of the OMEs. These are then put together with other entities in multiple domains to define a framework. Table 1 illustrates the information typically contained in the seven types of attributes in each of the eight OMEs using simple examples.

The eight OMEs are more formally defined in [1], and can be explained as follows:

1. *Personnel* includes those employees who are engaged directly or indirectly in manufacturing processes.
   A personnel digital twin can include availability, certification level, or other key attributes relevant to manufacturing. It is not required to be a full three-dimensional model of a human, such as an avatar. However, recent developments towards metaverse standards [5] may place a greater emphasis on the notion of avatars. Again, it will be a 'fit for purpose' digital representation, which means that the type and form of the personnel digital twin will totally depend on the stakeholders' requirements.
2. *Equipment* is a physical element that carries out an operation that is directly or indirectly involved in a manufacturing process.
   Equipment can include hand tools, computer numerical control (CNC) machines, conveyer belts, and robots.
3. *Material* is physical matter that is used to produce a manufactured product (such as a metal block) or that aids the manufacturing process (such as a coolant).

TABLE 1. ILLUSTRATIVE EXAMPLES OF ATTRIBUTES OF OBSERVABLE MANUFACTURING ELEMENTS (OME).

OME / **Attribute**	Personnel	Equipment	Material	Process	Facility	Environment	Product	Supporting Document
Identifier (Mandatory)	Employee ID number	Asset ID number	Material bar code	Process ID number	Facility ID number	Appropriate identifier	Product ID number	Document ID number
Characteristics	Skill level	Drilling machine	Hazardous	Milling	ISO class 5 clean room	Temperature and humidity	Color: white	A PDF document
Schedule	Working hours	Maintenance schedule	Purchase schedule	Once a week	Periodic utilization	Not applicable	Between process #1 and process #2	Revised monthly
Status	At work or on leave	Available	Tested	In-process now	Normal	Normal	In process	Current and complete
Location	Work site	Room #	Room and shelf #	Relative location	Relative location	Relative location	In warehouse #3	Stored in Facility #2
Report	Activity report	Reported high temperature	Material handling report	Equipment #1 completed milling operation	Window in clean room #1 is broken	Temperature in milling room #1 increases during operation	Passed quality test #2	Revised document released two days ago
Relationship	Working on Equipment #1	Operates on Material #1	Handling requires skill level #1 of Personnel	Executed with Personnel skill level #2	Clean room #1 evacuated when temperature exceeds limit	Air conditioning turned on during milling operation	Produced by machine #3	Engineer #2 produced document #3

4. *Process* is an observable sequence of physical operations in manufacturing.

   More broadly, a process can include fabrication process, assembly process, inspection process, maintenance process, and even management process.
5. *Facility* is infrastructure that is related to or affecting manufacturing.

   A facility can include special purpose room, building, energy supply, and water supply.
6. *Environment* is a condition supplied by facilities for the correct execution of a manufacturing process.

   An environmental condition can include temperature, humidity, and illumination.
7. *Product* is an output of a manufacturing process.

   A product can be an intermediate product or an end product.
8. *Supporting document* is any form of artifact (such as requirement, plan, model, specification) that assists manufacturing.

   Of all the OMEs, the supporting document is the least obvious element to be included in the observable list. However, there are numerous examples of physical books, printed documents, and mechanical mockups that are still in use, and these deserve to be included as observables.

The overarching assumption here is that each instance of the OME is a physical (equivalently, chemical/biological) element that has a 'material existence' and it can be twinned digitally. The digital twin of each OME has the seven attributes illustrated in Table 1, and each of the attributes can be represented in some appropriate informational scheme. The simplicity of the examples in Table 1 is only for illustrative purpose – in reality, the actual attributes can contain quite elaborate set of information.

The informational content of the seven attributes of Table 1 is further elaborated in [3] and can be explained as follows. It is instructive to observe that each of these attributes can utilize standardized terminology, concepts, and information models developed by other organizations.

1. *Identifier* is a value that conforms to ISO 8000-115 [6] to uniquely identify an OME. It is the only one of the seven attributes that is mandatory; the rest of the attributes are optional.

   For example, the identifier can be a universally unique identifier (UUID), uniform resource locator (URL), uniform resource name (URN), object identifier (OID), domain specific ID.
2. *Characteristic* is a typical or noticeable feature of an OME.

   For example, a characteristic can be derived from IEC 62264-2 (B2MML) [7], eCl@ss [8], ISO 13584-42 (PLIB) [9], or IEC 61360 (CDD) [10].
3. *Schedule* is the temporal information bound to a manufacturing process.

   For example, a schedule can be derived from ISO 8601 series [11], or it can be a simple start/stop statement.
4. *Status* is a condition of an OME involved in a manufacturing process.

   For example, a status can be derived from VDMA 24582 [12].
5. *Location* is geographical or relative location information of an OME.

   For example, a location can be derived from ISO 6709 [13], GPS (Global Positioning System) coordinates, or a postal address.
6. *Report* is a description of activities done by or onto an OME.

   For example, a report can be derived from QIF (Quality Information Framework) [14], or MTConnect [15].
7. *Relationship* is the connection information between two or more OMEs.

   For example, a relationship can be derived from IEC 62264-2 [16]. The *relationship* attribute can play a significant role in building an entity-attribute-relationship structure for information modeling or database design. These issues will be addressed in more detail in Section 5.

It is desirable that each of the attributes of an 'observable' in Table 1 is also measurable and/or computable. For example, the environmental characteristic of 'temperature' is measurable. Similarly, the process schedule is computable from a process plan. It is not always true that every observable is measurable or computable [17]. This scientific conundrum is avoided in ISO 23247 by considering only those attributes of observables that are measurable and/or computable.

Examples of Extensible Markup Language (XML) schema instances for the OMEs and their attributes can also be found in [3]. Figure 1 shows a snippet of an example XML instance for an OME, which is a drilling equipment in this case. It contains all the seven attributes listed above for an equipment.

Some useful observations can be made from a study of such examples in the standard. The information models for the OMEs and their attributes are not standardized in the current ISO 23247 series. But the general definitions and explanations of the OMEs and their attributes found in the standard can be used to select appropriate information models. Hence, the ISO 23247 series is not a standard for information models. It is rather a framework standard, as described more in Section 5. Other appropriate standards may be used for various purposes (e.g., MTConnect for data collection, STEP (STandard for the Exchange of Product model data) for product representation [18], and QIF for quality information modeling) when developing digital twins based on this framework standard.

```xml
<?xml version="1.0" encoding="utf-8" ?>
<EquipmentInformation>
  <MandatoryInformationAttribute>
    <UUID>e78651cd-3401-4e9w-921c-e80f6324a1cc</UUID>
  </MandatoryInformationAttribute>
  <OptionalInformationAttributes>
    <EquipmentCharacteristics>
      <Functionality>drilling
      </Functionality>
    </EquipmentCharacteristics>
    <EquipmentSchedule>
       <value>Maintenance for Machine #2 is scheduled on every Monday</value>
    </EquipmentSchedule>
    <EquipmentStatus>
       <value>Up and running</value>
    </EquipmentStatus>
    <EquipmentLocation>
       <name>relative</name>
       <value>Machine #1: Work Unit #2 in Room #3</value>
       <gps>
         <longitude>-77.1659474</longitude>
         <latitude>39.1865667</latitude>
         <altitude>12</altitude>
      </gps>
    </EquipmentLocation>
    <EquipmentReport>
      <MaintenanceReport timestamp="2022-03-15T10:10:35.153141">
        <startdate>2022-05-14T10:00:10Z</startdate>
        <enddate>2022-05-14T16:00:10Z</enddate>
      </MaintenanceReport>
    </EquipmentReport>
   <EquipmentRelationship>
     <value>WorkUnit #3 must have at least 2 persons for safety reasons</value>
   </EquipmentRelationship>
  </OptionalInformationAttributes>
</EquipmentInformation>
```


FIGURE 1. EXAMPLE OF AN XML INSTANCE FOR THE SEVEN ATTRIBUTES OF A DRILLING EQUIPMENT.

3. FIT FOR PURPOSE

In analyzing the ISO 23247 series of standards, a natural question that arises is why only eight OMEs, and seven attributes for each, have been selected for standardization. The justification is that, as far as one can see from various case studies and use cases examined till now, they have been found to 'fit for purpose' in manufacturing. Several use cases are presented in the Annexes of ISO 23247-4 to provide empirical support for this claim. There have also been several studies conducted during the standardization process to gather requirements from examples of digital twin applications [19]. A few of the use case scenarios are described briefly below to illustrate this point.

- *Minimizing the impact of equipment downtime* [19]: The objective here is to use process and equipment data to monitor, troubleshoot, diagnose, and predict faults and failures in a manufacturing equipment. The data can then be used to control the equipment itself. The manufacturing *equipment* may serve as an OME in this case and its digital twin should have, at the minimum, the attributes of identification, characteristics, schedule, status, location, report, and relationship as illustrated in Table 1. It is also possible that the manufacturing *process* (whether it is discrete, batch, or continuous) may serve as an OME and the same set of attributes are applicable for its digital twin.

- *Optimizing production planning and scheduling* [19]: The objective here is to collect data from shop-floor systems, such as production equipment, manufacturing execution systems (MES) and enterprise resource planning (ERP) systems, to analyze the status of the production system and any fluctuations in customer demand, inventory, and resources. This knowledge can then enable demand-driven on-time delivery, resource (e.g., material, personnel, and equipment) optimization, cycle-time reduction, and inventory-cost reduction. It is easy to see from Table 1 that this ambitious goal will involve all the eight OMEs, at the minimum, and their digital twins will involve all the seven attributes, again at the minimum.

- *Advanced metrology* [4]: The objective here is to create digital twins of as-built parts with complex geometries, such as aircraft wings, so that they can be assembled with fasteners of the right length to enable weight reduction. The aircraft wing components and fasteners can be the *product* OMEs with corresponding digital twins and their attributes. The measuring equipment is another OME, and its digital twin will have its appropriate attributes.

Some general observations can be made from these use case scenarios. There are no hard 'proofs' about the necessity and sufficiency of the standardized OMEs and their digital twins' attributes. The ISO 23247 series of standards has identified a few important ones that are necessary in several use case scenarios – they may not be sufficient and may have to be augmented with other attributes. Also, in some cases, some of these OMEs and the digital twin attributes may not be necessary for the intended purpose. The strongest statement one can make is that the standardized OMEs and their attributes in the ISO 23247 series are useful in various contexts – in other words, they are 'fit for purpose.' Such type classifications based on empirical evidence are quite common in standardization.

4. SYNCHRONIZATION

Another natural question that arises is about the difference between a digital twin and what currently exist in computational modeling and simulation (such as finite element analysis and discrete event simulation). While simulations and digital twins both use digital models to replicate products and processes, there are some key differences between the two. The most notable is that a digital twin creates a virtual environment able to study several simulations, backed up by synchronized real data and a two-way flow of information between the digital twin and the sensors that collect this data. This increases the accuracy of predictive analytical models, offering a greater understanding for the management and monitoring of products, policies, and procedures. This two-way synchronization is a key feature in digital twin, distinguishing it from conventional offline modeling and simulation. Precious work on real-time simulations for monitoring and controlling systems, e.g., [20,21], can be regarded as digital twins.

The synchronization can be event-based or time-based. When it is event-based, the updates occur in response to an event. When it is time-based, updates occur more or less continuously from a time-stamped data stream. Again, the 'fit for purpose' will dictate the information fidelity and the speed with which the synchronization is imposed. Such offline and real-time synchronization and information fidelity issues have been addressed in several studies, as described in [19]. All these studies, along with use case scenarios discussed in Section 2, have pointed out the need for *sensors* to communicate information from an OME to its digital twin, and the need for *actuators/controllers* to communicate commands from a digital twin to its OME, for synchronization. This two-way communication is depicted in Fig. 2, which will serve as the basis for a digital twin framework addressed in Section 5.

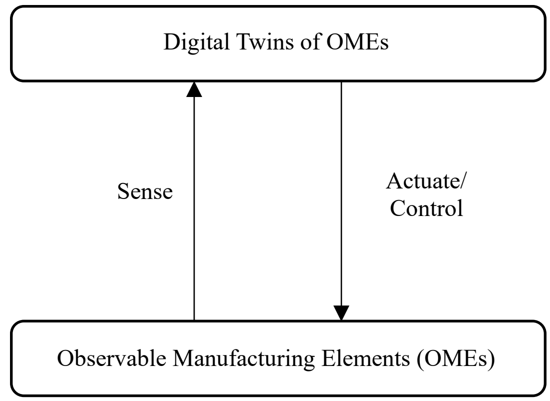

FIGURE 2. A SIMPLE DEPICTION OF TWO-WAY COMMUNICATION FOR SYNCHRONIZATION.

A further elaboration of the two-way synchronization is provided in [1]. When sensors provide measured data from an OME to update its digital twin, it is called a *driven* digital twin. When a digital twin describes a plan or an operation to produce a product (which is an OME), it is called a *driving* digital twin.

Such a strong two-way requirement between OMEs and their digital twins imposed by synchronization has led to further developments and refinements of concepts and definitions in the ISO 23247 series. These developments and refinements are in the form of domains, events, and finally to the framework as described in the next section.

5. THE FRAMEWORK

The need for sensors and actuators/controllers to maintain synchronization between OMEs and their digital twins, as shown in Fig. 2, provides a strong motivation to the definition of four layers of *domains* in the ISO 23247 series. A further refinement of these domains has led to the definition of several *entities* that depend on their *function* – hence to the concept of *functional entities*. When these refinements are integrated within an enterprise information architecture, a final digital twin *framework* for manufacturing emerges. These developments are described below.

5.1 Domains

The two-way communication between OMEs and their digital twins shown in Fig. 2 can be formalized in the form of interconnected *domains*. Figure 3 provides a simple illustration of how this is accomplished as four interconnected layers of domains in ISO 23247-2 [2].

A quick comparison of Figs. 2 and 3 makes the case for the Observable Manufacturing Domain (as a container of the OMEs), the Digital Twin Domain (as a container of the digital twin entities of the OMEs), the interfacing Device Communication Domain (as a container of entities for sensors and actuators/controllers), and the bidirectional links between them.

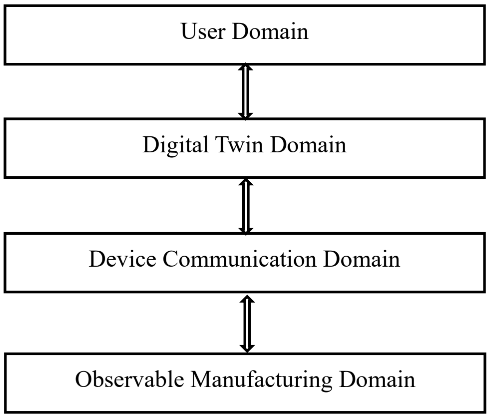

FIGURE 3. FOUR LAYERS OF DOMAINS.

The introduction of a User Domain as a distinct layer at the top in Fig. 3 needs some explanation. This domain is required to facilitate users – which may include software applications such as Product Lifecycle Management (PLM), MES, ERP, and Manufacturing Operations Management (MOM) – to interact with the OMEs and their digital twins; this can also include the much-needed human-machine interface. The User Domain can thus be quite large and complex.

While the domain-based 'reference model' in the form of the four layers in Fig. 3 gives some conceptual clarity, these domains need to be refined with more information for industrial applications. The digital twin framework for manufacturing in the ISO 23247 series is concerned with refinements in the top three domains of Fig. 3, and these three domains are further elaborated with entities and sub-entities.

5.2 Entities

The digital twin framework for manufacturing begins to take shape in Fig. 4 with the introduction of entities to represent informational content in the top three domains of Fig. 3. In addition, a new Cross-system Entity is introduced in the framework. The four entities within the dotted box of Fig. 4 constitute bulk of the informational content in the digital twin framework and they are explained below.

- *User entity* can be used to host application software systems. As mentioned in Section 5.1, these entities correspond to PLM, ERP, MOM and other applications, as well as the human-machine interfaces.
- *Digital twin entity* represents the OMEs digitally. It consists of the following three sub-entities:
  - *Operation and management sub-entity* maintains information about OMEs, including digital modeling, presentation, representation, and synchronization.
  - *Application and service sub-entity* provides functionalities such as simulation, analysis of data captured from OMEs, and reporting production status.
  - *Resource access and interchange sub-entity* provides the information exchange between the digital twin entity and the user entity, with support for interoperability (for example, using standardized data models).
- *Device communication entity* has the following two sub-entities:
  - *Data collection sub-entity* collects data from the OMEs, using sensors and the associated software.
  - *Device control sub-entity* controls and actuates OMEs using appropriate software.
- *Cross-system entity* resides across domains (represented by the entities) to provide common functionalities such as data translation, data assurance, and security support.

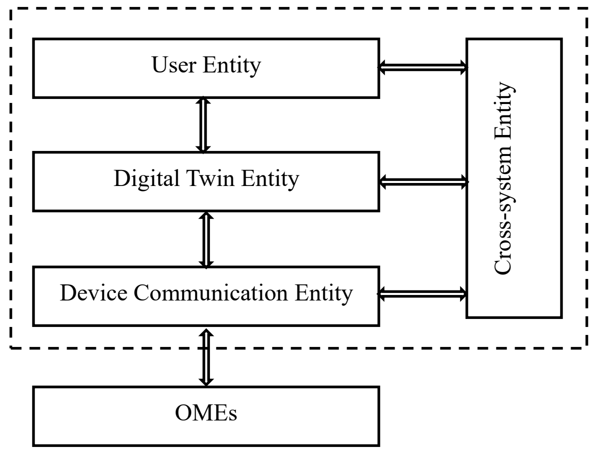

FIGURE 4. ENTITIES IN THE FRAMEWORK.

The introduction of entities in the framework is critically important for information modeling purposes. As indicated in Section 2, these entities and the attributes (which include the *relationship* attribute) of the digital twins of OMEs provide the necessary pieces to put together the *entity-attribute-relationship* structure in any data modeling scheme and for any database implementation. It also provides a foundation for the selection of existing standards to support the development of various functionalities of the digital twin.

5.3 Putting Together

The digital twin framework for manufacturing is now almost ready to be put together. The final touch to Fig. 4 within the dotted box is provided in [2] by enriching the sub-entities explained in Section 5.2 with some *functional entities*. Rather than enumerating all the functional entities in [2], it is instructive to pick one entity within the dotted box and examine how its sub-entities are further subdivided into functional entities. The Device Communication Entity in Fig. 4 has been chosen for this purpose. Recall that the Device Communication

Entity has two sub-entities called Data Collection Sub-entity and Device Control Sub-entity.

The Data Collection Sub-entity has the following functional entities:

- *Collection identification functional entity* identifies the data needed from OMEs.
- *Data collecting functional entity* collects the data from OMEs.
- *Data pre-processing functional entity* performs data pre-processing such as filtering and aggregation.

The Device Control Sub-entity has the following functional entities:

- *Control identification functional entity* identifies the OME that needs to be controlled.
- *Controlling functional entity* controls the OME by sending commands to a device in a language understood by the device.
- *Actuation functional entity* actuates an OME in response to a request from the user entity or the digital twin entity.

Other sub-entities in Section 5.2 are also similarly enriched by subdividing them into functional entities in [2]. Hierarchically, it can be seen that entities contain sub-entities, and sub-entities contain functional entities.

It may appear from Figs. 3 and 4 that the domain and entity layers in the digital twin framework are hierarchical. But this is not strictly necessary. For example, the actuation functional entity resides in the device communication entity, and it can actuate an OME by working with the digital twin entity above it or with the user entity that is one more layer away. This option enables the framework to operate flexibly in a fully automated mode or in a semi-automated mode. For example, if the digital twin sends a command to an OME in response to a sensed data (using the device communication layer for both), it completes an automatic loop. On the other hand, if a user sends a command directly to an OME to execute a process (which is sensed and updated by its digital twin using the device communication layer), then the manufacturing is run in a semi-automatic mode.

In summary, the standardized entities, sub-entities, and functional entities provide the basis for creating lightweight metadata for manufacturing. They contain links to detailed data (perhaps in standardized formats) from other applications that provide services to the manufacturing enterprise. This explains the difference between a standardized framework found in the ISO 23247 series and numerous standardized data models found elsewhere for information exchange in a manufacturing enterprise.

5.4 Use Cases

The ISO 23247 standard has been tested in pilot projects by Boeing, Lockheed Martin, and Sandvik on their discrete manufacturing processes (a robot cell for drill and fill operations, weight reduction for an aircraft skin, and tool life optimization for gear box machining), and has demonstrated value in industrial operational environments [4, 22]. In the Boeing test case, the standard was applied to develop a robot "drill and fill" system for airframe manufacturing to enable a flexible schedule, which is automatically adjusted based on the availability of robots. In the Lockheed Martin project, the standard was used to develop a digital twin that helped to reduce airframe weight by optimizing the length for various fasteners that hold aircraft together. The standard was used by Sandvik to develop a cutting tool life optimization digital twin that helped increase tool life for milling operations by 15 %.

6. LOOKING AHEAD

The initial four parts of the ISO 23247 series provide a fundamental generic digital twin framework for manufacturing. It is envisioned that the framework can be extended and specialized to several manufacturing industries that employ different manufacturing processes and technologies. For example, the emerging biomanufacturing sector can use the generic framework to develop its digital twins and this may constitute a future part of the ISO 23247 series. Similarly, digital twins for additive manufacturing may be created, an additional part in the ISO 23247 series of standards can be dedicated to the AM domain. Alternatively, other standards development organizations may adopt the current ISO 23247 series to create the digital twins for their customer industries. All these options are currently under active consideration. The following subsections discuss a few more concrete ideas of potential new parts to create digital twins using a more systematic approach that is easier to develop, easier to scale (and integrate), more trustworthy, and able to utilize the Metaverse.

6.1 Digital Twin Development Supported by Digital Thread

The digital twin framework standard can guide users to implement their individual digital twins. According to an Accenture study, most companies are missing out on 35 % to 65 % of possible value of digital twin investments because digital twins were often developed in silos for one particular functional area. These digital twins mainly (1) focused on front-end experience without a comprehensive strategy for data integration and data sharing; (2) needed duplicated infrastructure for isolated, untimely data; (3) could only perform local functional optimization, not the enterprise-wide optimization; and (4) missed the opportunity to leverage customers' data [23]. For example, a standalone CAD-based simulation allows designers to test different scenarios against a set of parameters, making it useful for product design purposes. However, the scope of a product digital twin should be able to reach much further to include all stages of a product's lifecycle. This increased scope means that the product digital twin can find uses outside of design and can help improve processes and support wider business decisions.

However, effectively taking the lifecycle approach is challenging. Guidelines and methodologies on how to support digital twin development using a digital thread of the product lifecycle will be needed for digital twins to access the various product lifecycle information including data for design, manufacturing, inspection, and use. Digital Thread uses digital tools and representations for design, evaluation, and life cycle management of products and ensures that information can be accessed by digital twins readily, reliably, and securely.

6.2 Integration of Multiple Digital Twins

To achieve digital transformation in a manufacturing environment, multiple digital twins will need to be developed and integrated with the support of a digital thread. For example, digital twins of a part and the machine that manufactures the part should interact dynamically and seamlessly; digital twins of cutting tools, a machine tool, and a part should interact to determine the tool wear, tolerance conformance, and the machine health; and, in a supply chain, digital twins of partners coordinate and communicate in real-time. It is always challenging to aggregate, compose, and integrate multiple applications to achieve a new goal. Standard methods and guidelines will reduce the time and risk for such undertakings.

A potential new part of ISO 23247 on this topic could provide guidelines on how to enable multiple digital twins to effectively communicate and interoperate. The new part could provide generic methodologies, principles, and examples to help users understand the problem and derive an appropriate solution to the problem. In the examples cited in the last paragraph, relevant standards and technologies could be selected and applied to demonstrate the integration.

6.3 Building Digital Twins from Reusable Components

Digital twins can be broadly classified as descriptive (what happened?), diagnostic (why did it happen?), predictive (what will happen?), and prescriptive (how can we make it happen?) analytics. Depending on the application requirements, digital twins could be developed for different operational levels, including equipment, work cells, production lines, factories, and supply chains. While some approaches exist to support component reuse [21], most of them are not designed specifically for digital twins. Therefore, currently, almost all digital twins are implemented from scratch, which makes implementations time-consuming and costly. Customized designs also make a digital twin difficult to modify, extend, and reuse. Manufacturing knowledge, information attributes, and use case configurations are often developed multiple times using different specialized abstractions for different applications. Reusability of digital twin components in a digital twin library could lead to considerable reduction in the development cost, time, and the required level of expertise.

A potential new part of ISO 23247 on this topic could provide guidelines on how to build up component libraries, and how to create templates for organizing information and models. Reusable digital twin components may include templates for data collection, common information attributes, modular models, applicable enabling technologies, and relevant standards for various digital twin functionalities. The new part could provide generic methodologies, architectures, frameworks, knowledge bases, and examples for building and using digital twin component libraries to enable users to create digital twin applications easier, faster, and cheaper.

6.4 Credibility Assessment of Digital Twins

The current ISO 23247 series provides a framework and guideline for implementing digital twins in manufacturing; however, it does not cover the aspect of Verification, Validation, and Uncertainty Quantification (VVUQ) and testing – in short, a credibility assessment of digital twins. To ensure that the developed digital twins are useful, the results generated by the digital twins must be trustworthy for real manufacturing needs. Model credibility assessment including VVUQ techniques need to be applied throughout the life cycle of digital twins. Verification and Validation (V&V) activities are necessary to ensure that a digital twin meets its intended purpose and design goals. Uncertainty Quantification (UQ) produces a measure of performance that users can apply as part of a credibility assessment for a given digital twin. Credibility assessment of digital twins may also include factors beyond VVUQ.

Digital twin testing will need a test system, which could be a test suite for both the OME and its digital twin. For example, if the test system can run a set of tests and is unable to distinguish between an OME and its digital twin with a value bigger than a predefined probability threshold, then the digital twin can be regarded as a reasonable representation of the OME. Trust in a digital twin also involves trust in the data collected from the OME, trust in the mathematical model used in the digital twin, trust in the data updating procedure, and trust in the decision recommendations and control. All these aspects will have a measurable uncertainty. The existence of a measurable uncertainty means that validation (comparison with reality) needs to be treated as a statistical process. Comparison of real data with model results can be used to generate an estimate of the probability that the digital twin is a consistent representation of the OME.

A potential new part of ISO 23247 on this topic could provide guidelines on and methodologies for how to measure uncertainty, how to perform digital twin testing, how to select or construct a credibility assessment framework to perform VVUQ activities, and how to assess the credibility of the developed digital twins.

6.5 Digital Twins and the Metaverse

The maturity of technologies for virtual reality (VR), augmented reality (AR), and extended reality (XR) in the electronic gaming and video entertainment industry can now be brought to enhance the visualization experience to manufacturing. For example, it has been demonstrated that AR technologies can be integrated with three-dimensional geometrical product specification and verification standards and practices [24]. Such developments in the manufacturing sector show a trend that leads naturally to recent industrial interest in metaverse and its standards [5].

A major feature of metaverse is the immersive visualization experience along with its human-machine interface. The hardware and software technologies developed by metaverse can be used by the digital twin framework for manufacturing, especially in cases where human involvement is still emphasized. For example, the user domain and user entity in Figs. 3 and 4 can use human-machine interfaces that could be provided by the metaverse. Alternatively, a metaverse may be a parallel virtual world that may subsume some of the digital twins of a manufacturing enterprise that the metaverse represents. So, the interaction between digital twin and metaverse may follow a few of the scenarios such as the following:

- The metaverse is designed as a component in the user-domain of a digital twin. It will require interaction and synchronization with the digital twin, and in turn with the OME.
- The metaverse is designed to represent one or more of the OMEs as a separate 'system' in parallel with the digital twin. It will not need to be strictly synchronized with the digital twin.
- The metaverse is designed to provide a broader view of the manufacturing environment in which multiple OMEs exist and their digital twins may become parts of the metaverse. The metaverse should be calibrated, from time to time, depending on the requirements, with the manufacturing environment including both OMEs and their digital twins.

These different scenarios for integrating metaverse technologies could be introduced as a new part of the ISO 23247 series including the metaverse concept, its definition, possible scenarios for integrating with digital twins, and guidelines and methodologies for such integration.

6.5 Extending the Framework to Specific Sectors

Based on the generic framework provided by the initial four parts of the ISO 23247 series, extensions and specializations can be developed as new parts of the standard for specific manufacturing sectors such as biomanufacturing, semiconductor manufacturing, and additive manufacturing. The new parts may include a specialization of the digital twin framework by adding new functional entities or replacing existing functional entities to fit the new requirements. For example, new functional entities (e.g., digital thread entity, credibility assessment entity) will need to be added to satisfy the requirements discussed in Subsections 6.1 to 6.4. The new parts may also include the implementations of use cases for those particular manufacturing sectors, and these use-case implementations may, in turn, help identify new requirements in the manufacturing sector. The use cases can be published as technical reports, which would be also new parts of the standard. For example, in an adaptive control use case in biomanufacturing, a machine learning digital twin of the process should be developed and periodically updated [25]. In addition, new functional entities needed for the special requirements could be generalized may result an extension of the existing ISO 23247 parts.

7. CONCLUDING REMARKS

The ISO 23247 (Digital Twin Framework for Manufacturing) standard series with four parts was published in Oct. 2021. As the first ISO digital twin framework standard for manufacturing, it provides a foundation for future digital twin standards. In addition to the test cases discussed in Section 5.4, more and more manufacturing enterprises have started to apply the standards for their digital twin implementations. Research organizations, Standard Development Organizations (SDOs), and industrial consortia such as the Industry IoT Consortium (IIC) and the Digital Twin Consortium (DTC) are also referencing or adopting the standard for the development of new relevant standards, methodologies and tools, and digital twin prototypes.

The definition of "digital twin in manufacturing" has been adopted and referenced widely by researchers and practitioners. There are also many international implementations and testing of the standard; for example, Change2Twin, a European project consortium that provides digital twin solutions to SMEs, adopted ISO 23247 and is using it for digital twin implementations [26]. The Fraunhofer Institute of Optronics has adopted the standard to develop Industry 4.0-compliant digital twins [27]. Such international interests indicate that there is a global need for a generic framework for digital twins described in this paper. They also indicate that the framework standard needs to be updated to include more capabilities to address new problems, as proposed in this paper.

ACKNOWLEDGEMENTS

The authors would like to thank ISO TC 184 SC 4 WG 15 committee members and Paul Cirino for valuable discussion.

The work presented in this paper is an official contribution of the National Institute of Standards and Technology (NIST) and not subject to copyright in the United States. Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST. Nor does it imply that the products identified are necessarily the best available for the purpose.

REFERENCES

[1] ISO 23247-1. ISO 23247-1: Automation Systems and Integration - Digital Twin Framework for Manufacturing – Part 1: Overview and general principles. International Organization for Standardization, Geneva, Switzerland (2021).

[2] ISO 23247-2. ISO 23247-2: Automation Systems and Integration - Digital Twin Framework for Manufacturing – Part 2: Reference architecture. International Organization for Standardization, Geneva, Switzerland (2021).

[3] ISO 23247-3. ISO 23247-3: Automation Systems and Integration - Digital Twin Framework for Manufacturing – Part 3: Digital representation of manufacturing elements.

International Organization for Standardization, Geneva, Switzerland (2021).

[4] ISO 23247-4. ISO 23247-4: Automation Systems and Integration - Digital Twin Framework for Manufacturing – Part 4: Information exchange. International Organization for Standardization, Geneva, Switzerland (2021).

[5] Trevett, N. The Metaverse Standards Forum, Fostering Interoperability Standards for an Open Metaverse. 2022. https://metaverse-standards.org/

[6] ISO 8000-115. ISO 8000-115: Data quality - Part 115: Master data: Exchange of quality identifiers: Syntactic, semantic and resolution requirements (2018).

[7] IEC 62264-2. IEC 62264-2: Enterprise-control system integration - Part 2: Objects and attributes for enterprise-control system integration (2015).

[8] ECLASS. An ISO/IEC-compliant data standard for goods and services. https://eclass.eu/en.

[9] ISO 13584-42. ISO 13584-42: Industrial automation systems and integration - Parts library - Part 42: Description methodology: Methodology for structuring parts families (2010).

[10] IEC 61360-1. IEC 61360-1: Standard data element types with associated classification scheme - Part 1: Definitions - Principles and methods (2017).

[11] ISO 8601. ISO 8601: Date and time format (2017).

[12] VDMA 24582. VDMA 24582: Fieldbus Neutral Reference Architecture for Condition Monitoring in Production Automation (2014). Verband Deutscher Maschinen- und Anlagenbau e.V.

[13] ISO 6709. ISO 6709: Standard representation of geographic point location by coordinates (2008).

[14] QIF. The Quality Information Framework Standard. (2020). http://qifstandards.org/

[15] MTConnect. MTConnect standardizes factory device data. (2022). https://www.mtconnect.org/

[16] IEC 62264-2. IEC 62264: Enterprise-control system integration - Part 2: Objects and attributes for enterprise-control system integration (2015).

[17] P.A.M. Dirac, The Principles of Quantum Mechanics, Clarendon Press, U.K., 1982. ISBN-13: 978-1607965602.

[18] ISO 10303. ISO 10303-1: Industrial automation systems and integration - Product data representation and exchange - Part 1: Overview and fundamental principles (2021).

[19] G. Shao and M. Helu, "Framework for a digital twin in manufacturing: Scope and requirements," Manufacturing Letters, vol. 24, pp. 105–107, 2020, DOI: 10.1016/J.MFGLET.2020.04.004.

[20] Y. J. Son, S. B. Joshi, R. A. Wysk, and J. S. Smith, "Simulation-based shop floor control," Journal of Manufacturing Systems, vol. 21, issue 5, pp. 380-394, 2002. DOI: 10.1016/S0278-6125(02)80036-X.

[21] Y. J. Son, R. A. Wysk, and A. T. Jones, "Simulation-based shop floor control: formal model, model generation and control interface," IIE Transactions, 35:1, pp. 29-48, 2003. DOI: 10.1080/07408170304428.

[22] ISO TC184 SC4 WG15. "Digital Twin Framework for Manufacturing – ISO 23247." (2020). URL https://www.ap238.org/iso23247/.

[23] Accenture. "Think thread first: Surf the wave of product data." (2020). URL https://www.accenture.com/us-en/insights/industry-x/thread-first-thinking.

[24] Vernica, T., Lipman, R., Kramer, T., Kwon, S., and Bernstein, W. Z. "Visualizing Standardized Model-Based Design and Inspection Data in Augmented Reality." ASME. J. Comput. Inf. Sci. Eng. August 2022; 22(4): 041001. https://doi.org/10.1115/1.4053154

[25] Rathore, A., Mishra, S., Nikita, S., Priyanka, P. Bioprocess Control: Current Progress and Future Perspectives. Life 11, 557 (2021).

[26] Pileggi, P., Bujari, A, Barrowclough, O., Haenisch, J. and Woitsch, R. Overcoming Nine Digital Twin Barriers for Manufacturing SMEs. (2020). Change2Twin. https://www.change2twin.eu/about/download/

[27] Jacoby, M., Volz, F., Weißenbacher, C., Stojanovic, L. and Usländer T. "An approach for Industrie 4.0-compliant and data-sovereign Digital Twins: Realization of the Industrie 4.0 Asset Administration Shell with a data-sovereignty extension" at - Automatisierungstechnik, vol. 69, no. 12, 2021, pp. 1051-1061. https://doi.org/10.1515/auto-2021-0074