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R	Document, report (excluding the periodic and final reports)	x
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc	
DATA	Data sets, microdata, etc	
DMP	Data management plan	
ETHICS	Deliverables related to ethics issues	
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OTHER	Software, technical diagram, algorithms, models, etc	

Dissemination level		
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**LIST OF ABBREVIATIONS**

<b>AAS</b>	Asset Administration Shell
<b>ANSI</b>	American National Standards Institute
<b>DPP</b>	Digital Product Passport
<b>DTDL</b>	Digital Twins Definition Language
<b>IEC</b>	International Electrotechnical Commission
<b>IEEE</b>	Institute of Electrical and Electronics Engineers
<b>IIC</b>	Industrial Internet Consortium
<b>IoT</b>	Internet of Things
<b>ISO</b>	International Organization for Standardization
<b>ISA</b>	International Society of Automation
<b>JTC 1</b>	Joint Technical Committee 1
<b>MDS</b>	Manufacturing Data Space
<b>MTConnect</b>	A manufacturing technical standard
<b>OPC UA</b>	Open Platform Communications Unified Architecture
<b>RAMI 4.0</b>	Reference Architectural Model Industrie 4.0
<b>SC 41</b>	Subcommittee 41 (specifically within ISO/IEC JTC 1)
<b>XML</b>	Extensible Markup Language
<b>JSON</b>	JavaScript Object Notation

## 1. Executive summary

Digital twins are rapidly transforming industries by providing virtual representations of physical assets, processes, and systems. Their power is amplified when they can seamlessly interact and exchange information – a concept known as interoperability. This paper examines the current landscape of digital twin interoperability, exploring the diverse types of digital twins, the various levels of interoperability (technical, syntactic, semantic, and organizational), and the inherent challenges. The core of the paper focuses on existing and emerging standards and approaches that are driving interoperability, including key frameworks like RAMI 4.0, ISA-95, ISO 23247, and the IIC Digital Twin Framework. We also delve into crucial modelling and semantic interoperability standards like DTDL, IEC 62832, AAS, and OPC UA. Finally, we highlight promising emerging standards such as the Manufacturing Data Space (MDS), Digital Product Passport (DPP), IEEE P2806, and the work of ISO/IEC JTC 1/SC 41. By understanding these standards and approaches, organizations can effectively develop and deploy interoperable digital twin solutions, unlocking significant potential for automation workflows and driving innovation.

## 2. Introduction

The increasing complexity of industrial automation workflows demands sophisticated tools for design, simulation, monitoring, and control. Digital twins, virtual representations of physical entities, have emerged as a powerful solution to address these challenges. They enable organizations to analyze, optimize, and even predict the behaviour of their physical assets in a virtual environment. However, the true potential of digital twins is realized when they can seamlessly interact and exchange information with each other and other systems. This is where interoperability becomes crucial.

This paper provides a comprehensive overview of current standards and approaches for achieving digital twin interoperability in automation workflows. We begin by exploring the diverse landscape of digital twins, categorizing them based on scope, interaction, and capability levels. We then delve into the different levels of interoperability, highlighting the importance of addressing technical, syntactic, semantic, and organizational aspects. The challenges to interoperability, such as data volume, security concerns, legacy system integration, and the lack of common data standards, are also discussed.

The core of the paper focuses on the existing and emerging standards that are shaping the future of digital twin interoperability. We examine established frameworks and architectures, including RAMI 4.0, ISA-95, ISO 23247, ISO/IEC 30141, the IIC Digital Twin Framework, and IPC 2551. We also explore the critical role of modelling and semantic interoperability, highlighting standards like DTDL, IEC 62832, the Asset Administration Shell (AAS), and OPC UA. Finally, we look at emerging standards like the Manufacturing Data Space (MDS), Digital Product Passport (DPP), IEEE P2806, and the work of ISO/IEC JTC 1/SC 41, which are poised to further advance digital twin interoperability. By providing a comprehensive overview of these standards and approaches, this paper aims to guide organizations in developing and implementing interoperable digital twin solutions for their automation workflows.

### 3. Interoperability in Digital Twins

The concept of interoperability is fundamental to realizing the full potential of digital twins. It refers to the ability of two or more digital twins, or a digital twin and another system, to exchange information and utilize the information that has been exchanged. Without interoperability, digital twins risk becoming isolated silos of data, limiting their value and hindering collaboration. This chapter explores the critical aspects of interoperability in the context of digital twins, examining the diverse landscape of digital twins, defining the different levels of interoperability, and outlining the key challenges that must be addressed to achieve seamless data exchange and collaboration. A clear understanding of these elements is crucial for developing and deploying effective digital twin solutions that can integrate seamlessly within complex automation workflows.

#### 3.1. Understanding the Diverse Landscape of Digital Twins

This section explores the diverse landscape of digital twins, examining the different types that exist based on various criteria. It delves into how these different types of digital twins interact with each other and the physical world, providing a comprehensive understanding of their capabilities and potential applications. Understanding the different types and levels of digital twins is crucial for selecting the appropriate digital twin technology for a specific application and enabling effective communication and collaboration between different stakeholders involved in the development and deployment of digital twins.

##### 3.1.1. Digital Twins Based on Scope

Digital twins can be categorized based on their scope, which refers to the extent of the physical asset or system they represent. This categorization helps to define the boundaries and functionalities of a digital twin, clarifying its role and purpose within a specific context. Common categories include product digital twins, process digital twins, system digital twins, and enterprise digital twins.

- **Product digital twins** represent a single product such as a machine, a car, or a consumer electronic device, encompassing its entire lifecycle from design and manufacturing to operation and disposal. This comprehensive representation enables simulation, analysis, and optimization throughout the product's lifecycle.
- **Process digital twins** focus on a specific manufacturing process, such as machining, assembly, or quality control, capturing detailed data related to process parameters, equipment, materials, and environmental conditions to enable optimization and improvement.
- **System digital twins** represent a complex system comprising multiple products and processes, such as a production line, a factory, or a supply chain, capturing the interactions and dependencies between different components to enable simulation and analysis of the overall system behaviour.
- **Enterprise digital twins** take the broadest perspective, representing an entire enterprise, including its products, processes, systems, and business operations, to provide a holistic view enabling strategic decision-making and optimization across different departments and functions.

##### 3.1.2. Digital Twins Based on Interaction

Digital twins can also be categorized based on their level of interaction with the physical world. This categorization reflects the dynamic nature of digital twins and their ability to not only reflect the physical world but also influence it.

- **One-way digital twins** receive data from the physical asset, enabling monitoring and analysis of the asset's performance, but without any feedback or control loop from the digital twin to the physical asset. This type of interaction is suitable for applications where the primary goal is to observe and understand the physical asset's behaviour.

- **Two-way digital twins** enable bidirectional data flow between the physical asset and the digital twin, allowing for real-time monitoring, analysis, and control of the asset. This enables optimization and automation of the asset's operation, making it crucial for applications where active control and optimization are required.

### 3.1.3. 5 Levels of Capability in Digital Twins

The 5 levels of capability in digital twins model provides a framework for assessing the level of sophistication and integration of a digital twin. This model helps to understand the evolutionary path of a digital twin, from a basic representation to a highly integrated and autonomous system. Levels 1 and 2 are categorised to one-way interaction and levels 3 and above are capable of two-way interaction between physical asset and the digital twin.

The five levels are the Digital Twin Maturity are listed in Figure 1.

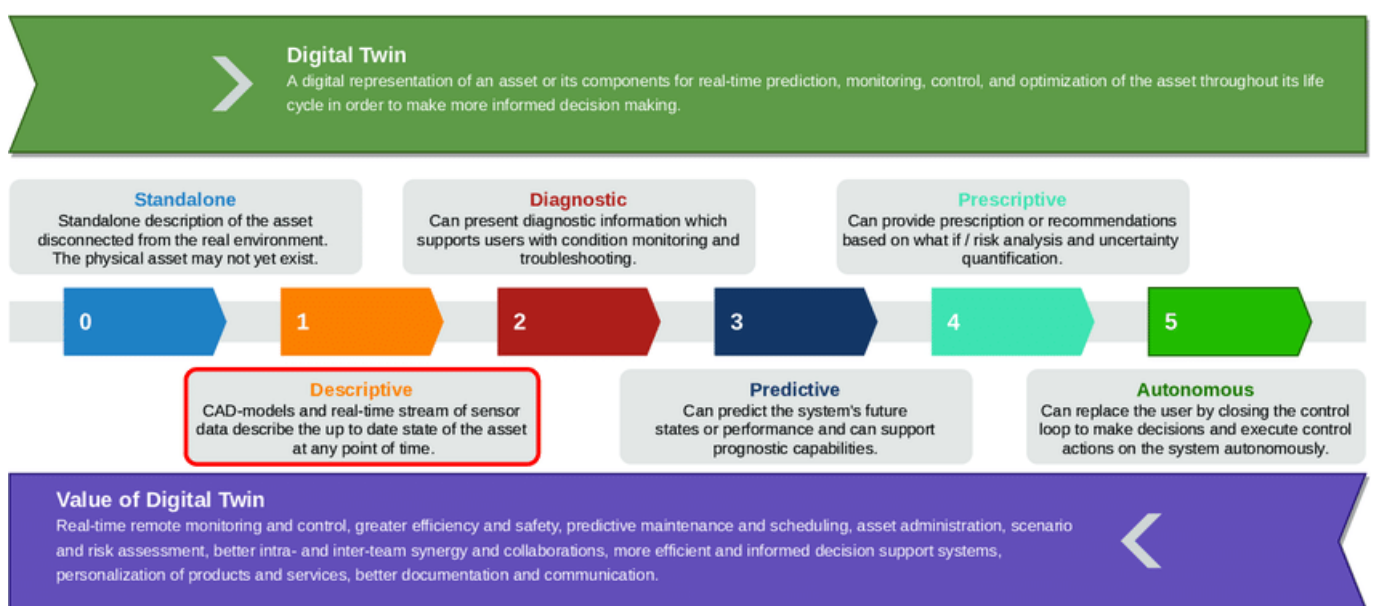


Figure 1: The five levels of digital twin maturity

- **Level 1 - Descriptive:** describes state of the asset using sensor data
- **Level 2 - Diagnostic:** presents real-time data and information about the physical asset's performance and troubleshooting.
- **Level 3 - Predictive:** can predict the future states and performance of the physical asset.
- **Level 4 - Prescriptive:** Provides prescriptions or recommendations based on risk analysis and uncertainty quantification.
- **Level 5 - Autonomous:** can autonomously control and optimize the operation of the physical asset without human intervention.

### 3.1.4. The Importance of Understanding Different Types of Digital Twins

Understanding the different types and levels of digital twins is crucial for selecting the appropriate digital twin technology for a specific application. It also enables effective communication and collaboration between different stakeholders involved in the development and deployment of digital twins. By considering the scope, interaction level, and maturity level of a digital twin, organizations can make informed decisions about their digital twin strategy and ensure that their digital twins meet their specific needs and requirements. This understanding also fosters a common language and framework for discussing

and developing digital twin solutions, promoting interoperability and collaboration across different domains, industries, and stakeholders.

### **3.2. Different Levels of Interoperability**

Interoperability in the context of digital twins is not a monolithic concept but rather encompasses different levels, each with its own specific requirements and challenges. To achieve seamless communication and data exchange between digital twins and other systems, it is essential to address interoperability at various levels, ensuring that data can be exchanged, understood, and utilized effectively across different platforms and applications. This section explores the different levels of interoperability that are crucial for realizing the full potential of digital twins.

#### **3.2.1. Technical Interoperability (Data Exchange)**

Technical interoperability focuses on the ability of different systems and applications to exchange data seamlessly. This involves establishing standardized communication protocols, interfaces, and data formats that enable the transfer of data between digital twins and other systems without loss or corruption. Technical interoperability ensures that data can be physically transmitted and received between different platforms, laying the foundation for higher levels of interoperability.

#### **3.2.2. Syntactic Interoperability (Data Format)**

Syntactic interoperability deals with the structure and format of the data being exchanged. It ensures that the data is encoded and decoded in a consistent manner, allowing different systems to interpret and understand the data correctly. This involves using standardized data formats, such as XML or JSON, and defining clear rules for data representation and organization. Syntactic interoperability ensures that the data received by one system can be parsed and understood by another system, enabling meaningful data exchange.

#### **3.2.3. Semantic Interoperability (Meaning & Context)**

Semantic interoperability goes beyond the structure and format of data to address its meaning and context. It ensures that the data exchanged between digital twins and other systems is not only understood but also interpreted in a consistent and meaningful way. This involves using standardized vocabularies, ontologies, and semantic models to define the meaning of data elements and their relationships. Semantic interoperability enables different systems to share a common understanding of the data, facilitating collaboration and knowledge sharing.

#### **3.2.4. Organizational Interoperability (Process & Governance)**

Organizational interoperability focuses on the alignment of processes, workflows, and governance structures between different organizations or departments involved in the development and deployment of digital twins. It ensures that there is a common understanding of roles, responsibilities, and procedures for data exchange and collaboration. This involves establishing clear agreements on data ownership, access control, and data quality standards. Organizational interoperability enables seamless collaboration and coordination between different stakeholders, ensuring that digital twins can be effectively integrated into existing workflows and processes.

### **3.3. Challenges in Digital Twin Interoperability**

Digital twin technology offers great potential, but there are challenges to overcome in ensuring different digital twins can seamlessly work together. These challenges arise from the complexity of digital twins, their connections with various systems, and the ever-changing technology landscape.

- **Large quantities of data and complex calculations:** Especially as digital twins become more intricate, this can slow down performance and cause delays. Edge computing, which processes data closer to its source, offers a way to manage this by reducing the burden on central servers.
- **Data security:** Digital twins often handle sensitive information that is shared between different parties. In collaborations between factories, it's crucial to protect confidential information and ensure data ownership remains clear. Secure data sharing methods and encryption are important to address this.
- **Integrating older systems:** Systems that were not designed with digital twins in mind is a hurdle. These older systems often lack the capability to easily connect with newer digital twin platforms, requiring middleware solutions to bridge the gap and integrate older legacy systems.
- **Lack of common data standards:** Data standards are needed to ensure quality and reliability in building digital twins. The used standards need to be agreed between the different parties.

#### 4. Standards and Approaches for digital twin interoperability

This chapter delves into the crucial role of standards and standardized approaches in fostering digital twin interoperability. Interoperability, or the ability of digital twins to seamlessly communicate and exchange information with other systems and applications, is essential for realizing the full potential of digital twin technology. This chapter explores various aspects of interoperability, including reference architectures and frameworks, modelling and semantic interoperability, and emerging standards. By examining these key areas, this chapter aims to provide a comprehensive overview of the current landscape and future directions of digital twin interoperability, highlighting the importance of standardization in enabling effective collaboration, data exchange, and innovation within and across different domains.

##### 4.1. Reference Architectures & Frameworks

This section explores various reference architectures and frameworks that provide a foundation for the development and implementation of digital twins, with a focus on their role in promoting interoperability. These architectures and frameworks offer standardized approaches for modelling, data exchange, and communication, ensuring that digital twins can seamlessly integrate with other systems and applications within their respective domains. The following subchapters delve into specific examples, including RAMI 4.0, ISA-95, ISO 23247, ISO/IEC 30141, the IIC Digital Twin Framework, and IPC 2551, highlighting their key features and contributions to digital twin interoperability.

##### 4.1.1. RAMI 4.0 (Reference Architectural Model Industrie 4.0)

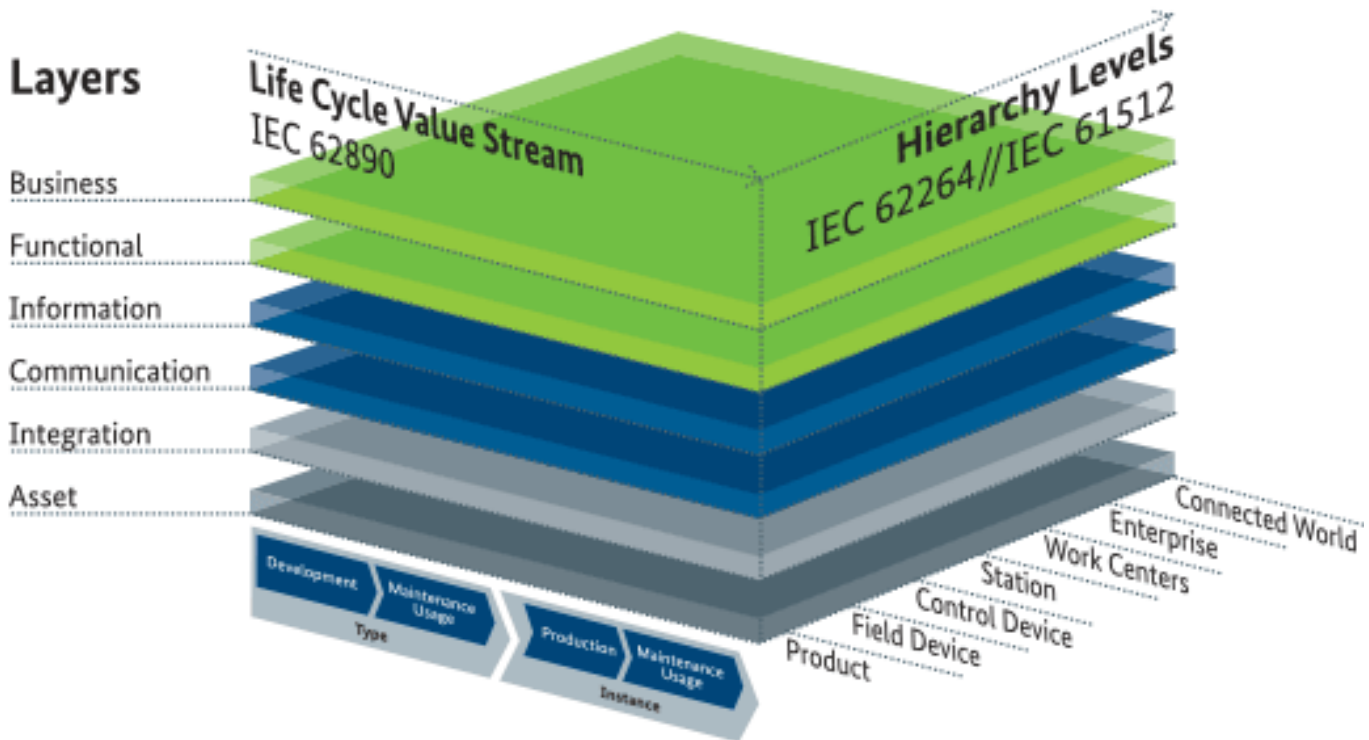


Figure 2: RAMI 4.0 model overview

The RAMI 4.0 standard provides a three-dimensional framework for understanding and categorizing the various aspects of Industry 4.0. This framework is highly relevant for digital twin interoperability as it enables a structured approach to integrating digital twins into the broader Industry 4.0 landscape. By considering the hierarchy levels, life cycle and value stream, and layers defined by RAMI 4.0, digital twins can be developed and deployed in a way that ensures compatibility and interoperability with other Industry 4.0 components.

Key aspects of RAMI 4.0:

- **Hierarchy Levels:** The hierarchy axis defines different levels of the manufacturing process, from the product level to the connected world level. This allows digital twins to be placed at specific levels based on their functionalities, ensuring proper interaction with other components.
- **Life Cycle and Value Stream:** The life cycle and value stream axis represent the different stages of a product's life cycle, from development to production and usage. Digital twins can be associated with specific stages, enabling them to contribute to various phases of the product lifecycle and interact with relevant systems and stakeholders.
- **Layers:** The layers axis defines the different layers of the manufacturing system, from the physical components to the information and business layers. This layered approach allows digital twins to be integrated into specific layers based on their functionalities, ensuring efficient data exchange and collaboration.

By adhering to the RAMI 4.0 framework, digital twins can be seamlessly integrated into the Industry 4.0 environment, promoting interoperability, data exchange, and collaboration. This contributes to the development of robust and interconnected digital twin solutions that enhance manufacturing operations and decision-making within the context of Industry 4.0.

#### 4.1.2. ISA-95 (International Society of Automation - 95)

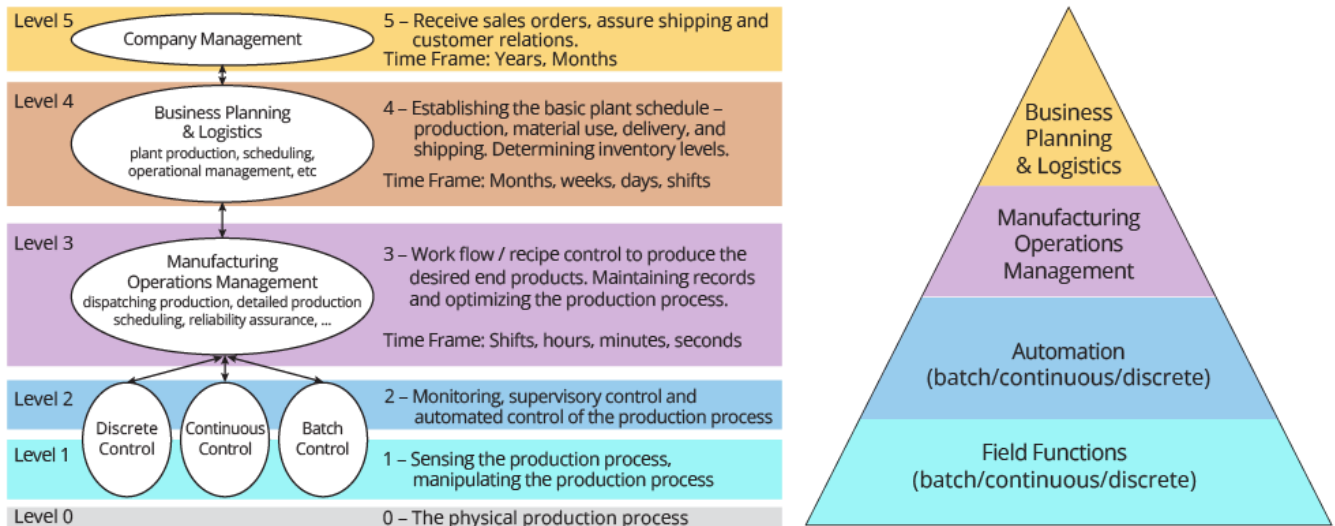


Figure 3: ISA-95 model overview

The ISA-95 standard, also known as ANSI/ISA-95 or IEC 62264, is an international standard for the integration of enterprise and control systems. It provides a framework for organizing and exchanging information between different levels of a manufacturing organization, which is essential for digital twin interoperability.

Key aspects of ISA-95:

- **Hierarchical Model:** ISA-95 defines a hierarchical model with five levels, ranging from process control (Level 0) to enterprise level (Level 4 and 5). This model provides a clear structure for organizing and exchanging information between different levels of the manufacturing operation, allowing digital twins to interact with specific levels based on their functionalities.
- **Data Exchange:** The standard specifies mechanisms for data exchange between different levels, enabling seamless communication between enterprise systems and plant floor devices. This facilitates the integration of digital twins with various data sources, allowing for real-time monitoring, analysis, and control.
- **Activity Models:** ISA-95 defines activity models for common manufacturing operations, such as production scheduling and inventory management. Digital twins can leverage these models to simulate and optimize these activities, improving overall efficiency and productivity.
- **Object Models:** The standard provides object models for manufacturing entities, such as equipment, materials, and personnel. These models can be used to represent and manage digital twins within the manufacturing system, ensuring consistency and interoperability.

By adhering to the ISA-95 standard, digital twins can be seamlessly integrated into the manufacturing environment, enabling efficient data exchange, collaboration, and optimization. This contributes to the development of robust and interoperable digital twin solutions that enhance manufacturing operations and decision-making.

#### 4.1.3. ISO 23247 (Digital Twin Framework for Manufacturing)

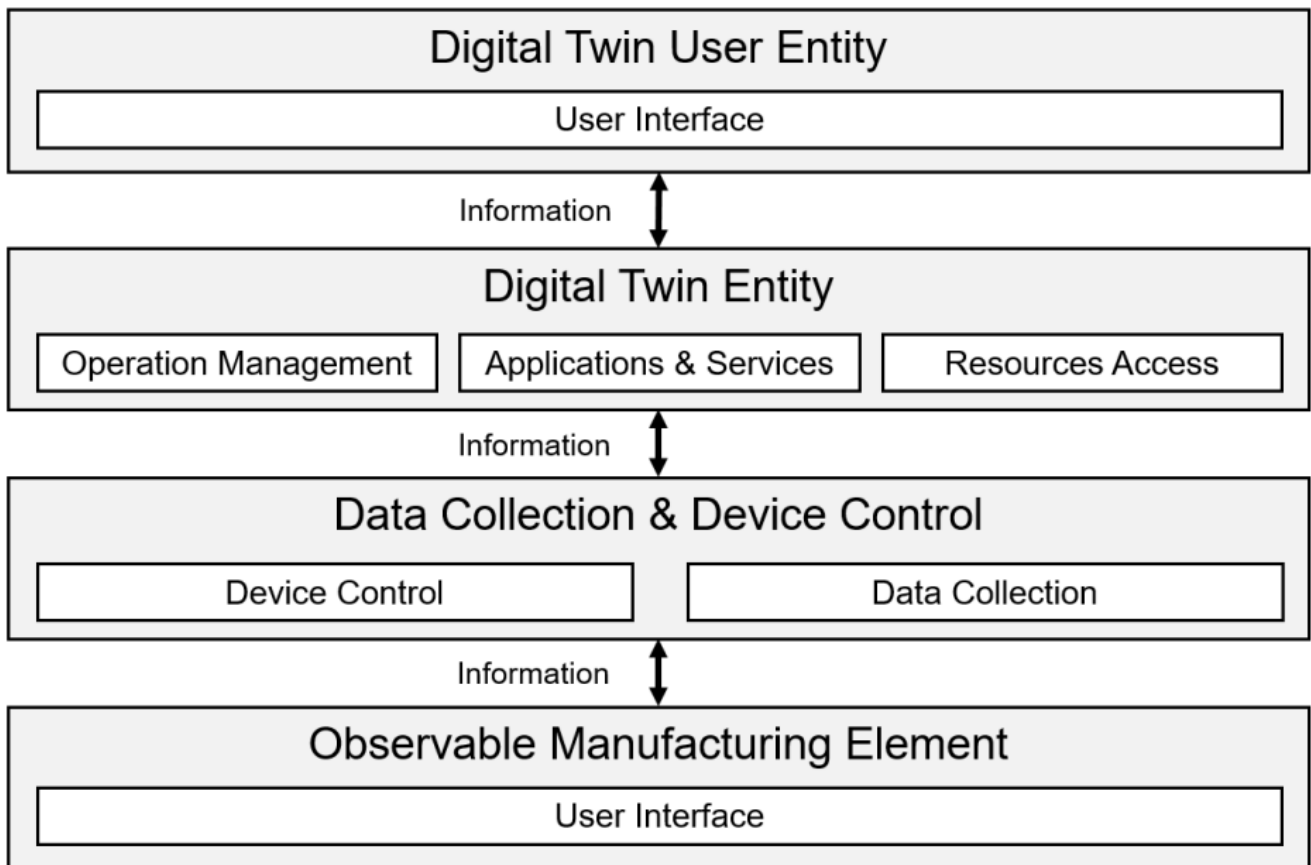


Figure 4: ISO 23247 overview

The ISO 23247 standard provides a comprehensive framework for developing and implementing digital twins in manufacturing. This framework is crucial for ensuring that digital twins are interoperable, enabling them to communicate and exchange information with other systems and stakeholders throughout the manufacturing lifecycle. The standard defines key concepts, characteristics, and a four-layer architectural model for digital twins, promoting a standardized approach to their creation and utilization.

Key aspects of ISO 23247:

- **Standardized Definitions:** The standard provides clear definitions of key concepts related to digital twins, such as digital twin instances, aggregates, and classes. This common understanding facilitates interoperability by ensuring that different stakeholders use the same terminology and concepts.
- **Four-Layer Architecture:** It defines a four-layer architecture for digital twins, consisting of the business, functional, information, and integration layers. This layered approach promotes modularity and interoperability, allowing different systems and applications to interact with digital twins at specific layers based on their needs and functionalities.
- **Data Interoperability:** The standard emphasizes the importance of data interoperability, enabling seamless data exchange between digital twins and other systems. It leverages existing standards like MTConnect and OPC/UA to ensure that data can be shared and understood across different platforms and applications.
- **Lifecycle Management:** ISO 23247 addresses the entire lifecycle of a digital twin, from its creation to its retirement. This lifecycle approach ensures that interoperability is maintained throughout the digital twin's existence, allowing it to interact with different systems and stakeholders at various stages.

By adhering to the ISO 23247 standard, manufacturers can ensure that their digital twins are interoperable with other systems and applications, promoting collaboration, data exchange, and efficient information flow throughout the manufacturing process. This contributes to the development of robust and interconnected digital twin solutions that enhance manufacturing operations and decision-making.

#### 4.1.4. ISO/IEC 30141 (IoT Reference Architecture)

The ISO/IEC 30141 standard defines a reference architecture for the Internet of Things (IoT), providing a standardized framework for designing and implementing IoT systems. This standard is relevant to digital twin interoperability as it enables seamless communication and data exchange between digital twins and various IoT devices and systems. Key aspects include a common IoT system architecture with functional domains, standardized interfaces for interoperability, and security and privacy considerations. Due to limited access to the full standard, this chapter provides only a concise summary.

#### 4.1.5. IIC Digital Twin Framework (Industrial Internet Consortium)

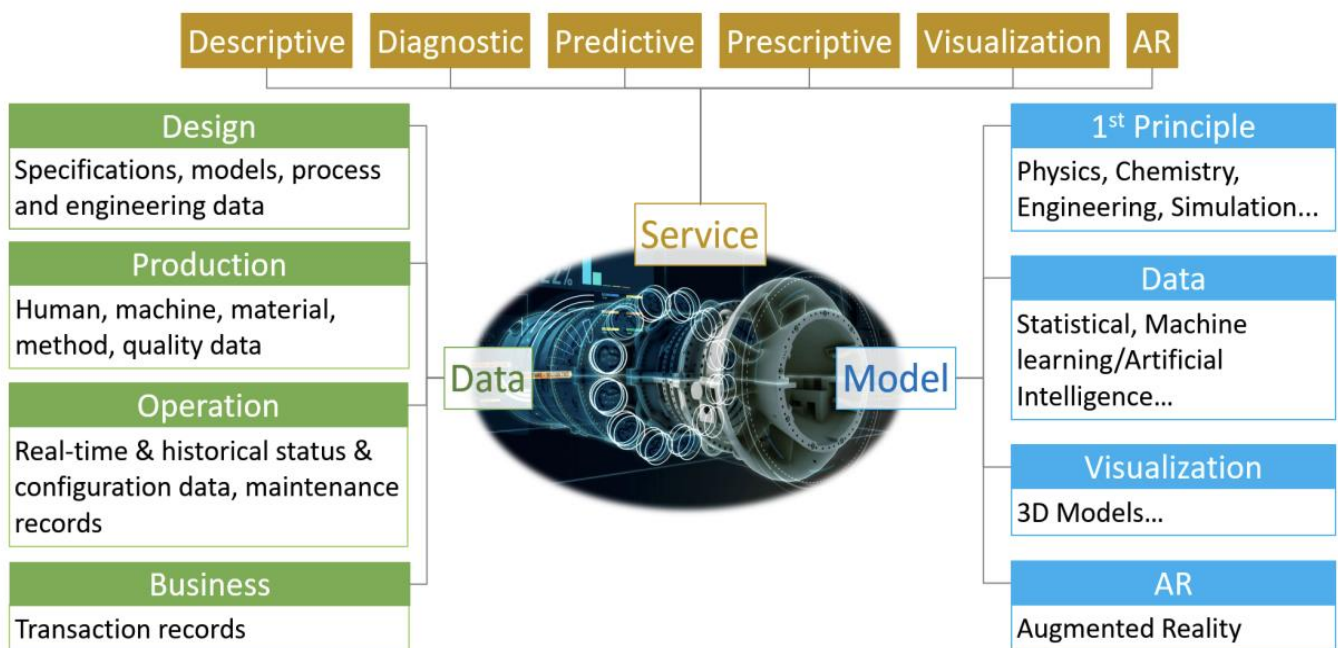


Figure 5: IIC Digital Twin Framework

The Industrial Internet Consortium (IIC) Digital Twin Framework provides a comprehensive guide for the development and implementation of digital twins in industrial settings. This framework is highly relevant for digital twin interoperability as it emphasizes the key characteristics and functionalities necessary for seamless communication and data exchange between digital twins and other systems. It also outlines various deployment patterns and use cases, promoting a standardized and consistent approach to digital twin implementation.

Key aspects of the IIC Digital Twin Framework:

- **Formal Definition:** The framework provides a clear and concise definition of a digital twin, emphasizing its role as a digital representation of a physical asset or system. This shared understanding facilitates interoperability by ensuring that different stakeholders have a common understanding of what constitutes a digital twin.
- **Key Characteristics:** It outlines the key characteristics of a digital twin, such as connectivity, homomorphism, modularity, and actionability. These characteristics ensure that digital twins are designed and implemented in a way that enables interoperability with other systems and applications.

- **Deployment Patterns:** The framework defines different deployment patterns for digital twins, such as prototype, instance, aggregate, and class. This allows for flexibility in implementation while maintaining interoperability, as digital twins can be deployed based on specific needs and functionalities.
- **Use Cases and Applications:** It provides various use cases and applications of digital twins in industrial settings, showcasing their potential benefits and functionalities. This promotes interoperability by demonstrating how digital twins can be integrated into different systems and processes to enhance overall performance and efficiency.

By adhering to the IIC Digital Twin Framework, organizations can ensure that their digital twins are interoperable with other systems and applications, promoting data exchange, collaboration, and efficient information flow. This contributes to the development of robust and interconnected digital twin solutions that enhance industrial operations and decision-making.

#### 4.1.6. IPC 2551 (International Standard for Digital Twins)

The IPC 2551 standard aims to establish a standardized framework for defining, creating, and utilizing digital twins, particularly within the manufacturing industry. This standardization is crucial for digital twin interoperability as it ensures that different digital twins can communicate and exchange information effectively, regardless of their specific implementations or the platforms they reside on. By providing a common set of definitions, guidelines, and data formats, IPC 2551 promotes the seamless integration and collaboration of digital twins within and across various systems and applications.

Key aspects of IPC 2551:

- **Standardized Definition:** The standard provides a clear and concise definition of a digital twin, establishing a common understanding across the industry. This shared definition is essential for interoperability, as it ensures that all stakeholders are referring to the same concept when discussing and implementing digital twins.
- **Data Exchange and Interoperability:** IPC 2551 focuses on enabling efficient data exchange and interoperability between digital twins and other systems. It achieves this by defining standardized data formats and protocols, allowing different digital twins to communicate and share information seamlessly.
- **Smart Value Chains:** The standard promotes the creation of smart value chains by enabling the integration of digital twins across different stages of the product lifecycle. This integration allows for better collaboration, data-driven decision-making, and optimized processes, ultimately leading to improved efficiency and productivity.
- **Reduced Physical Prototyping:** By establishing a robust digital twin framework, IPC 2551 aims to reduce or eliminate the need for physical prototyping. This not only saves time and resources but also improves interoperability by ensuring that digital twins accurately represent their physical counterparts, allowing for reliable simulations and analysis.

By adhering to the IPC 2551 standard, organizations can ensure that their digital twins are interoperable with other systems and applications, promoting data exchange, collaboration, and efficient information flow throughout the manufacturing process. This contributes to the development of robust and interconnected digital twin solutions that enhance manufacturing operations and decision-making.

## 4.2. Digital Twin Modelling and Semantic Interoperability

This section delves into the critical aspects of digital twin modelling and semantic interoperability, examining the standardized approaches and languages that enable effective data exchange and collaboration between digital twins and other systems. The following subchapters explore specific standards and

frameworks that address these aspects, including the Digital Twins Definition Language (DTDL), IEC 62832 (Digital Factory Framework), Asset Administration Shell (AAS, part of RAMI 4.0) and OPC UA (Open Platform Communications Unified Architecture). These standards play a crucial role in ensuring that digital twins can seamlessly integrate into different environments, facilitating communication, data exchange, and collaboration across various systems and applications.

#### 4.2.1. Digital Twins Definition Language (DTDL)

The Digital Twins Definition Language (DTDL) is a language designed specifically for describing digital twin models. It provides a standardized way to represent the characteristics, properties, and relationships of digital twins, enabling interoperability between different digital twin implementations and platforms. DTDL focuses on semantic interoperability, ensuring that the meaning and context of data exchanged between digital twins are well-defined and understood by all involved systems.

Key aspects of DTDL:

- **Standardized Language:** DTDL offers a standardized way to describe digital twin models, ensuring consistency and clarity across different implementations. This promotes interoperability by providing a common language for defining and exchanging information about digital twins.
- **Semantic Interoperability:** The language focuses on semantic interoperability, ensuring that the meaning and context of data exchanged between digital twins are well-defined and understood. This is crucial for enabling meaningful interactions and collaboration between digital twins, as it allows them to interpret and utilize data consistently.
- **Model Reusability:** DTDL allows for the creation of reusable digital twin models, which can be shared and adapted across different applications and industries. This promotes interoperability by providing a common foundation for building and integrating digital twins, reducing the need for custom development and ensuring consistency.
- **Extensibility:** The language is designed to be extensible, allowing for the incorporation of new concepts and functionalities as needed. This ensures that DTDL can adapt to evolving digital twin technologies and requirements, maintaining interoperability in the face of advancements.

By utilizing DTDL, developers can ensure that their digital twins are semantically interoperable, enabling seamless communication and data exchange with other systems and applications. This contributes to the development of robust and interconnected digital twin solutions that enhance various industries and applications.

#### 4.2.2. IEC 62832 (Digital Factory Framework)

The IEC 62832 standard, known as the Digital Factory Framework, provides a standardized approach for creating digital representations of manufacturing systems. This framework is highly relevant for digital twin interoperability as it enables the consistent modelling and exchange of information between digital twins and other digital factory components. Using this standard, digital twins can be seamlessly integrated into the digital factory environment, facilitating communication, data exchange, and collaboration across different systems and applications.

Key aspects of IEC 62832:

- **Standardized Model Elements:** The standard defines a set of standardized model elements for representing various aspects of a manufacturing system, such as equipment, processes, and resources. This ensures consistency in modelling and facilitates interoperability between digital twins and other digital factory components.

- **Digital Representation:** IEC 62832 provides a framework for creating comprehensive digital representations of manufacturing systems, encompassing their physical and logical components. This enables digital twins to accurately reflect the real-world factory environment, facilitating simulation, analysis, and optimization.
- **Lifecycle Management:** The standard supports the entire lifecycle of a manufacturing system, from design and engineering to operation and maintenance. This lifecycle approach ensures that digital twins remain interoperable throughout their lifespan, allowing for continuous data exchange and collaboration.
- **Semantic Interoperability:** IEC 62832 promotes semantic interoperability by defining clear semantics for the model elements and their relationships. This ensures that the meaning and context of data exchanged between digital twins and other systems are well-defined and understood, enabling meaningful interactions and collaboration.

By utilizing the IEC 62832 standard, manufacturers can ensure that their digital twins are interoperable with other digital factory components, promoting data exchange, collaboration, and efficient information flow. This contributes to the development of robust and interconnected digital twin solutions that enhance manufacturing operations and decision-making within the context of the digital factory.

#### 4.2.3. Asset Administration Shell (AAS, part of RAMI 4.0)

The Asset Administration Shell (AAS) is a key component of the RAMI 4.0 framework, serving as a standardized digital representation of an asset. It provides a structured approach for organizing and accessing information about assets, enabling interoperability between different systems and applications within the Industry 4.0 environment. The AAS facilitates communication, data exchange, and collaboration by providing a standardized interface for interacting with assets and their associated data.

Key aspects of AAS:

- **Standardized Interface:** The AAS provides a standardized interface for accessing and managing information about assets, ensuring consistency and interoperability between different systems and applications. This allows digital twins to seamlessly interact with other components in the Industry 4.0 environment.
- **Information Model:** The AAS includes an information model that defines the structure and semantics of the data associated with an asset. This model facilitates interoperability by ensuring that different systems and applications can interpret and utilize the data consistently.
- **Submodels:** The AAS can be further divided into submodels, each representing a specific aspect or domain of the asset. This modular approach promotes interoperability by allowing different systems and applications to access and interact with specific aspects of the asset based on their needs and functionalities.
- **Semantic Interoperability:** The AAS promotes semantic interoperability by using standardized data formats and vocabularies. This ensures that the meaning and context of data exchanged between digital twins and other systems are well-defined and understood, enabling meaningful interactions and collaboration.

By utilizing the AAS, digital twins can be seamlessly integrated into the Industry 4.0 environment, promoting interoperability, data exchange, and collaboration. This contributes to the development of robust and interconnected digital twin solutions that enhance manufacturing operations and decision-making within the context of Industry 4.0.

#### 4.2.4. OPC UA (Open Platform Communications Unified Architecture)

OPC UA (Open Platform Communications Unified Architecture) is a platform-independent, service-oriented architecture that provides a standardized framework for data exchange and communication in industrial automation systems. It is highly relevant for digital twin interoperability, modelling, and semantic interoperability due to its ability to enable secure and reliable data exchange between digital twins and other systems, while also providing rich information modelling capabilities.

Key aspects of OPC UA:

- **Standardized data models:** OPC UA offers a vast collection of standardized data models for various types of industrial equipment, ensuring consistent data representation across different systems. These standardized data models provide a common language for digital twins and other systems to exchange information about industrial assets, processes, and phenomena, facilitating interoperability and understanding.
- **Information model:** The OPC UA information model, based on a flexible, object-oriented structure, enables the representation of complex digital twin structures and relationships. This information model allows digital twins to capture the intricate details of physical assets and their interactions, supporting comprehensive and accurate digital representations.
- **Extensible security profiles:** OPC UA incorporates robust security mechanisms, including authentication, authorization, and encryption, ensuring secure data exchange between digital twins and other systems. This ensures that sensitive data exchanged between digital twins and other systems remains confidential and protected from unauthorized access and modification.
- **Service-oriented architecture (SOA):** The service-oriented architecture of OPC UA promotes modularity and flexibility, allowing digital twins to easily integrate with various services and applications. This modularity enables digital twins to interact with a wide range of systems and services, promoting interoperability and facilitating the development of complex, interconnected solutions.
- **Cross-platform compatibility:** OPC UA is designed to be platform-independent, enabling interoperability between digital twins running on different operating systems and hardware platforms. This cross-platform compatibility ensures that digital twins can be deployed and interact seamlessly across diverse environments, regardless of the underlying technology stack.
- **Open-source implementations:** Open-source implementations of OPC UA are available, providing developers with the tools and resources to build and deploy digital twin solutions based on this standard. These open-source implementations promote accessibility and flexibility, allowing developers to customize and extend OPC UA to meet the specific needs of their digital twin applications.

These key aspects of OPC UA collectively contribute to its significance in the realm of digital twin interoperability. By enabling seamless and standardized data exchange, OPC UA ensures that digital twins and other systems can readily share and interpret information, regardless of the specific platform or technology used. This fosters a cohesive and interconnected environment where data flows freely and accurately between different components. Moreover, OPC UA prioritizes secure communication and data protection, safeguarding digital twin interactions from unauthorized access and potential cyber threats. This security aspect is crucial for maintaining the integrity and confidentiality of sensitive information shared within the digital twin ecosystem.

Furthermore, OPC UA's service-oriented architecture promotes modularity and extensibility, allowing digital twins to seamlessly integrate with a wide range of services and applications in the industrial automation domain. This flexibility enables the development of complex, interconnected solutions that can adapt to evolving needs and technological advancements. The platform-independent nature of OPC UA further enhances interoperability, allowing digital twins to be deployed and interact seamlessly across diverse environments, regardless of the underlying hardware or operating system. This fosters a truly

interconnected ecosystem where digital twins can collaborate and exchange information without constraints.

Additionally, OPC UA provides comprehensive data representation and modelling capabilities, empowering developers to build intricate digital twins that accurately reflect the complexities of the physical world. This high-fidelity representation enables more accurate simulations, analysis, and decision-making based on the digital twin's insights. Finally, OPC UA promotes semantic interoperability by ensuring a consistent understanding of data meaning across different systems. This shared understanding facilitates meaningful collaboration between digital twins and other systems, as they can interpret and utilize data in a unified and consistent manner.

### **4.3. Emerging Standards**

This section explores emerging standards that are still under development but hold significant promise for advancing digital twin interoperability. These standards address various aspects of digital twin technology, including data exchange, communication, and integration with other systems. The following subchapters provide concise overviews of the Manufacturing Data Space (MDS), Digital Product Passport (DPP), IEEE P2806, and ISO/IEC JTC 1/SC 41, highlighting their key objectives and potential contributions to the evolving landscape of digital twin interoperability.

#### **4.3.1. MDS (Manufacturing Data Space)**

The Manufacturing Data Space (MDS) is an emerging initiative aimed at establishing a secure and interoperable data-sharing ecosystem for the manufacturing industry. While still under development, the MDS promises to be highly relevant for digital twin interoperability by providing a standardized framework for data exchange and collaboration across different stakeholders in the manufacturing value chain. Key characteristics include secure data sharing, data sovereignty and trust, and cross-domain interoperability. By fostering a collaborative data environment, the MDS can unlock the full potential of digital twins, enabling data-driven insights, optimization, and innovation across the manufacturing sector.

#### **4.3.2. (DPP) Digital Product Passport**

The Digital Product Passport (DPP) is an emerging standard aimed at creating a standardized digital record of a product's lifecycle. This passport will contain essential information about the product, such as its origin, composition, environmental impact, and disposal instructions. The DPP is relevant for digital twin interoperability as it provides a standardized way to access and exchange information about the physical product that the digital twin represents. This can facilitate communication and collaboration between different stakeholders involved in the product lifecycle, such as manufacturers, suppliers, and customers. Key characteristics of the DPP include standardized data formats, interoperability with other systems, and support for the circular economy. While still under development, the DPP has the potential to significantly enhance the interoperability and value of digital twins by providing a comprehensive and accessible source of information about the physical product.

#### **4.3.3. IEEE P2806 (Digital Twin Standard for Smart Manufacturing)**

The IEEE P2806 standard is under development to define a standardized architecture for digital twins in smart manufacturing environments. This standard aims to enable interoperability between physical assets and their digital counterparts, facilitating data exchange and collaboration across different systems and applications. Key characteristics include a standardized system architecture, data interoperability, and support for various manufacturing processes. By promoting a consistent approach to digital twin development and implementation, IEEE P2806 can enhance interoperability and unlock the full potential of digital twins in smart manufacturing.

#### **4.3.4. ISO/IEC JTC 1/SC 41**

ISO/IEC JTC 1/SC 41 is a subcommittee dedicated to developing international standards for the Internet of Things (IoT) and related technologies. This subcommittee plays a crucial role in promoting digital twin interoperability by establishing a standardized framework for IoT systems and their interaction with digital twins. Key areas of focus include data interoperability, security, and privacy, ensuring that digital twins can seamlessly integrate into the broader IoT ecosystem. By providing a common set of guidelines and specifications, ISO/IEC JTC 1/SC 41 contributes to the development of robust and interconnected digital twin solutions that leverage the full potential of the IoT.

## 5. Conclusions

Digital twin technology holds immense promise for revolutionizing automation workflows, but its full potential hinges on achieving seamless interoperability. This paper has explored the multifaceted nature of digital twin interoperability, highlighting the diverse types of digital twins, the various levels of interoperability, and the challenges that must be overcome. We have examined a range of existing and emerging standards and approaches that are driving progress in this field.

From established frameworks like RAMI 4.0 and ISA-95 to crucial modelling languages like DTDL and OPC UA, the standards landscape is evolving rapidly. Emerging initiatives such as the Manufacturing Data Space and the Digital Product Passport further underscore the growing importance of interoperability. While challenges remain, the ongoing development and adoption of these standards are paving the way for a future where digital twins can seamlessly collaborate and exchange information, enabling more efficient, resilient, and innovative automation workflows.

Organizations seeking to leverage digital twin technology must prioritize interoperability from the outset. By understanding the standards and approaches discussed in this paper, they can make informed decisions about their digital twin strategy, ensuring that their solutions can integrate effectively with existing systems and contribute to a connected and data-driven future. Continued research and collaboration across industries will be crucial for further advancing digital twin interoperability and unlocking its transformative potential.

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