NIST Advanced Manufacturing Series 400-2

Use Case Scenarios for Digital Twin Implementation Based on ISO 23247

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https://doi.org/10.6028/NIST.AMS.400-2

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

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May 2021

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National Institute of Standards and Technology Advanced Manufacturing Series 400-2
Natl. Inst. Stand. Technol. Adv. Man. Ser. 400-2, 30 pages (May 2021)

This publication is available free of charge from:
https://doi.org/10.6028/NIST.AMS.400-2

Abstract

As a key part of digital transformation, digital twin is an important concept for achieving smart manufacturing. However, there remains many challenges about the digital twin concept and how it can be implemented in real manufacturing systems, especially among small and medium-sized enterprises. Relevant standards that provide common terminology and implementation guidelines can help address these challenges. This paper discusses the concept, definitions, applications, and recent standardization efforts of digital twins. In particular, International Organization for Standardization (ISO)/Draft International Standard (DIS) 23247, Digital Twin Framework for Manufacturing, is introduced. The scenarios of three digital-twin use cases in manufacturing are explored in depth and the procedures of implementing such use cases according to the ISO/DIS 23247 framework are presented. The designs of these use case scenarios can be implemented at the National Institute of Standards and Technology (NIST) Smart Manufacturing Systems (SMS) Test Bed or on any manufacturing shop floor that has similar maturity level of digital transformation. In addition, the procedures of design and implementation of ISO/DIS 23247 can be used for developing additional applications of digital twins in manufacturing.

Keywords

Digital Twin; Framework; Standards; Smart Manufacturing; Use Cases.

Table of Contents

List of Tables

List of Figures

1. Introduction

The goal of smart manufacturing is to enable fully integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs [1]. With smart manufacturing, the manufacturing operations could have embedded knowledge gained from using advanced technologies such as Internet of Things (IoT), data analytics, modeling and simulation, and optimization to respond in real-time to the changes in raw material costs, custom orders, inventory levels, and so on. To achieve smart manufacturing goals, manufacturers are investing in digital transformation of their processes and equipment. The digital twin is the center of the digital transformation.

A digital twin is a digital representation of a physical element and is created by using IoT and sensor data. It monitors physical operations, controls the physical element, tests what-if scenarios, predicts the future behavior of the physical element, and supports decision-making. The digital twin concept has gained much attention from both academia and industry lately. However, there are still challenges, especially among small and medium-sized enterprises (SMEs), for implementing digital twins for their operations because there exist a variety of definitions of digital twins, inconsistent terminologies, and no standardized procedures for creating digital twin applications. Standards that provide precise definitions, common terminologies, implementation framework or guidelines will help address these challenges.

Since the digital twin concept is still in its early stage, there are not many standards specifically developed for digital twins. A recently developed International Organization for Standardization (ISO)/Draft International Standard (DIS), ISO 23247, Digital Twin Manufacturing Framework, is one of such standards. However, existing standards for data collection, data security, information modeling, system modeling, simulation, visualization, and networking, which have been developed for generic or specific purposes, can also support digital twin applications.

To demonstrate the implementation of the ISO 23247 standard and the use of supporting standards, this paper describes three use case scenarios of digital twins in manufacturing according to the framework defined in the standard. The rest of the paper is organized as follows: Section 2 provides background information including a brief introduction of digital twins in manufacturing, relevant digital twin standards, and the NIST Smart Manufacturing System (SMS) Test Bed. Section 3 introduces the ISO 23247 series. Section 4 explores three manufacturing use cases of digital twins that can be implemented based on ISO 23247. Finally, Section 5 concludes the paper and discusses future work.

2. Background

Smart manufacturing depends on modeling and analysis to make decisions that lead to across-the-board operational improvements. Digital twins of manufacturing applications use modeling and simulation, data analytics, and optimization to help ensure production optimization. Relevant standards are the key to facilitating digital twin implementations. Testing and demonstration of relevant standards for digital twins can help promote the standards and speed up the acceptance of the digital twin concept. In this section, we describe digital twins in manufacturing, relevant standardization efforts, and the NIST SMS Test Bed.

2.1 Digital Twins in Manufacturing

A digital twin in manufacturing is defined as "a fit for purpose digital representation of an Observable Manufacturing Element (OME) with synchronization between the OME and its digital representation" in [2]. An OME is an entity that has an observable physical presence or operation in manufacturing. It could be personnel, equipment, material, process, facility, environment, product, or supporting document.

Digital twins of OMEs are usually developed using near real-time operational data collected by using smart sensors and metrology technologies during production. Using these collected data, other parameters may be learned or calculated. Digital twins use all these data (i.e., external collected data, internal control feedback data, and learned parameters) to accurately and dynamically track OME working status, optimize the quality and delivery reliability of products, and improve the manufacturing process efficiency. Typical digital twin applications in manufacturing include, but are not limited to:

- On-line/off-line analytics digital twins that perform descriptive analytics to identify what happened or is happening, diagnostic analytics to identify why it happened or is happening, predictive analytics to identify what is likely to happen, and prescriptive analytics to identify how we can make it happen and what will be the consequences [3].
- Real-time control digital twins that monitor and control the OMEs in real-time
- Equipment health check digital twins that monitor equipment status and conditions for optimal maintenance scheduling
- Scheduling and routing digital twins that help make optimal scheduling decisions online/offline
- Virtual commissioning digital twins that test and evaluate the controller designs and control strategies even without the physical system
- Predictive maintenance digital twins that schedule and adjust maintenance activities for production equipment before failures happen

- Product digital twins that help learn about previously products to optimize new and existing product designs

There is no single digital twin that can provide all the solutions for a given manufacturing system, equipment, or process. Different digital twins may be developed with different scope and objectives. In certain cases, multiple digital twins may need to be integrated to cover a larger scope [4].

The benefits of applying digital twins in manufacturing may include, but not limited to:

- Achieving in-loop planning and validation by dynamically re-sequencing or adjusting a manufacturing process during production in response to unexpected exceptions that occur on the shop floor
- More accurate planning of production schedules by having more timely and complete models of equipment capability, reliability, accuracy, and productivity.
- Realizing predictive maintenance of equipment by adjusting processes more quickly and resolving scheduling issues without interrupting production to reduce cost and improve productivity
- Better part/assembly traceability by dynamically validating the part, adjusting downstream processes, and digitally recording the changes
- More reliably monitoring equipment health by detecting anomalous performance in real-time using Key Performance Indicators (KPIs) and predicting the remaining useful life of equipment
- Enabling testing and validation of control strategies by using virtual commissioning without the need of installing or purchasing the real manufacturing equipment

2.2 Digital Twin Standards

Standards can serve as force multipliers for the digital transformation of manufacturing. Standards for digital twins would enable context-dependent instantiations, composability, interoperability, and reusability of the digital twin components. Standards would also support other digital twin requirements such as digital thread, data synchronization, data assurance and data security, and user interfaces. Voluntary, consensus-based standards provide transparency and critical guidance in the methods for developing, deploying, structuring, and using digital twins in manufacturing.

The following standards are noted because of their relevance to the digital twin concept. These standards are developed for modeling of digital twins in manufacturing or digital factories. The list may not be regarded a complete list.

- IEC TS (The International Electrotechnical Commission Technical Specifications) 62832, Digital Factory Framework. The specification defines a framework to establish and maintain the digital representation of a production system throughout its life cycle. A consistent exchange of information between all processes and partners related to a production system can be achieved by the support of the framework. Information, therefore, can become understandable, reusable, and changeable through the entire production system life cycle [5].
- IEEE (The Institute of Electrical and Electronics Engineers) P2806, System Architecture of Digital Representation for Physical Objects in Factory Environments. The standard supports the creation of digital factories. It describes the objective, components, data sources required, and procedure of digital representation in factory environments [6].
- IPC (The Institute for Interconnecting and Packaging Electronic Circuits) 2551, International Standard for Digital Twins. The standard is part of the IPC Factory of the Future standards. The IPC digital twin is comprised of the digital twin product, manufacturing process, and lifecycle frameworks. Within the digital twin architecture, the standard stipulates and defines digital twin properties, types, complexities, and readiness levels. It also includes historical information about a product, including the history of design in terms of revision and engineering changes, and manufacturing information (i.e., digital thread) [7].
- DIN SPEC, the Asset Administration Shell (AAS). AAS describes an asset electronically in a standardized manner. Its purpose is to exchange asset-related data among industrial assets, between assets and production systems or engineering tools. AAS supports implementations of digital twins for industrial applications [8].
- ISO 23247, Digital Twin Framework for Manufacturing. The standard series defines a framework that provides a generic guideline, a reference architecture, methods, and approaches for case-specific, digital-twin implementations. The standard supports the composability of models and interoperability among modules. It also provides examples of data collection, communication, integration, modeling, and applications of relevant standards [4]. This is the standard we use for the use case scenario designs in Section 4. Section 3 will provide more details on this standard.

2.3 NIST Smart Manufacturing System Test Bed

The NIST SMS Test Bed is being established to support smart manufacturing research and development across the product life cycle. The Test Bed provides configuration infrastructure for cyber-physical systems that support system integration and digital twin implementation. In addition, it also generates near real-time operational data for researchers, both from internal and external, to develop and validate smart manufacturing technologies. Digital thread can be generated and used to support information exchange regarding product design, fabrication, and inspection [9]. Digital thread is the information flow that shares and connects the product's data throughout its lifecycle [10].

The Test Bed consists of three major components, shown below:

- The Computer-Aided Technologies (CAx) Lab. It contains several computer-aided technology tools to support computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided inspection (CAI), product data management (PDM), verification and validation (V&V). The tools in the CAx Lab allow conformance testing to standards, CAD/CAM modeling for design and manufacturing, and digital twin testing across the product lifecycle.
- The Manufacturing Lab. It mimics the configuration of a contract-manufacturing shop and includes several machine tools (e.g., Computer Numerical Control (CNC) milling and CNC turning) and inspection equipment (e.g., Coordinate Measuring Machine (CMM) and digital micrometers).
- Data publication web services. The services are capable of distributing manufacturing operational data from the Test Bed. Operational data is collected from the Manufacturing Lab using the MTConnect standard [11]. That data is aggregated and published internally and externally of NIST via web services.

3. ISO 23247 – Digital Twin Framework for Manufacturing

This section introduces the ISO/DIS 23247, Digital Twin Framework for Manufacturing. The goal of this standard series is to provide a generic development framework that can be instantiated for case-specific implementations of digital twins in manufacturing [4]. The standard has four parts: (1) overview and general principles, (2) reference architecture, (3) digital representation, and (4) information exchange. These four parts provide guidelines and procedures for defining scope and objectives, analyzing modeling requirements, promoting common terminology usage, implementing a generic reference architecture, and supporting information modeling of OMEs and information synchronization between a digital twin and its OME. Each of the four parts of the standard is briefly described in the following subsections.

3.1 ISO 23247 Part 1: Overview and General Principles

ISO 23247-1 provides general principles and requirements for developing digital twins in manufacturing. It defines terminologies used by the standard's four parts [2]. Physical systems are defined as OMEs, which need to be modelled using available standards and technologies based on the use case's specific scope and context.

Synchronization between a digital twin and its OME enables the digital twin to be kept current with its OME using communication protocols at a rate defined by the application. The synchronization ensures not only dynamically updating information of status, conditions, part geometries, and manufacturing resource changes but also constantly optimizing the OMEs.

3.2 ISO 23247 Part 2: Reference Architecture

ISO 23247-2 provides a reference architecture for digital twins in manufacturing. It includes a reference model from both domain and entity points of view. There are four domains in the reference architecture as shown below:

- Observable manufacturing domain. This domain is outside of the digital twin framework. It provides a context for the digital twin development and interacts with the data collection and device control domain.
- Data collection and device control domain. This domain links the OMEs to their digital twins for synchronization by collecting data from the sensors of the OMEs and controlling and actuating the OMEs.
- Core domain. This domain is responsible for overall operation and management of a digital twin. It hosts applications and services such as data analytics, simulation, and optimization to enable provisioning, monitoring, modeling, and synchronization. It also interacts with the users of the digital twin and other digital twins.
- User domain. This domain is responsible for users' interaction with the digital twins. A user can be a human, a device, an application or a system that uses applications and services provided by the digital twins.

Each domain has a logical group of tasks and functions, which are performed by the functional entities (FEs). Fig.1 shows a functional entity view of the reference model [12]. It consists of five major entities.

1. OMEs. The OME entities consist of resource specific FEs. OMEs are monitored and controlled.
2. Data Collection and Device Control Entity (DCDCE). The DCDCE has Data Collection Sub-Entity for collecting data from the OME and feeding data to the Core Entity, and Device Control Sub-Entity for controlling and actuating the OME.
3. Core Entity (CE). The CE is a digital twin entity, it includes Operation and Management Sub-Entity, Application and Service Sub-Entity, and Resource Access and Interchange Sub-Entity for digitally representing and maintaining OMEs. Within each sub-entity, there are several FEs, for example, Simulation FE in the Application and Service Sub-Entity.

4. User Entity (UE). The UE provides user interfaces to interact with the CE. The UE may be a human operator or an existing enterprise application such as manufacturing execution system (MES), enterprise resource planning (ERP) system, or other digital twins.
5. Cross-System Entity (CSE). The CSE resides across domains to provide common functionalities such as data translation, data assurance, and security support.

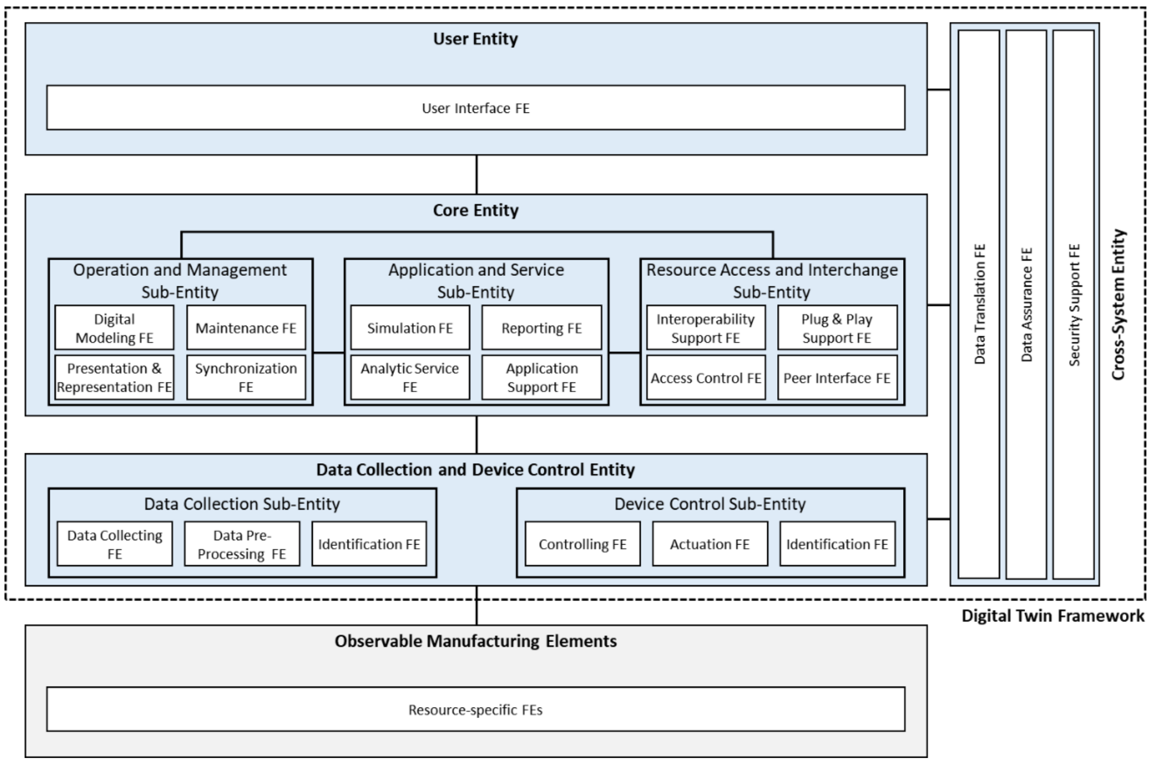

Fig. 1. Functional view of the digital twin reference model for manufacturing [12]

3.3 ISO 23247 Part 3: Digital Representation

ISO 23247-3 describes the basic information attributes for typical OMEs. Digital representation of OMEs includes both static and dynamic information [13]. Whenever possible, existing standards should be used to represent OMEs. For example, IEC 62264-2 (Enterprise-control system integration - Part 2: Model object attributes) can be used to represent OME information [14]. In a use case, the most appropriate information model shall be selected for the OME. Each OME shall use the enterprise unique identifier if possible.

3.4 ISO 23247 Part 4: Information Exchange

ISO 23247-4 presents technical requirements for information exchange between entities within the framework [15]. The identified networks include (1) user network that connects UE and CE, (2) service network that connects sub-entities within CE, (3) access network that connects DCDCE to CE and to UE, respectively, and (4) proximity network that connects DCDCE to OMEs. If CE is implemented using a single system, a service network is not needed.

This part of the standard also provides example use cases that implement the framework and a list of standards and technologies that can be selected for information exchange.

3.5 Procedures of Applying the Framework to a Digital Twin Use Case

To implement the digital twin framework defined in ISO 23247 for manufacturing use cases, the following high-level procedure should be followed.

- Standards and technologies should be selected for data collection from the OMEs. A list of relevant standards is provided in [15].
    - Select data standards and sensor interfaces for data collection
    - Select methods and tools for data processing
- Standards and technologies are selected for control of the OMEs.
    - Select methods and tools for interface development to control OMEs
    - Select methods and tools for translating control commands to device specific instructions
- Standards and technologies are selected for communication between DCDCE and CE. A list of relevant standards is provided in [15].
    - Select proximity networks for data communication
    - Select proximity networks for control command communication
- Standards and technologies are selected for digital representations of the OMEs. A list of relevant standards is provided in [13].
    - Select applicable FEs for digital twin development
    - Develop these FEs using selected standards and technologies
    - Integrate completed FEs using modular interfaces or using service networks if more than one system is used
- Standards and technologies are selected for communication between digital twins and users including human and enterprise applications such as CAD, CAM, CAI, MES, MOM and ERP. A list of relevant standards is provided in [15].
    - Select user networks for data communication
    - Develop graphical user interface for human users to visualize digital twin results

- Integrate digital twins with existing enterprise applications

4. Digital Twin Use Case Scenarios for Smart Manufacturing

The ISO/DIS 23247 can be implemented for various manufacturing applications. In this section, we discuss three potential digital twin use cases in the NIST SMS Test Bed. For each use case, a summary of the use case is provided using a table template developed by the ISO/IEC JTC 1/AG11. An implementation diagram that maps the use case components to the selected FEs of the framework is also developed. In addition, a high-level description of the implementation is presented.

4.1 Machine Health Digital Twin

A machine health digital twin can use process and equipment data to monitor, troubleshoot, diagnose, and predict faults and failures in manufacturing equipment. Through using process and equipment data, a digital twin can generate actionable recommendations for the users or deliver control commands to control the equipment. A machine health digital twin may include the following functionalities: (1) define maintenance objectives and goals, (2) collect maintenance and performance measurement data, (3) analyze collected equipment status data, and (4) generate control commands or actionable recommendations. Table 1 provides a summary of the Machine Health Digital Twin for the use case number 1.

Table 1 A summary of the Machine Health Digital Twin use case

ID	Case number 1
Use case name	Machine Health Digital Twin
Application field	Smart manufacturing
Life cycle stage(s)/phase(s) coverage	Production
Status	Proof of concept
Scope	Automated machining process monitoring and schedule adjustment based on machine conditions
Initial (Problem) Situation	Machine breakdowns will cause delays in the production system and lead to reduction in throughput. The challenges for effectively minimizing the negative impact of a machine failure include systematically collecting, visualizing, and analyzing machine operational parameters and acting upon the situation in a timely manner. Often time, there is either no usable, actionable machining process data available or no actionable recommendations can be made automatically during production. This

	leads to inefficiencies that affect every component of a manufacturer's operations, from unexpected machine downtime, production losses to inability to improve processes or justify capital expense.
Objective(s)	Minimize machine downtime impact
Short description	Machine tools may breakdown during machining processes. Often time, it is too late to find out the failures, so the broken machines have to be taken out of production for maintenance and repair. It is time-consuming and very costly. A machine health digital twin will use near real-time machine and machining process data to monitor, troubleshoot, diagnose, and predict faults and failures for the machine. The machine health digital twin can provide actionable recommendations for users or send control commands directly to the machine by: 1. Monitoring machine conditions and status 2. Visualizing data such as utilization, overall machine effectiveness, and machine downtime by shift, process, or operator 3. Validating and updating adjusted machining process schedules 4. Scheduling machine maintenance
Stakeholders	Manufacturing shop floor personnel, researchers, and machine vendors.
Key technologies	Data analytics, modeling and simulation
Relevant standards	MTConnect, AP238 (STEP-NC), and AP242 (Managed model-based 3D engineering) for machining data collection, machine tool modeling respectively.

Fig. 2 shows a high-level mapping of the Machine Health Digital Twin to the reference architecture defined in ISO/DIS 23247. A typical operational procedure of a machine health digital twin and a list of potential functional entities in each domain are briefly discussed as follows:

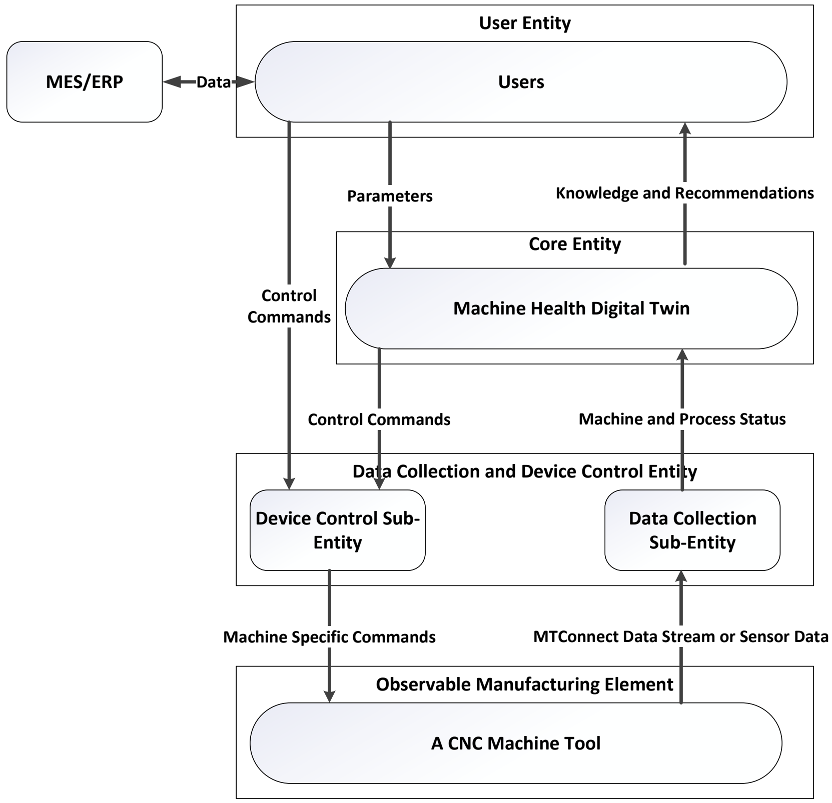

Fig. 2. A mapping of the Machine Health Digital Twin to the ISO/DIS 23247 reference architecture.

- Through the DCDCE, the Machine Health Digital Twin collects, stores, and analyzes machine information and KPIs such as spindle speeds, feed rates, machine energy consumption, temperature, pressure, volume, vibrations, noise levels, and humidity. The KPI values can reflect any abnormalities for certain situations. For example, machine status and conditions can be continuously monitored using the MTConnect data standard and some smart sensors. In addition, static data for building the digital twin can be selected either from the machine specifications provided by machine vendors or from the handbooks such as Shock and Vibration Handbook [16]. The FEs within DCDCE include:
    - Data Collecting FE. The FE collects machine and process data from the machine using the MTConnect standard.

  - Data Pre-processing FE. The FE pre-processes the collected data, e.g., data cleaning, data integration, and data transformation.
  - Controlling FE. The FE controls the machine through the user or the digital twin. In some cases, a translator may be needed to convert control commands to a machine specific format.
  - Actuation FE. The FE actuates the machine valves according to the commands from the user or the digital twin.
- In the CE, the machine health digital twin simulates the machining process and dynamically compares the collected machine operational KPIs with their permissible values. Depending on the nature and severity of the problem, any major deviation from the allowed limits is addressed, either by sending the machine control commands automatically or by sending notices to the user (e.g., maintenance personnel) with actionable recommendations; thus the problem can be resolved before it causes any major failure or damages. The control commands that are sent to the machine directly could control an on/off switch, warning alarm, or automatic shut-off system. The machine health digital twin allows users to visualize data such as utilization, overall equipment effectiveness, and machine downtime by shift, process, or operator. For those new faults that there exists no prior knowledge on KPI limits, and possible solutions, experts' opinion will be sought and added as new knowledge to the digital twin for future reference. Therefore, the capability of the digital twin can be continuously strengthened to become more comprehensive. In the CE, the applicable FEs for the digital twin (a subset of the FEs in Fig. 1) are presented below.
  - Digital Representation FE. The FE models static information of the machine and dynamic data collected from machining processes to represent the machine's characteristics, status, and conditions. Information models defined in relevant standards (e.g., STandard for the Exchange of Product model data (STEP)) can be used [17].
  - Simulation FE. The FE simulates and predicts the behavior of the machine. Both normal operation data and failure data are needed to build the machine simulation, which should be modeled using relevant standards or commercial simulation tools.
  - Analytic Service FE. The FE analyzes data collected from the machine, machining process, and the simulation results.
  - Application Support FE. The FE provides services for implementing a predictive maintenance application.

    - Synchronization FE. The FE synchronizes the digital twin parameters with the status of the machine.
    - Presentation FE. The FE presents information in an appropriate format of text, tables, charts, audio or video for human users to view and understand the digital twin results.
    - Reporting FE. The FE generates digital twin analysis and prediction reports.
- In the UE, the users may be decision makers, maintenance personnel or machine operators who interact with the digital twin, the machine, or existing enterprise systems such as product lifecycle management (PLM) systems, MES, and ERP systems. The actionable recommendations or decisions including suggested operating parameters are presented to the user by the digital twin. A corresponding action can be taken at an appropriate time (either online or offline) by the responsible party so that the problem can be addressed timely.
- Three FEs are included in the Cross-System Entity (CSE):
    - Data Assurance FE. The FE ensures the accuracy and integrity of the collected data.
    - Security Support FE. The FE secures the machine health digital twin in authentication, authorization, confidentiality, and integrity.
    - Data Translation FE. The FE supports translations of the exchanged data between entities. The translations may be through protocol conversion, syntax adaptation, and semantic awareness.

4.2 Scheduling and Routing Digital Twin

To respond to the market demand for more customized products, manufacturing systems need to be more flexible to produce different products using the same resources. This includes routing flexibility and machine flexibility, i.e., an operation can be executed in more than one machine or a machine can perform more than one operation for resource sharing. A scheduling and routing digital twin can collect data from shop-floor systems such as production equipment, MES, and ERP systems to analyze the current status of the production system for identifying possible fluctuations in customer demand, inventory, and resources (i.e., material, labor, and equipment). The digital twin uses the knowledge from data modeling and analysis to enable demand-driven, on-time delivery, resource optimization, cycle-time reduction, and inventory-cost reduction. Table 2 provides a summary of the Scheduling and Routing Digital Twin for the use case number 2.

Table 2 A summary of the Scheduling and Routing Digital Twin use case.

ID	Case number 2
Use case name	Scheduling and Routing Digital Twin
Application field	Smart manufacturing.
Life cycle stage(s)/phase(s) coverage	Production
Status	Proof of concept
Scope	Automated manufacturing process tracking and schedule adjustment based on variable conditions of production in a manufacturing cell
Initial (Problem) Situation	Manufacturing process requirements can vary based on customer order changes, resource availability, and inventory levels. Manual adjustments of the manufacturing schedules are time-consuming and create risks of not meeting production goals. In addition, the changes may not be properly tracked.
Objective(s)	Optimize schedules and routings during production.
Short description	Manufacturing cells need to deal with dynamic events that may be unexpected, e.g., condition changes within the manufacturing environment, machine breakdowns, customer order changes, unsatisfied inventory levels, and unavailability of labor. Manual adjustments of the manufacturing process are time-consuming and increase risks for the adjusted process not being properly tracked and updated. Therefore, a dynamic schedule is needed to respond to the situation in real-time. A digital twin of scheduling and routing can help: 1. Identify changes during manufacturing 2. Adjust manufacturing process requirements based on real situation 3. Generate and validate adjusted manufacturing process schedules and routings
Stakeholders	Manufacturing shop floor personnel, researchers, and equipment vendors.
Key technologies	Automation, data analytics, simulation, optimization
Relevant standards	MTConnect, STEP, and Core Manufacturing Simulation Data (CMSD) [18] for equipment and process data collection and digital twin modeling.

Fig. 3 shows a high-level mapping of the Scheduling and Routing Digital Twin to the reference architecture defined in ISO/DIS 23247. A typical operational procedure of a scheduling and routing digital twin and a list of potential FEs in each domain are briefly discussed as follows:

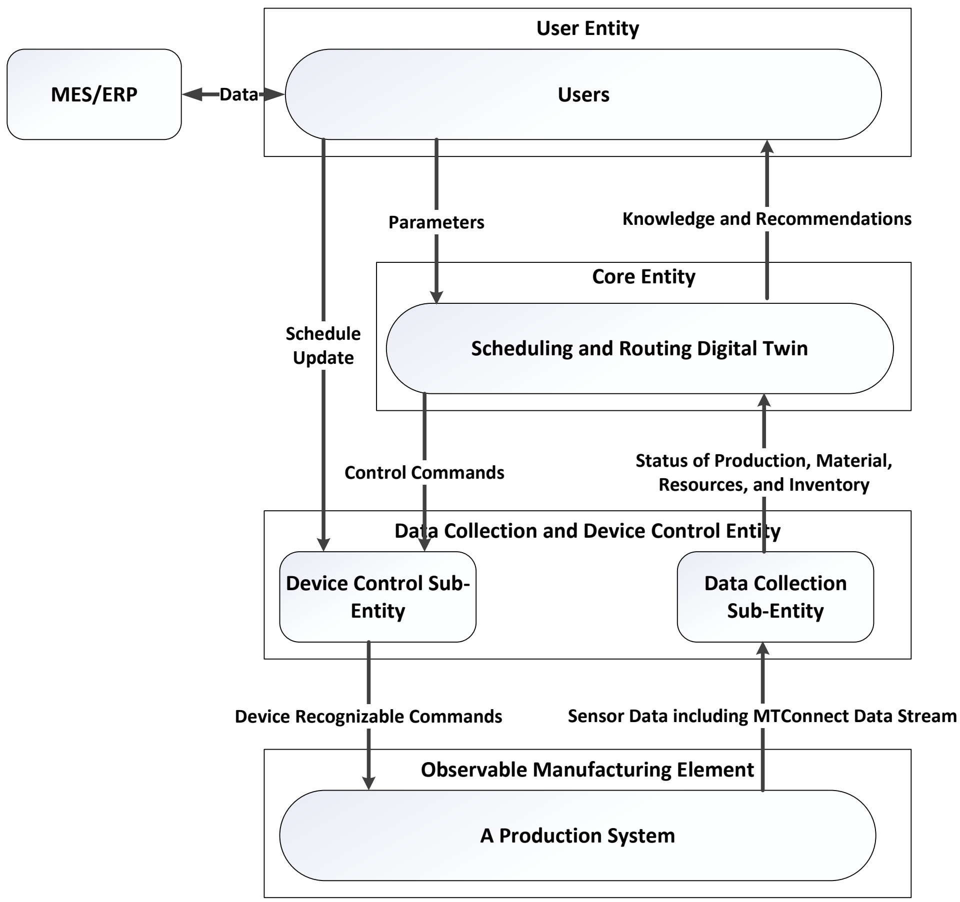

Fig. 3. A mapping of the Scheduling and Routing Digital Twin to the ISO/DIS 23247 reference architecture.

- Through the DCDCE, the scheduling and routing digital twin collects near real-time data from the manufacturing systems to analyze the current status of the production system and possible fluctuations in customer demand, inventory, and resources. Data standards (e.g., MTConnect) and smart sensors are used for collecting such data. The digital twin updates the production schedule according to the shop floor changes to achieve demand-driven, on-time delivery, resource optimization, cycle time reduction, and inventory-cost reduction.

    - Data Collecting FE collects equipment and process data from the shop floor.
    - Data Pre-processing FE pre-processes collected data, e.g., data cleaning, data integration, and data transformation.
    - Controlling FE controls the manufacturing equipment either by the user or by the digital twin.
    - Actuation FE actuates the machine valves according to the commands received from the user or the digital twin.

- In the CE, the Scheduling and Routing Digital Twin dynamically analyzes the production requirements and the production system's operational KPIs to reconfigure the system to handle dynamic events and the uncertainty during the processes. For example, maintenance activities need to be scheduled to ensure minimum interruption of the production. Another example is process preemption, i.e., to restart a process from the same point when an operation has been interrupted to minimize the negative impact. Therefore, scheduling and routing need to be updated dynamically. The Scheduling and Routing Digital Twin also needs to model (1) the precedence constraints among the operations of different products; (2) the transportation time of an element (e.g., raw material, a product component); (3) just-in-time concept that enables the due-date satisfaction and unnecessary inventory cost reduction; (4) processing times with unexpected overtime caused by resources deterioration, setup mistakes, or negative impact from the environment; (5) buffer storage capacity [19].
    - Digital Representation FE models static information of the manufacturing system and dynamic data collected from the manufacturing processes to represent the system's capability, characteristics, status, and conditions. Standardized information models should be used.
    - Simulation FE simulates and predicts the behavior of the manufacturing processes. CMSD and commercial simulation tools can be used.
    - Analytic Service FE analyzes the data collected from the manufacturing equipment, the manufacturing processes, and the simulation results.
    - Synchronization FE synchronizes the digital twin parameters with the status of the machine.

- Presentation FE presents information in an appropriate format of text, tables, charts, audio or video for human users to view and understand the digital twin results.
- Reporting FE generates digital twin analysis and recommendation reports.

- Through the UE, control commands or an updated optimal production schedule can be sent to the shop floor automatically or sent to the users, who interact with both the digital twin and DCDCE, with actionable recommendations. The actionable recommendations or decisions including suggested adjustment of the production schedule are communicated from the digital twin to the users. The users can visualize data such as order status, resource availability, inventory levels for components and products, resource utilization, production throughout, overall equipment effectiveness, and machine downtime by shift, process, or operator.
- The following FEs are from the CSE:
    - Data Assurance FE ensures the accuracy and integrity of collected data.
    - Security Support FE secures the digital twin in authentication, authorization, confidentiality, and integrity.

4.3 Virtual Commissioning Digital Twin

Commissioning a manufacturing system can be very expensive and time-consuming. As an alternative, virtual commissioning can be used to identify and resolve issues before investment and avoid costly adjustments during or after installation of manufacturing equipment. Virtual commissioning uses simulation technology to design, test, evaluate control systems before connecting them to the real equipment or system. Virtual commissioning can be used for any of the four levels on a manufacturing shop floor: (1) machine level, (2) production cell level, (3) production line level, and (4) production system level [20].

A virtual commissioning digital twin is a dynamic, virtual representation of its corresponding physical element (e.g., a machine, a cell, a line or a system) that is used to substitute its physical element for the purpose of commissioning. It needs to be modeled at the level of sensors and actuators. For example, the Programmable Logic Controller (PLC) logic and rules need to be represented within a machine digital twin. Depending on the purpose, there could result many different virtual commissioning digital twins, for example, a virtual commissioning of an existing production system (i.e., the manufacturing equipment was installed but needs adjustment) or a virtual commissioning of a newly designed production system (i.e., manufacturing equipment is not in place or not even purchased).

This case is about a virtual commissioning digital twin of a CNC machine tool that has not been installed, however, a virtual commissioning digital twin is designed and developed to test and optimize control strategies, control parameters, and NC programs. A real controller is connected to the digital twin so that potential errors of control programs and control strategies can be detected before the real commissioning stage. By testing against the digital twin, various control strategies can be tried out. The digital twin's response to different control strategies can be visualized and analyzed. After optimizing the control strategies virtually, the newly developed and validated control program can be deployed onto the physical machine, when available. Table 3 provides a summary of the Virtual Commissioning Digital Twin of a CNC machine tool for use case number 3.

Table 3 A summary of the Virtual Commissioning Digital Twin use case.

ID	Case number 3
Use case name	Virtual Commissioning Digital Twin
Application field	Smart manufacturing.
Life cycle stage(s)/phase(s) coverage	Design
Status	Proof of concept
Scope	Perform virtual commissioning using a digital twin to ensure an optimal, on-time, cost-effective installation and operation of a CNC machine tool.
Initial (Problem) Situation	CNC machine tools are normally large, heavy, and difficult to handle or requires to be assembled on a production site, which makes the installation and commissioning of a machine a very complex and time-consuming process. Any unpredicted problems would delay the process and might cause costly consequences.
Objective(s)	Optimize the control strategy using a digital twin of a machine tool.
Short description	The design and implementation of a new machining system involve many tasks. Before production, commissioning, an important step, needs to be performed to integrate controls, identify and fix control system bugs, test and verify parts' NC programs, test and optimize the servo dynamic parameters, finalize operational procedures, etc. Using a real machine for these tasks not only is time-consuming, but also interrupts its production, or even results a wrong investment decision (i.e., bought and installed a machine that is not best suited for the production requirements). Virtual commissioning help streamline the commissioning process, optimize designs, eliminate the risk of machine tool damage, and reduce cost. A

	virtual commissioning digital twin helps develop, test, verify, diagnose, and adjust the control system in a virtual environment. The digital twin also maintains a record of abnormal events during virtual commissioning for future reference. The digital twin enables: 1. Control code testing and debugging 2. Machining simulation, possibly, problem identification (e.g., collisions), and what-if scenario analysis 3. Optimize control parameters such as servo parameters 4. NC program verification 5. The development of operating procedures 6. The training of operators
Stakeholders	Manufacturing shop floor personnel, researchers, and equipment vendors.
Key technologies	Automation, simulation, and control
Relevant standards	CMSD, STEP and MTConnect may be used to describe digital twins of the machine.

Because the real machine tool is not yet installed in this case, this digital twin is different from the other two digital twins discussed in 4.1 and 4.2. This digital twin does not have real-time connection with the machine. Instead, after the Virtual Commissioning Digital Twin is developed, the digital twin will be controlled by a real physical controller (Supervisory controller, a higher level controller) to test and evaluate the control strategies, the NC programs, and other machine parameters (e.g., servo parameters). Tabletop PLCs, sensors and actuators may be needed to emulate the real inputs and outputs.

Ideally, a digital twin of a machine tool is provided by its machine vendor so that the virtual commissioning can start with that digital twin. In reality, a virtual commissioning digital twin often needs to be developed from scratch. Fig. 4 provides a high-level mapping of the Virtual Commissioning Digital Twin to the reference architecture defined in ISO/DIS 23247. The dotted arrows represent the abstract connections between the real machine and its digital twin. The CE and the UE work together to perform the virtual commissioning. The completed and verified digital twin of the CNC machine tool will be connected to the supervisory controller to test the control strategies.

The design and operational procedure of the Virtual Commissioning Digital Twin is briefly discussed as follows:

- Data required to model the machine tool digital twin include static information, such as machine specification and machine handbooks from the vendor of the machine and operational data such as velocity, position, and torque data from different components, from the similar operational machines. The DCDCE helps collect such data.

- The Virtual Commissioning Digital Twin should behave as the real machine. In the CE, the digital twin models (1) logical representations of the machine including the machine's characteristics and behavior. For example, the digital twin mimics the real machine, sends messages when needed, and accepts commands for corresponding actions; (2) physical description, including geometrical, electrical, and kinematics of the machine, which allows users to simulate the machine's functionalities and better understand the machine's capability, capacity, safety, and ergonomics [21]; (3) control algorithms including proportion and integration (PI) parameters that drive the machine simulation; and (4) uncertainties including these discussed in [22] to improve model accuracy. Appropriate standards and technologies, e.g., SETP AP 242, CAD/CAM tools, simulation software, and Augmented Reality (AR) and Virtual Reality (VR) applications, can be used for the digital twin modeling.
    - Digital Representation FE models static information of the machine and dynamic data from the machining processes to represent the machine's capability, characteristics, and behavior. Standardized information models such as CMSD can be used.
    - Simulation FE simulates and predicts the behavior of the machine. CMSD and 3D commercial simulation tools can be used.
    - Presentation FE presents information in an appropriate format of text, tables, charts, audio or video for human users to view and understand the digital twin results.
    - Reporting FE generates digital twin analysis and recommendation reports.
- In the UE, a supervisory controller sends control commands generated by various control strategies to the digital twin. These control commands drive the simulation of the digital twin. The what-if capability of the digital twin allows the user to optimize the control strategies and visualize data generated from different options. Once the optimal control strategy is developed, tested, and selected, it is ready for use with the physical machine, when available. In addition, both dynamic commissioning and kinematic commissioning need to be performed [23].
    - Dynamic commissioning: Dynamic performance depends on the load and machining parameters such as servo parameters, which need to be tested and tuned for achieving stable dynamic performance.

- Kinematic commissioning: The machine motions of all axes are driven by the NC programs. The digital twin will assess NC programs for collision control and part accuracy.

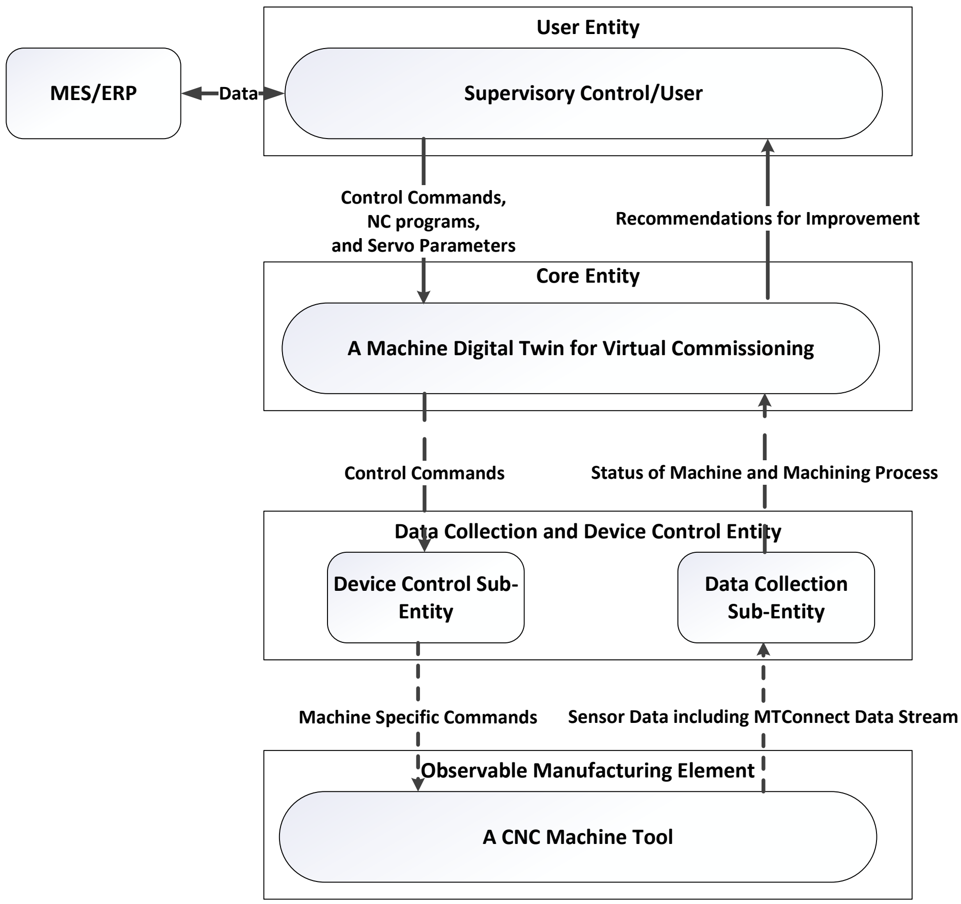

Fig. 4. A mapping of the Virtual Commissioning Digital Twin to the ISO/DIS 23247 reference architecture.

After the virtual commissioning, the controller programs will be updated with the optimal control strategies. In some cases, when the real machine is installed, the digital twin can then be connected to the real machine to perform real-time analysis for various purposes, e.g., machine health check. The dotted arrows in Fig. 4 therefore become solid. In other cases, the digital twin will be replaced by the real machine, i.e., the updated supervisory controller will control the real machine. The disconnected digital twin can continue to serve as a virtual commissioning twin for other machines or be used as an off-line simulation model.

5. Conclusion and Future Work

As a key part of digital transformation, digital twin is an important concept helping achieve smart manufacturing. Relevant standards can facilitate the design and implementation of digital twins in manufacturing by providing common terminology and implementation guidelines. In this paper, ISO/DIS 23247, Digital Twin Framework for Manufacturing, is introduced. To demonstrate the use of this standard, three digital-twin in manufacturing use case scenarios are explored in depth and the procedures of implementing such use cases according to the ISO/DIS 23247 framework are presented.

In the near future, the design and implementation for these use cases will be realized at the NIST SMS Test Bed or on any manufacturing shop floor with similar maturity level on digital transformation. In addition, using the same approach, more manufacturing use cases of digital twins can be designed and implemented. The results of these implementations can serve as useful inputs for subsequent standards and technology development.

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