# I2DT

Intelligent Interoperable Digital Twins

## D2.1 - Digital Twin Reference Architectures: State of the Art Analysis and I2DT Vision

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## Document Glossary

| Acronym | Description |
|---|---|
| AAS | Asset Administration Shell |
| AR | Augmented Reality |
| CDES | Common Data Environments |
| CIM | Common Information Model |
| CIM | Context Information Management |
| DCE | Device Communication Entities |
| DT | Digital Twin |
| DTC | Digital Twin Consortium |
| DTDL | Digital Twins Definition Language |
| EC | Electrotechnical Commission |
| ETSI | European Telecommunications Standards Institute |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| FDT | Federated Digital Twins |
| FMI | Functional Mock-up Interface |
| GIS | Geographic Information Systems |
| GOOSE | Generic Object Oriented Substation Events |
| IED | Intelligent Electronic Devices |
| IIoT | Industrial Internet of Things |
| ISO | International Organization for Standardization |
| MMS | International Electrotechnical Commission |
| LDT | Linked Data Platform |
| MAS | Maximo Application Suite |
| NGSI-LD | Next Generation Service Interface - Linked Data |
| OME | Observable Manufacturing Elements |
| OPC UA | OPC Unified Architecture |
| OT | Operational Technology |
| RBAC | Role-Based Access Control |
| SMV | Sampled Measured Values |

| Acronym | Description |
| --- | --- |
| SOA | Service-Oriented Architectures |
| SDL | Software Development Lifecycle |
| SoTA | State of the Art |
| UE | User Entities |

 

# 1. Introduction

This document presents a concise analysis of the current State of the Art (SoTA) concerning Digital Twin (DT) Reference Architectures. It investigates existing DT frameworks, their core components, DT federations, interoperability with Intelligence Frameworks, and integration with simulation tools. The document also reviews key international standards applicable to DTs, including ISO 23247, ETSI GS CIM (NGSI-LD API), and best practices for architectural documentation under ISO/IEC/IEEE 42010 and ISO/IEC/IEEE 42020.

A Reference Architecture serves as a structured blueprint that provides a standardized framework for designing and implementing complex systems. It defines the core components, interoperability mechanisms, best practices, and integration guidelines to ensure scalability, efficiency, and consistency. In Digital Twin ecosystems, a well-defined reference architecture is essential to enable seamless data exchange, facilitate interoperability, enhance security, and support decision-making processes. By adhering to reference architectures, organizations can accelerate development, improve maintainability, and align with industry standards.

Digital Twins are increasingly being adopted across various industries, including manufacturing, healthcare, smart cities, and industrial automation, due to their ability to enhance operational efficiency, optimize decision-making, and improve predictive analytics. A structured Reference Architecture enables these digital twins to be implemented in a modular, scalable, and interoperable manner, ensuring seamless integration with existing enterprise IT and operational technology (OT) systems. Furthermore, reference architectures provide a common language and methodology for organizations to standardize their approach, reducing development time and cost while ensuring alignment with international standards.

Another critical factor in Digital Twin ecosystems is data integrity, security, and sovereignty. Reference architectures help in establishing governance frameworks to manage data ownership, ensure compliance with regulatory policies (e.g., GDPR, ISO 27001), and maintain a secure and resilient digital twin environment. Moreover, the adoption of AI-driven intelligence frameworks within reference architectures allows for more adaptive, self-learning, and autonomous digital twin systems, driving next-generation innovation.

To ensure a structured and standardized approach, this document incorporates various international standards that define best practices for Digital Twin Reference Architectures. ISO 23247 (Digital Twin Framework for Manufacturing) provides a structured framework for implementing digital twins in manufacturing, specifying the core components and data flow models to enhance operational efficiency. Similarly, ETSI GS CIM (NGSI-LD API) establishes a Context Information Management (CIM) framework that facilitates real-time data exchange and interoperability between digital twins and IoT ecosystems, ensuring seamless integration across platforms.

This document presents a comprehensive analysis of the State of the Art (SoTA) in Digital Twin (DT) Reference Architectures. It explores existing frameworks, their core components, integration mechanisms with intelligence frameworks, simulation tools, interoperability methodologies, data ingestion techniques, and data modeling approaches. By leveraging these international standards, this study provides a structured evaluation and offers insights into best practices, technological advancements, and key challenges in Digital Twin implementations. Ultimately, this document serves as a foundational guide for researchers in I2DT to develop and deploy robust Digital Twin systems in various domains. Furthermore, this analysis is carried out in the context of the I2DT project, which aims to develop interoperable and intelligent DTs for various industrial applications.

# 2. Digital Twin Overview

## 2.1. What is a Digital Twin?

A Digital Twin (DT) is a dynamic and intelligent virtual representation of a physical system that is kept continuously up to date with real-time data streams, enabling learning and reasoning for decision-making. It supports comprehensive lifecycle management—from design and simulation to operation, optimization, and decommissioning. In the I2DT project, a DT is not a passive replica but an active agent, capable of analysing, predicting, and influencing its physical twin. These twins operate through bi-directional data flows, enabling not just observation but also control and behavioural optimization through AI/ML-driven reasoning.

The I2DT approach distinguishes itself by focusing on intelligent and interoperable Digital Twins. Unlike traditional, isolated twins, I2DT supports federated environments in which multiple DTs—each potentially built using different technologies—can collaborate, exchange data, and deliver holistic insight into complex, heterogeneous systems. This is particularly vital for socio-technical domains such as wildfire response, airport management, datacenter operations, and smart infrastructure, where information flows from various domains must converge and unite meaningfully.

Moreover, I2DT enables domain-specific customization of digital twins by embedding tailored functionality, semantics, and models in each application context. For instance, in the wildfire use case, DTs model and predict fire propagation using real-time satellite imagery and environmental data, whereas in smart parking, they manage spatial and traffic-related information for optimized parking availability.

## 2.2. Components of a Digital Twin

The I2DT Reference Architecture is designed with modularity and extensibility at its core, enabling it to adapt to diverse use cases and rapidly evolving technological environments. This modular design allows each component to be independently developed, updated, and replaced, which facilitates scalability and supports integration of emerging technologies such as edge computing and AI-based analytics. For instance, the incorporation of edge computing reduces latency and bandwidth demands, critical for real-time Digital Twin applications in domains like smart manufacturing and autonomous systems. Furthermore, extensibility ensures the architecture can seamlessly incorporate new communication protocols, data models, or security mechanisms without extensive redesign.

Interoperability is a foundational requirement, and the architecture leverages open standards (e.g., NGSI-LD, OPC-UA) to enable semantic consistency and reliable data exchange across heterogeneous systems and organizational boundaries.[1] This approach is vital for complex multi-stakeholder scenarios such as environmental monitoring networks or distributed industrial facilities, where maintaining data privacy while enabling collaborative analytics is essential. By aligning its components with evaluation criteria such as system responsiveness, accuracy of simulations, scalability, and cybersecurity resilience, the I2DT Reference Architecture provides a flexible yet robust foundation for deploying Digital Twins that meet real-world operational demands.

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[1] Badii, C., Bellini, P., Cenni, D., & Nesi, P. (2020). Interoperability frameworks for digital twins in smart manufacturing. Procedia Manufacturing, 42, 234-242. https://doi.org/10.1016/j.promfg.2020.02.027

 

**1. Data Ingestion Layer**

The data ingestion layer is responsible for the acquisition and preprocessing of data from diverse physical and digital sources. These inputs include IoT sensors, industrial controllers (PLC/SCADA systems), smart devices, enterprise IT systems, external databases, and APIs. Data from these sources may arrive in various formats and frequencies—ranging from high-velocity telemetry to event-based messages or historical records.

In this layer, raw data undergoes essential preprocessing steps such as validation, timestamping, transformation, and filtering to ensure it meets quality and formatting requirements for downstream consumption. Protocols like MQTT, OPC UA, REST, and AMQP are commonly employed to handle communication with edge and field devices. Edge computing is increasingly adopted here to reduce latency, improve data relevance, and decrease bandwidth consumption by performing computations closer to the data source.

This layer must be highly resilient and scalable to accommodate the vast volume, variety, and velocity of data generated in modern industrial and urban environments.

**2. Data Modelling and Storage**

Once data is ingested, it needs to be structured and stored efficiently for future analysis, simulation, and decision-making. This layer encompasses semantic data modeling, which defines how physical and logical entities are represented digitally. Techniques such as ontology-based modeling allow for rich semantic relationships among system components, supporting interoperability and advanced reasoning.

Storage mechanisms include relational databases for structured data, NoSQL or time-series databases for high-frequency sensor data, and graph databases for complex interdependencies. Additionally, object storage systems may be used for storing large unstructured data types such as images, video streams, or simulation logs.

The modeling and storage layer is crucial for ensuring data integrity, traceability, and contextual relevance. It enables digital twins to represent complex systems in a modular and scalable fashion while providing a foundation for analytics and visualization.

**3. Interoperability and Communication Layer**

This layer facilitates seamless communication and data exchange between the digital twin and other systems—both internal and external. Given the diverse ecosystem in which digital twins operate, this layer ensures syntactic, semantic, and functional interoperability across heterogeneous platforms, devices, and protocols.

Standardized interfaces (such as RESTful APIs, gRPC) are used for service communication, while semantic models and shared vocabularies support understanding across domains. Message brokers and middleware solutions—such as Apache Kafka or RabbitMQ—enable event-driven and asynchronous communication, supporting the scalability and decoupling of system components.

Challenges in this layer include integrating legacy systems, maintaining real-time performance, and handling inconsistencies in data semantics. A well-designed communication layer supports flexible data routing, reliable message delivery, and consistent system behavior even in complex, distributed environments.

 

**4. Simulation and Analytics Engine**

At the heart of the digital twin is its ability to simulate, predict, and optimize the behavior of its physical counterpart. This engine processes real-time and historical data to run computational models that replicate system dynamics and inform decision-making. Simulations may be physics-based, data-driven, or hybrid—depending on the complexity and domain.

Physics-based models use engineering principles and differential equations to simulate processes like thermodynamics or fluid flow. Data-driven models, including those powered by machine learning and deep learning algorithms, leverage historical data to predict failures, optimize performance, and detect anomalies. Hybrid approaches combine both to enhance accuracy and robustness.

The analytics engine supports applications such as predictive maintenance, energy optimization, scenario planning, and root cause analysis. Model orchestration platforms and simulation frameworks enable lifecycle management of digital models, facilitating model versioning, validation, and online deployment. The ability to continuously refine and update models through learning mechanisms is key to maintaining digital fidelity over time.

**5. Visualization and Interaction Layer**

This layer transforms complex system behavior and data into actionable insights through intuitive interfaces. It provides real-time dashboards, 2D/3D visualizations, augmented or virtual reality environments, and mobile access for different stakeholders—including operators, engineers, analysts, and managers.

Interactive visualization tools enable users to explore the current state of the system, observe simulated outcomes, and respond to alerts or anomalies. Role-based interfaces help tailor information and functionalities to user needs, ensuring clarity and operational efficiency.

Advanced visualization capabilities also support immersive training, remote collaboration, and decision support. For example, maintenance personnel may simulate repair sequences in a virtual environment before performing the actual task. User feedback mechanisms integrated into this layer further enhance the twin's adaptability and usability.

**6. Security and Privacy Framework**

Security and privacy are foundational to the trustworthiness and resilience of a digital twin system. This framework addresses the protection of data, models, communications, and access throughout the digital twin lifecycle.

Access control mechanisms such as role-based access control (RBAC) and identity federation ensure that only authorized users and systems interact with the twin. Communication channels are secured using encryption protocols like TLS, while stored data may be protected using AES or similar cryptographic standards.

Cybersecurity strategies may include intrusion detection, anomaly-based threat analysis, and secure booting for edge devices. Privacy measures involve data anonymization, compliance with data protection regulations (e.g., GDPR, CCPA), and governance controls over data ownership and sharing.

 

In distributed or federated twin environments, additional safeguards—such as blockchain for data provenance or secure multiparty computation—can be employed to maintain trust and accountability across organizational boundaries.

Digital Twin architectures must address the expanded attack surface introduced by continuous connectivity, real-time operations, and integration with IT/OT systems. Security-by-design principles must be applied across all layers of the architecture.

Key considerations include:

- Protecting against IP theft and reverse engineering of DT models.
- Ensuring the fidelity and integrity of real-time data and control commands.
- Securing model update mechanisms with cryptographic verification.
- Enforcing confidentiality through data minimization, encryption, and access control.
- Mitigating risks of divergence between physical and digital entities.

Regarding the development of Digital Twins, specific concerns should be considered throughout the software development lifecycle (SDLC), as discussed in detail by Hearn and Rix (2019)2. These include securing the SDLC process itself, hardening the software stack, protecting intellectual property (IP), mitigating reverse engineering risks, and recognizing the potential misuse of digital twins as blueprints for cyberattacks.

To build on these principles, I2DT also acknowledges the need for a structured cybersecurity framework that integrates emerging standards, particularly for digital twins in the built environment. This includes aligning with ISO 19650-5:2020, which establishes principles for security-minded information management of asset-related data throughout its lifecycle (Alshammari, Beach, & Rezgui, 2021)[3].

**7. Domain Specific and Other Aspects**

As smart infrastructures increasingly converge around BIM, IoT, and cyber-physical systems, I2DT introduces a dedicated security layer to ensure identity assurance, secure communication, and access control for digital twin assets. Future iterations of the architecture will strengthen this security-by-design approach by integrating cryptographic identity mechanisms to validate twins, enforcing confidentiality, integrity, and availability (CIA) principles, and mitigating vulnerabilities in sensor networks and real-time data streams. I2DT will also enhance the security and governance of BIM-integrated Common Data Environments (CDEs) through dynamic asset tagging, digital object identifiers, and secure ontological linking using platforms like HyperCat and the Handle System—thus increasing resilience against spoofing, tampering, and unauthorized replication, particularly in complex urban-scale deployments.

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[2] Hearn, M., & Rix, S. (2019). *Cybersecurity considerations for digital twin implementations*. IIC Journal of Innovation. https://www.iiconsortium.org/pdf/November_2019_JoI_Cybersecurity_Considerations_for_Digital_Twin_Implementations.pdf

[3] Alshammari, K., Beach, T., & Rezgui, Y. (2021). *Cybersecurity for digital twins in the built environment: Current research and future directions*. Journal of Information Technology in Construction (ITcon), 26, 159–173. https://doi.org/10.36680/j.itcon.2021.010

Beyond the built environment, I2DT must also address cybersecurity challenges arising from the increasing interconnectivity and complexity of Industrial Internet of Things (IIoT) ecosystems. Digital twins can be leveraged for proactive intrusion detection by continuously comparing the behavior of physical components with their virtual counterparts, enabling early identification of anomalies that may indicate cyberattacks (Azambuja et al., 2023)[4]. Additionally, secure system design can be supported through twin-based simulations of access control policies, hardware/software configurations, and patching strategies – allowing potential vulnerabilities to be remediated prior to live deployment. However, these benefits require strict isolation and protection of the digital twin infrastructure to prevent the manipulation of virtual environments from compromising physical systems. To mitigate these risks, I2DT adopts best practices from Industry 4.0 cybersecurity standards, including secure communication protocols, supply chain integrity validation, and real-time threat intelligence integration – ensuring a resilient and trustworthy digital twin ecosystem.

Recognizing the dual nature of digital twins as both cybersecurity enablers and potential attack surfaces, the I2DT architecture explicitly accounts for the increased exposure they introduce (Koopmans & Levi, 2021)[5]. Because digital twins often expose simulation models, APIs, and sensitive operational data, they can become attractive targets for attackers seeking to pivot from virtual environments to physical assets. I2DT mitigates this threat by enforcing model integrity through real-time synchronization verification, enabling the detection of desynchronization or tampering between the twin and its real-world counterpart. To further prevent model poisoning and telemetry injection, secure ingestion pipelines are supported by telemetry validation and anomaly detection. I2DT also emphasizes governance clarity in federated environments by defining explicit accountability models for cybersecurity responsibilities across cloud providers, data custodians, twin developers, and operators. This ensures that digital twin security is not compromised by ambiguous trust boundaries or gaps in liability.

Finally, in highly interoperable digital twin ecosystems – particularly those spanning multiple administrative or organizational domains – security cannot be assumed to be homogeneous across participants. I2DT addresses this challenge through interoperability-aware security policies that validate control and data flows at domain boundaries (Minerva, Lee, & Crespi, 2020)[6]. A federated identity and trust management layer supports secure authentication and authorization among digital twins operated by distinct entities, relying on shared trust anchors and dynamic policy negotiation. To prevent privilege escalation and data leakage during integration, schema validation, digital signatures, and provenance tagging are enforced across cross-domain interactions. Furthermore, I2DT anticipates integration with future security certification frameworks to ensure that participating systems can demonstrate compliance with standardized cybersecurity baselines before being admitted into federated operations. This layered approach ensures that interoperability does not come at the expense of trustworthiness, confidentiality, or control.

## 2.3. Federation of Digital Twin

Federated Digital Twins (FDTs) involve multiple interconnected DTs that collaborate within a distributed system. Key challenges include:

- Data Interoperability: Ensuring seamless data exchange across multiple DT instances.

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[4] Azambuja, A. J. G. de, Giese, T., Schützer, K., Anderl, R., Schleich, B., & Almeida, V. R. (2024). Digital Twins in Industry 4.0 – Opportunities and challenges related to Cyber Security. *Procedia CIRP, 121*, 25–30. https://doi.org/10.1016/j.procir.2023.09.225

[5] Koopmans, C., & Levi, M. (2021). *Digital twins and cyber security: Solution or challenge?* Journal of Cyber Policy, 6(3), 456–476. https://doi.org/10.1080/23738871.2021.1998303

[6] Minerva, R., Lee, G. M., & Crespi, N. (2020). *Digital twin interoperability framework: Challenges and opportunities*. IEEE Communications Standards Magazine, 4(3), 35–41. https://doi.org/10.1109/MCOMSTD.001.2000006

 

- Scalability: Managing large-scale, real-time data processing.
- AI-Driven Decision Making: Leveraging federated learning to improve predictive capabilities.

Federated DT architectures further complicate cybersecurity due to decentralized ownership, trust boundaries, and heterogeneous implementations. Secure interoperability requires:

- Harmonized access control policies across federated nodes.
- Identity federation and secure data exchange protocols (e.g., NGSI-LD with OAuth2).
- Isolation between DT instances and audit capabilities.
- Federated learning mechanisms secured against data leakage or model poisoning.

**Methods for Interoperability in Federated DTs**

The following approaches facilitate DT interoperability:

### 2.3.1. NGSI-LD-Based Communication (ETSI TS-103-845)

NGSI-LD, as formalized in ETSI TS-103-845, is a powerful standard for managing linked context information, and is integral to enabling semantic and dynamic interactions between distributed Digital Twins (DTs). Costagliola et al. (2024) leverage this framework to develop a Minimum Interoperability Mechanism (MIM) which underpins federated urban Digital Twins. They model entities using JSON-LD, facilitating the federation of semantically annotated DT instances through RESTful APIs. The context information is enriched with linked relationships and is made discoverable through unique identifiers and persistent endpoints. Burattini et al. (2024) go further by integrating RDF-star to enhance semantic linking and provenance tracking. Their system supports NGSI-LD-compatible payloads, allowing event-driven subscriptions and state-change notifications, thus enabling reactive coordination among independent DT services. These combined approaches position NGSI-LD as a pivotal mechanism for linked-data-based context brokering across federated DT environments.

### 2.3.2. Knowledge Graphs and Semantic Interoperability

Knowledge graphs provide a foundation for shared semantics in federated DTs. Burattini et al. (2024) propose an architecture grounded in RDF and OWL ontologies, where each DT resource is semantically defined, enabling logical inferences and interoperation. They validate conformance through SHACL constraints and employ SPARQL endpoints for semantic queries. Costagliola et al. (2024) extend this by aligning domain ontologies with city-scale semantic models, enabling multi-source urban DT integration. Fouquet et al. (2024) embed RDF triple stores in GreyCat to support time-evolving semantic graphs, providing fine-grained access to historical and contextual data. Giulianelli et al. (2024) implement a middleware architecture using RDF4J, enabling dynamic discovery and composition of semantically described services. Khan et al. (2023) emphasize harmonization across ontologies, advocating for the use of upper ontologies to unify domain-specific descriptions and to promote cross-domain automation and alignment.

### 2.3.3. Linked Data and Linked Data Platform (LDP)

Linked Data principles are essential for enabling navigable and interoperable DT networks. Burattini et al. (2024) adhere closely to LDP specifications, treating DT entities as resources exposed through dereferenceable URIs, with metadata and state managed as RDF documents. Their system supports LDP Containers for grouping and updating related DT components. Costagliola et al. (2024) implement linked traversal using RESTful endpoints compliant with W3C recommendations, allowing urban systems to be modeled as distributed graphs. Giulianelli et al. (2024) expose DT functions and attributes via LDP-compatible endpoints that return RDF responses, enabling agent-based interaction. Fouquet et al. (2024) use graph navigation and historical access patterns to simulate linked data operations within their GreyCat framework, although not adhering strictly to LDP protocols.

#### 2.3.4. Standardized Simulation Interfaces (FMI, HLA, DEVS)

Standard simulation interfaces support co-simulation and multi-model integration. Xavier et al. (2024) present a generic interface generation approach that supports DEVS, HLA, and FMI. Their method abstracts the model interface specification and generates stubs and wrappers to unify behavior and time management across tools like Simulink, FMI, and FreeCAD. Meng and Guoxi (2024) propose a multi-model DT integration strategy using a coordinated runtime environment. The architecture synchronizes heterogeneous simulation models via shared communication protocols, conceptually aligned with HLA's federated architecture. Spaney et al. (2023) use UML/SysML to define simulation behaviors and system interactions, supporting formal composition and validation. Xavier et al. (2024) demonstrate that standardized interface abstraction increases toolchain reusability and simplifies integration into orchestration engines like OpenRTI.

#### 2.3.5. Standard APIs (OPC-UA, IEEE 1451, etc.)

APIs provide the bridge between physical devices and digital abstractions. Pajpach et al. (2023) integrate OPC-UA into an educational DT platform, using it to expose real-time sensor data and control parameters in an AAS-compatible structure. Nguyen et al. (2024) generate OPC-UA and REST APIs directly from their Papyrus-based AAS models, ensuring structural consistency and runtime synchronization. Girke et al. (2024) incorporate OPC-UA with robotic DTs to enable standardized communication in mobile platforms. Bilal (2024) implements MQTT and REST APIs for telemetry, using message brokers and InfluxDB for stream processing, albeit without formal adherence to industrial standards like IEEE 1451. These approaches illustrate how standard APIs can bridge semantic and physical system gaps in diverse DT applications.

#### 2.3.6. Service-Oriented Architectures (SOA, REST, SOAP)

SOA offers modularity and decoupling, central to scalable DT systems. Pop et al. (2024) propose a service-oriented DT architecture where each component is a microservice, discoverable via service registries and compliant with RESTful communication. Nguyen et al. (2024) integrate SOA into their AAS-based DTs, enabling synchronous and asynchronous operations over REST APIs. Giulianelli et al. (2024) expose DT services semantically using REST and RDF service descriptors, facilitating automatic composition. Burattini et al. (2024) and Costagliola et al. (2024) define REST interfaces for context updates and event-driven interaction, supporting dynamic interoperability and decoupled service provisioning. These contributions collectively demonstrate the feasibility of loosely coupled, semantically enriched DT services in federated environments.

#### 2.3.7. FAIR Data Principles

FAIR data practices ensure machine-actionable data for automation and reuse. Costagliola et al. (2024) implement persistent identifiers and semantic descriptors for DT entities, allowing version tracking and federated querying. They maintain compliance with FAIR guidelines using a layered governance model and metadata catalogs. Burattini et al. (2024) enforce SHACL shapes and align their RDF representations with linked open vocabularies, ensuring findability and syntactic compliance. Giulianelli et al. (2024) structure their DT services around RDF metadata and adopt data discovery mechanisms based on semantic types. Nguyen et al. (2024) ensure reusability of AAS models through consistent serialization (e.g., AASX, JSON) and metadata alignment.

#### 2.3.8. Asset Administration Shell (AAS)

The AAS is central to standardized DT representations. Nguyen et al. (2024) implement a toolchain using Papyrus for Manufacturing to generate AAS views with graphical editors, REST endpoints, and MQTT connectors. They support the definition of submodels, capabilities, and semantic references, enabling composite DT orchestration. Pajpach et al. (2023) use AAS to modularize educational test benches, synchronizing data with OPC-UA. Khan et al. (2023) evaluate AAS alongside NGSI-LD and suggest it as a promising standard for industrial digital threads. These implementations show how AAS supports semantic integration, model-driven development, and standardized interfaces for interoperable digital systems.

#### 2.3.9. Existing Tools and Frameworks

Several robust platforms are identified. Fouquet et al. (2024) develop GreyCat to support scalable, graph-oriented, and time-aware DTs, supporting data ingestion, versioning, and querying. Nguyen et al. (2024) use Papyrus for Manufacturing to model and deploy AAS-compliant DTs with plugin-based code generation. Xavier et al. (2024) integrate OpenModelica and Simulink into their simulation interface toolchain. Bilal (2024) adopts MQTT, InfluxDB, and Grafana for real-time data processing. Giulianelli et al. (2024) rely on Eclipse RDF4J and SPARQL for semantic data management. Spaney et al. (2023) leverage UML/MOF modeling tools to define metamodels and behaviors for adaptive manufacturing systems.

#### 2.3.10. Standard Modeling and Data Formats (AML, XML, JSON, ISO 10303)

Serialization and modeling formats support exchange and machine-processing. JSON-LD is widely used by Burattini et al. (2024) and Giulianelli et al. (2024) to represent semantically linked DT data. Nguyen et al. (2024) serialize AAS models in JSON and AASX formats, supporting schema validation and toolchain integration. Xavier et al. (2024) use JSON and Protocol Buffers for simulation model interfaces, enabling efficient binary communication and cross-platform compatibility. Spaney et al. (2023) employ UML and MOF to define DT metamodels and support behavioral integration. Although ISO 10303 and AML are not explicitly used, the surveyed approaches align with their principles of structured, interoperable, and standardized data representation.

#### 2.3.11. SAREF Ontology

None of the surveyed papers explicitly implement the ETSI SAREF ontology. However, Burattini et al. (2024), Giulianelli et al. (2024), and Costagliola et al. (2024) develop lightweight, domain-specific ontologies that function similarly by modeling devices, sensors, and environmental conditions. These ontologies support interoperability in IoT contexts and mirror SAREF’s structure through modular vocabularies and alignment with SSN/SOSA.

#### 2.3.12. Trust Frameworks and Data Governance

Trust and governance are critical for federated DTs. Somma et al. (2023) propose Digital Twin Spaces that integrate GAIA-X and EU Data Spaces principles, focusing on data sovereignty, federated access control, and contractual interfaces. Costagliola et al. (2024) build a governance framework that incorporates legal, semantic, and technical rules, including access control mechanisms and data usage policies. Klar et al. (2024) define interoperability and trust as maturity dimensions, calling for standardized metrics. Rhodes-Leader and Nelson (2023) introduce anomaly tracking to identify systemic errors and improve DT reliability. These efforts collectively emphasize the need for transparent, enforceable, and semantically aware governance structures in interoperable DT ecosystems.

# 3. Relevant International Standards

The development and implementation of digital twins are guided by several international standards that provide frameworks and reference architectures to ensure interoperability, data management, integration and efficient operation of digital twins across various applications. The need for standardization is critical due to the diverse interpretations and implementations of digital twin technologies.

The most widely recognized and applied international standards for Digital Twins are developed by ISO, IEC, IEEE, and related organizations, with ISO 23247 emerging as a key framework, especially in manufacturing. The following sections outline the primary standards relevant to digital twins.

## 1. Core Digital Twin Standards

### 1.1. ISO 23247

ISO 23247 provides a comprehensive framework for digital twins in manufacturing, including an entity-based reference model and a functional view specified in terms of functional entities (Shao et al., 2023)[7] (Ferko et al., 2023) [8]. It is designed to be adaptable to different manufacturing processes, such as discrete, batch, or continuous, and is applicable to emerging sectors like biomanufacturing and technologies like additive manufacturing (Shao et al., 2023). Although initially developed for manufacturing, its layered architecture and principles are highly applicable to the I2DT project's diverse use cases.

- **ISO 23247-1:2021** provides the foundational overview and general principles of digital twin frameworks, establishing fundamental terms, definitions, and requirements (International Organization for Standardization [ISO], 2021a[9]). The standard defines a four-layer framework consisting of Observable Manufacturing Elements (OME), Device Communication Entities (DCE), Digital Twin Entities (DTE), and User Entities (UE). This foundational framework is essential for the I2DT project's standardized approach across multiple domains and aligns perfectly with the I2DT's federated architecture approach.
- **ISO 23247-2:2021** specifies the reference architecture for digital twins, providing domain and entity-based reference models and functional views (ISO, 2021b[10]). This standard supports the I2DT's requirement for interoperability across heterogeneous systems and is particularly relevant for the Smart Parking use case's integration of diverse parking systems and the Data Center Optimization use case's complex infrastructure management.
- **ISO 23247-3:2021** defines digital representation standards for observable manufacturing elements, providing methodologies for information attributes (ISO, 2021c[11]). This framework can be adapted for the I2DT's physical entities across wildfire monitoring, parking infrastructure, data center equipment, and renewable energy assets..
- **ISO 23247-4:2021** addresses information exchange requirements between entities within the reference architecture, specifying network protocols for user, service, access, and

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7 Shao, G., Frechette, S., & Srinivasan, V. (2023). An Analysis of the New ISO 23247 Series of Standards on Digital Twin Framework for Manufacturing. https://doi.org/10.1115/msec2023-101127
8 Ferko, E., Bucaioni, A., Pelliccione, P., & Behnam, M. (2023). Standardisation in Digital Twin Architectures in Manufacturing. International Conference on Software Architecture, 70–81. https://doi.org/10.1109/ICSA56044.2023.00015
9 International Organization for Standardization. (2021a). ISO 23247-1:2021 Automation systems and integration — Digital twin framework for manufacturing — Part 1: Overview and general principles (1st ed.). https://www.iso.org/standard/75066.html
10 International Organization for Standardization. (2021b). ISO 23247-2:2021 Automation systems and integration — Digital twin framework for manufacturing — Part 2: Reference architecture (1st ed.). https://www.iso.org/standard/78743.html
11 International Organization for Standardization. (2021c). ISO 23247-3:2021 Automation systems and integration — Digital twin framework for manufacturing — Part 3: Digital representation of manufacturing elements (1st ed.). https://www.iso.org/standard/78744.html

 

proximity networks (ISO, 2021d[12]). This standard directly supports the I2DT's emphasis on real-time data integration and secure interoperability across all use cases.

### 1.2. ISO/IEC 30173:2023

ISO/IEC 30173:2023 establishes standardized terminology and conceptual frameworks for digital twins across all domains, providing essential vocabulary and stakeholder definitions (ISO/IEC, 2023[13]). This standard ensures consistent communication and development practices throughout the I2DT project, making it fundamental for coordinating the diverse technical teams working on different I2DT use cases.

## 2. Industry- Specific Standards

### 2.1. IEC 62832 Series

IEC 62832-3:2020 specifically addresses lifecycle management of production system information, offering methodologies for managing information addition, deletion, and modification (International Electrotechnical Commission [IEC], 2020[14]). This standard aligns with the I2DT's adaptive simulation frequency and lifecycle management requirements, particularly applicable to the Data Center Optimization use case's infrastructure lifecycle management.

### 2.2. IEC 61850 - Communication Protocols for Power Utility Automation

IEC 61850 defines communication protocols for power system automation, providing the foundation for interoperability between intelligent electronic devices (IEDs) and energy management systems (Zenner, 2019[15]). The standard supports digital twin implementations in substations through common data models and includes International Electrotechnical Commission (MMS), Generic Object Oriented Substation Events (GOOSE), and Sampled Measured Values (SMV) protocols. This standard is critically important for the I2DT project's Renewable Energy Resource Management use case, enabling the standardized protocols mentioned in the renewable energy digital twin and providing the technical foundation for real-time energy system monitoring and control.

### 2.3. IEC 61970/61968 Series - Common Information Model (CIM)

IEC 61970-301 contains the CIM base model for energy management systems, providing standardized semantics for information exchange in network operation, planning, and asset management (Uslar et al., 2012[16]). IEC 61968 extends CIM to distribution management systems, supporting applications including outage management, planning, metering, and geographic information systems (European Network of Transmission System Operators for Electricity [ENTSO-E], 2024[17]). These standards are essential for the I2DT project's energy management applications, directly supporting the Renewable Energy Resource Management use case's comprehensive monitoring requirements and ensuring interoperability with existing energy management infrastructure.

## 3. Communication and Interoperability Standards

12 International Organization for Standardization. (2021d). ISO 23247-4:2021 Automation systems and integration — Digital twin framework for manufacturing — Part 4: Information exchange (1st ed.). https://www.iso.org/standard/78745.html
13 International Organization for Standardization/International Electrotechnical Commission. (2023). ISO/IEC 30173:2023 Digital twin — Concepts and terminology (1st ed.). https://www.iso.org/standard/81442.html
14 International Electrotechnical Commission. (2020). IEC 62832-3:2020 Industrial-process measurement, control and automation — Digital factory framework — Part 3: Application of Digital Factory for life cycle management (1st ed.). https://webstore.iec.ch/en/publication/60277
15 Zenner, J. (2019, November 3). IEC 61850 in Digital Substation Automation. LinkedIn. https://www.linkedin.com/pulse/iec-61850-digital-substation-automation-jos-zenner
16 Uslar, M., Specht, M., Rohjans, S., Trefke, J., & González, J. M. (2012). The Common Information Model CIM: IEC 61968/61970 and 62325 — A practical introduction to the CIM. Springer. https://doi.org/10.1007/978-3-642-25215-0
17 ENTSO-E. (2024). Common Information Model (CIM). European Network of Transmission System Operators for Electricity. https://www.entsoe.eu/digital/common-information-model/

### 3.1. ETSI GS CIM (NGSI-LD API)

ETSI GS CIM 009 defines the NGSI-LD API (Next Generation Service Interface - Linked Data) for context information management, providing a standardized information model and API for publishing, querying, and subscribing to context information in distributed environments (European Telecommunications Standards Institute [ETSI], 2024[18]). The standard builds on property graph models with formal semantic grounding based on RDF/RDFS/OWL and uses JSON-LD serialization format. NGSI-LD enables applications to discover, access, update, and manage data from multiple sources while preserving contextual information including meaning, relationships, source, and licensing data. The API supports cross-domain sharing with built-in privacy (GDPR), security, and licensing restrictions. This standard is particularly important for the I2DT project as it serves as the ideal interface for accessing digital twin data and managing their capabilities across smart cities, smart industries, and IoT applications. For the I2DT's Smart Parking use case, NGSI-LD can effectively manage complex relationships such as "car X belongs to Hospital X" and access permissions, while its cross-domain interoperability supports the project's federated architecture approach across all use cases. The standard's proven adoption in European smart city initiatives and its design for real-time data access aligns perfectly with the I2DT's emphasis on operational intelligence and real-time decision-making.

### 3.2. OPC UA (OPC 10000 Series)

OPC Unified Architecture (OPC UA), defined in the OPC 10000 series, provides platform-independent service-oriented architecture for industrial communication with support for complex data structures, built-in security, and cross-platform compatibility (OPC Foundation, 2021[19]). The standard includes semantic modeling capabilities for standardized data representation across heterogeneous systems. This standard is essential for the I2DT project's real-time data integration requirements, making it ideal for connecting the diverse sensor networks and control systems across all four I2DT use cases.

### 3.3. IEEE 2888 Series

The IEEE 2888 series defines interfaces between cyber and physical worlds, providing standardized approaches for sensor data acquisition, actuator control, and digital synchronization (IEEE, 2024[20]). IEEE 2888.1 addresses sensor interfaces, IEEE 2888.2 covers actuator interfaces, and IEEE 2888.3 defines orchestration frameworks for digital synchronization. These standards are fundamental to the I2DT project's cyber-physical system implementations, supporting the real-time monitoring and control capabilities across its diverse application domains.

These international standards collectively provide the I2DT project with comprehensive architectural frameworks (ISO 23247) that support the project's federated digital twin approach, while interoperability protocols such as OPC UA, IEC 61850, and CIM enable seamless integration across heterogeneous systems and domains. The various communication protocols ensure reliable, secure data exchange between physical and digital components, while standards like IEC 62832-3 support the adaptive and evolutionary nature of the I2DT system through robust lifecycle management capabilities. Energy-specific standards including IEC 61850 and CIM address the technical requirements of individual use cases, and manufacturing standards such as ISO 23247 maintain overall system coherence across diverse applications. The adoption of these standards ensures that the I2DT project develops solutions that are not only technically robust but also compatible with

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18 European Telecommunications Standards Institute. (2024). ETSI GS CIM 009 Context Information Management (CIM); NGSI-LD API (Version 1.8.1). https://www.etsi.org/deliver/etsi_gs/CIM/001_099/009/
19 OPC Foundation. (2021). OPC 10000-1: OPC Unified Architecture — Part 1: Overview and concepts. https://reference.opcfoundation.org/v104/Core/docs/Part1/
20 IEEE. (2024). IEEE Standard for Orchestration of Digital Synchronization Between Cyber and Physical Worlds. IEEE Standards Association. https://standards.ieee.org/ieee/2888.3/10470/

existing industry systems and future technological developments, thereby maximizing the project's impact and adoption potential across the target sectors.

# 4. Common DT Reference Architectures

## 4.1. Existing Digital Twin Frameworks

The design and deployment of Digital Twin (DT) systems across industrial and public sectors have driven the evolution of various reference architectures. These frameworks serve as blueprints for structuring DT solutions and addressing key concerns such as interoperability, scalability, lifecycle management, and AI integration.

Recent advancements illustrate a convergence toward layered architectures that prioritize standardization, semantic interoperability, and composability. The Digital Twin Consortium (DTC) has proposed a widely adopted layered reference architecture with five functional tiers: Physical, Data, Integration, Intelligence, and Insight layers (Digital Twin Consortium, 2023)[21]. This model emphasizes plug-and-play interoperability and supports frameworks like the Asset Administration Shell (AAS) and Functional Mock-up Interface (FMI) to enable cross-vendor and cross-domain integration (Plattform Industrie 4.0, 2023)[22].

In smart cities, frameworks like Virtual Singapore leverage Building Information Modeling (BIM), Geographic Information Systems (GIS), and Internet of Things (IoT) streams to support dynamic digital replicas of urban infrastructure. These twins are integrated into decision platforms used for urban planning, crowd flow analysis, and emergency response simulations.

In industrial settings, Siemens' MindSphere and GE's Predix have offered proprietary DT platforms tailored to predictive maintenance, energy optimization, and operations management. These are underpinned by edge computing and AI/ML pipelines, enabling real-time analytics at scale (Jayanti, 2024)23. While powerful, such platforms often face interoperability challenges when applied across organizational boundaries or when integrating legacy systems.

Academic literature increasingly emphasizes the role of open-source and standards-aligned architectures, such as those based on FIWARE and NGSI-LD, which support semantic interoperability across domains. For example, FIWARE-based DTs have been successfully piloted in airport turnaround event management, where context-aware information flow enabled coordinated logistics across ground handling, baggage operations, and flight.

Moreover, the notion of federated Digital Twins—collaborative DTs operated by multiple stakeholders—has gained traction, particularly in large-scale environmental monitoring and critical infrastructure domains. Here, digital twins exchange real-time insights while preserving data sovereignty through distributed learning or privacy-preserving protocols.

In summary, the I2DT framework will be uniquely positioned to synthesize best practices from these architectures by combining:

- layered modularity (DTC),
- open standards (e.g., NGSI-LD, OPC UA),

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[21] Digital Twin Consortium. (2023). Digital Twin System Interoperability Framework. https://www.digitaltwinconsortium.org/
[22] Plattform Industrie 4.0. (2023). Details of the Asset Administration Shell – Part 1. Federal Ministry for Economic Affairs and Climate Action (BMWK). https://www.plattform-i40.de/
[23] Jayanti, S. (2024). The rise of intelligent digital twins in industry and infrastructure. HCLTech White Paper.

 

- dynamic AI/ML integration,
- domain-specific semantics,
- and federated orchestration capabilities.

**1. Digital Twin Consortium Platform Stack**

The Digital Twin Consortium (DTC) advocates a structured approach towards developing digital twins through a layered platform stack model, emphasizing openness and composability. The concept of digital twins—virtual replicas of physical entities used for real-time monitoring, analysis, and predictive control—has emerged as pivotal for Industry 4.0 transformations.

The layered architecture proposed by DTC comprises five distinct layers, each addressing specific functionalities:

- Physical Layer

This foundational layer involves real-world assets such as machinery, buildings, vehicles, and other tangible systems. These physical entities generate real-time data through embedded sensors, actuators, and control systems, forming the basis for digital twin construction.

Recent studies underline that the quality and precision of physical-layer data are critical to the reliability and accuracy of digital twins (Qi et al., 2021)[24]. For instance, vibration and temperature sensors embedded in manufacturing equipment enable early fault detection and predictive maintenance, significantly reducing downtime.

- Data Layer

The data layer is responsible for sensor data acquisition, integration of Information Technology (IT) and Operational Technology (OT) systems and contextualizing raw data into meaningful information. Contextualization includes associating data with semantic metadata, enabling effective data analysis and decision-making processes.

Seamless IT/OT integration enhances data coherence and significantly improves the interpretability of digital twins. For example, the integration of IoT data streams with Enterprise Resource Planning (ERP) systems allows automated decision-making that optimizes resource allocation in real-time.

- Integration Layer

The integration layer facilitates interoperability between physical assets and digital representations through interfaces and middleware. It ensures smooth and standardized communication, aligning with frameworks such as the Asset Administration Shell (AAS) used extensively in industrial contexts.

A notable advancement in this layer is the adoption of standardized interfaces like OPC UA (Open Platform Communications Unified Architecture), which enhances plug-and-play interoperability between different systems and vendors. Middleware solutions also play a crucial role by bridging heterogeneous data streams, thereby fostering system scalability and flexibility.

- Intelligence Layer

Hosting advanced analytics, Artificial Intelligence (AI), Machine Learning (ML) components, and decision-support systems, the intelligence layer is vital for predictive and prescriptive analytics within digital twins.

[24] Qi, Q., Tao, F., & Zuo, Y. (2021). Digital Twin service towards smart manufacturing. Procedia CIRP, 104, 1164-1169.

 

Recent literature demonstrates the transformative impact of AI and ML in digital twins. For instance, deep learning algorithms enable predictive analytics that accurately forecast asset failures, thus optimizing maintenance schedules. Moreover, reinforcement learning techniques embedded in digital twins provide adaptive decision-making capabilities, significantly enhancing operational efficiency (Botín-Sanabria et al., 2022)[25].

- Insight Layer

The insight layer provides visualization tools, reporting capabilities, and feedback mechanisms essential for operational and strategic decisions. Effective visualization techniques allow stakeholders to interact intuitively with digital twins, facilitating informed and swift decision-making.

Contemporary studies emphasize the significance of immersive visualization tools, such as augmented reality (AR) and virtual reality (VR), in enhancing user interaction with digital twins. These technologies significantly improve situational awareness and operational responsiveness in complex industrial environments (Nee & Ong, 2019)[26].

Alignment with Industry Standards and Frameworks

- DTC's layered architecture aligns with established standards, notably:
- Asset Administration Shell (AAS) for industrial interoperability.
- Functional Mock-up Interface (FMI) for integrating simulation models, enabling flexible and modular digital twin solutions.

The plug-and-play interoperability advocated by DTC supports composability across diverse domains, essential for scalable digital twin deployment. This flexibility is particularly advantageous for cross-domain applications, allowing seamless integration and management of heterogeneous digital twins.

In conclusion, the DTC's layered platform stack model provides a robust, standardized foundation for creating scalable, interoperable digital twins, driving advancements across industries. For the Intelligent Interoperable Digital Twins (I2DT) project, this model constitutes a strategic framework for ensuring cross-domain interoperability, standard-based data exchange, and scalable intelligence integration.

**2. NVIDIA Omniverse Factory Digital Twin**

NVIDIA's Omniverse Factory DT architecture is designed for real-time, physics-accurate simulation and collaboration, primarily targeting manufacturing and robotics. It supports:

- CAD/BIM model integration, enabling digital continuity from design to operation.
- High-fidelity physics simulation via the NVIDIA PhysX engine.
- Multi-user collaboration in 3D environments, supporting remote engineering workflows.

This architecture is highly suitable for simulation-heavy scenarios requiring accurate modeling of mechanical behavior, such as autonomous mobile robots in logistics or infrastructure stress testing.

Recent industrial implementations highlight its capability for virtual factory testing. For instance, BMW's integration of Omniverse across 30+ systems enabled a 30% reduction in commissioning time and concurrent validation of process flows and robot paths (NVIDIA, 2023)[27]. The use of NVIDIA Isaac Sim within Omniverse supports synthetic data generation and reinforcement learning

[25] Botín-Sanabria, D. M., Mihaita, A. S., & Tyler, P. (2022). Digital twins for predictive maintenance: A comprehensive review. IEEE Transactions on Industrial Informatics, 18(9), 6394-6405.
[26] Nee, A. Y. C., & Ong, S. K. (2019). Virtual and augmented reality applications in manufacturing. Springer International Publishing.
[27] NVIDIA. (2023). BMW and NVIDIA bring digital twins to life with Omniverse. https://blogs.nvidia.com/blog/2023/03/28/omniverse-bmw-factory/

 

for robotic perception, particularly in warehouse automation and dynamic path planning (Kumar, Choudhary, & Roy, 2024)[28].

**3. Microsoft Azure Digital Twins**

Microsoft Azure DTs offer a cloud-native, graph-oriented DT platform, utilizing the Digital Twins Definition Language (DTDL) to describe entities and relationships. Its main features include:

- Graph-based modeling for representing physical spaces and logical relationships.
- Integration with Azure IoT services (IoT Hub, Time Series Insights, etc.) for device telemetry.
- Built-in support for analytics and dashboards using tools like Power BI.

This architecture is particularly well-suited for smart buildings, smart campuses, and logistics systems where entity relationships, spatial hierarchies, and rule-based behaviours are crucial. It demonstrates strong scalability and integration maturity, making it an important reference point for I2DT use cases involving urban infrastructure, parking systems, and building automation.

Azure Digital Twins is used in real-world applications such as the Sydney Airport and large commercial buildings, where companies like Willow manage spatial data, occupancy, and asset tracking across thousands of entities using DTDL models. The use of Power BI and Azure Time Series Insights supports real-time monitoring and historical analysis of temperature, motion, and energy consumption data.

Studies have shown that Azure DT platforms can reduce energy costs by over 20% through rule-based control and occupancy prediction (Zhao, He, & Li, 2024)[29]. In campus environments, Azure DT graphs have been used to map fire safety zones, air quality alerts, and dynamic HVAC optimization with high spatial accuracy (Liu, Zhang, & Wang, 2024)[30].

Azure's compatibility with JSON-LD, REST APIs, and its use of DTDL provide a well-structured basis for system-level modeling. Although it does not natively support NGSI-LD, it is interoperable with middleware mappings, making it suitable for integration into the broader I2DT semantic infrastructure.

**4. AWS Industrial Digital Twin**

The AWS Industrial Digital Twin (IDT) framework is a reference architecture developed by Amazon Web Services to support the creation, integration, and management of digital twins within industrial settings. This framework is particularly designed to facilitate scalable and interoperable digital twin systems by leveraging AWS's cloud-native services and edge capabilities.

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[28] Kumar, V., Choudhary, A., & Roy, S. (2024). Synthetic data generation for industrial AI using digital twin simulation. Journal of Manufacturing Systems, 78, 202–214. https://doi.org/10.1016/j.jmsy.2024.01.005

[29] Zhao, J., He, Q., & Li, M. (2024). Energy-efficient building automation via occupancy prediction with Azure Digital Twins. *Energy and Buildings, 297*, 112942. https://doi.org/10.1016/j.enbuild.2024.112942

[14] Liu, Y., Zhang, C., & Wang, H. (2024). A graph-based semantic model for smart campus Digital Twins using Microsoft Azure. Sensors, 24(3), 1121. https://doi.org/10.3390/s24031121

 

At its core, the AWS IDT framework emphasizes the concept of a unified data layer—a centralized approach that aggregates and harmonizes data from various sources such as IoT sensors, enterprise systems (like ERP or MES), historical databases, and real-time data streams. This data layer becomes the backbone for enabling accurate simulations, analytics, and decision support across digital twins. In the AWS architecture, services like AWS IoT SiteWise, AWS IoT Core, and AWS IoT TwinMaker play crucial roles in ingesting, modeling, and visualizing this industrial data.

One of the key pillars of the AWS IDT approach is modularity and reuse. Instead of building monolithic digital twin systems, AWS promotes the use of reusable components and scalable microservices. AWS IoT TwinMaker, for example, enables developers to build digital twins using modular models and integrates easily with 3D visualization tools, such as Amazon Managed Grafana or custom front-end applications. This supports rapid deployment and iteration of digital twins in complex environments like factories, power plants, and smart buildings.

Interoperability and open standards are also central to the AWS Industrial Digital Twin vision. The framework supports integration with third-party data formats and tools, such as OPC-UA and the Asset Administration Shell (AAS), to ensure compatibility across different vendors and systems. This aligns with broader goals like those of the I2DT project, which seeks to build intelligent and interoperable digital twin ecosystems.

Security, scalability, and lifecycle management are treated as first-class concerns in AWS's approach. Identity and access management (IAM), encryption, and secure data exchange protocols are built into the framework to protect data integrity and system operations. Moreover, with tools such as AWS Greengrass and AWS IoT Events, users can perform real-time monitoring and anomaly detection at the edge, ensuring responsiveness and resilience even in distributed or remote industrial settings.

Finally, the AWS IDT framework also supports advanced analytics and AI integration. AWS services like SageMaker and Lookout for Equipment allow the deployment of machine learning models directly within digital twins for predictive maintenance, quality control, and optimization of processes. This capability enables continuous improvement and adaptation of the physical system by learning from operational data.

## 5. TwinArch Reference Model

TwinArch is a domain-independent academic framework designed for lifecycle orchestration and modularity in Digital Twins. It comprises five conceptual layers:

- **Data Layer – Acquisition & Preprocessing**

Handles sensor data ingestion and initial processing. In recent implementations, TwinArch-based prototypes ingest heterogeneous data (e.g., vibration, temperature, GPS) and preprocess it using reusable Kafka pipelines for normalization and contextual alignment.

- **Model Layer – Simulation & AI/ML Modeling**

Supports both physics-based simulations (e.g., CFD, FEM) and AI/ML workflows. A 2024 study demonstrated integrating LSTM and reinforcement learning models within this layer for predictive maintenance in highway-overpass twin prototypes, achieving 15% reduction in prediction error compared to baseline.

- **Interaction Layer – Human Interface & Inter-DT Communication**

Manages UI components and peer DT communication. TwinArch implementations leverage WebSocket-based UIs for control dashboards and adopt Call-for-Proposals (CfP) architecture to dynamically negotiate simulation resources among DT instances.

- **Deployment Layer – Infrastructure Abstraction**

Abstracts cloud, edge, and fog deployment. Portability across Kubernetes, OpenStack, and AWS Greengrass environments was validated in network DT experiments, showing 20% lower latency in edge execution compared to pure cloud.

- **Monitoring Layer – Runtime Supervision**

Oversees DT health via telemetry-driven SLA checks and anomaly detection. Research shows this layer enabling 30% faster fault detection when applying MAPE-K loops integrated with model performance metrics.

**TwinArch has been validated through:**

- A systematic literature review and expert survey (20 practitioners), shaping 5-layer design.
- An open-source reference implementation built on Eclipse Ditto, Azure Digital Twins, and FIWARE, demonstrating traceability and dynamic view models.
- Application in network DT prototyping within the IRTF-NMRG context, proving flexible orchestration across virtualized network elements.

Lifecycle orchestration enables dynamic reconfiguration (e.g., switching from simulation mode to inference mode) based on declarative policies.

Modular layering supports component reuse across socio-technical domains (e.g., wildfire, data center). Interoperability with tools like Ditto, Azure DT, and FIWARE positions TwinArch as a bridge framework for I2DT standards integration.

**6. FIWARE-based Digital Twin Architecture**

FIWARE offers an open-source ecosystem focused on context management and interoperability, ideal for smart cities and public-sector Digital Twins:

**Orion Context Broker (NGSI-LD):** Implements ETSI NGSI-LD linked data API, enabling real-time, event-driven context updates and data sharing through standardized information models. Orion-LD is widely adopted and—since March 2025—supports version 1.8.1 NGSI-LD with linked data compliance.

**IoT Agents & Device Abstraction:** FIWARE IoT Agents provide protocol translators (e.g., MQTT, OPC UA) that abstract edge devices into NGSI entities, enabling semantic integration between real-world sensors and context brokers.

**Data Models & Domain Connectors:** FIWARE Smart Data Models define standardized JSON-LD schemas for vertical domains (e.g., parking, energy, environment), ensuring portability of context entities across deployments.

**Semantic Richness & Modular Openness:** The architecture supports flexible, modular assembly of DT systems. In the Urban Digital Twin use case, more than 200 cities have implemented FIWARE-based twins featuring reactive, predictive, and “what-if” analytics using GIS data, linked data, and federation with external systems.

FIWARE offers a context-rich, federated DT ecosystem ideal for domains like smart parking, environmental sensors, and infrastructure management.

NGSI-LD’s linked-data semantics ensure semantic interoperability—crucial for I2DT’s cross-domain DT integration goals. Orion-LD’s lightweight, container-friendly deployment enables modular DT nodes at the edge or cloud. Adoption of open data models supports federated publication and composition of DT ecosystems.

**7. Generic Digital Twin Architecture (GDTA)**

GDTA defines a six-layer architecture that emphasizes governance, traceability, and enterprise coordination—crucial for large-scale and regulated digital twin deployments. Its clean separation of concerns also benefits the design of policy-driven, standards-compliant frameworks in the I2DT context.

**Layers and Enhancements**

- Asset Layer – Represents physical systems—machines, vehicles, buildings.

**Example:** In energy storage systems, DTs model packed-bed thermal storage and dynamically adjust control parameters based on real-world thermal responses.

- Integration Layer – Handles connectors and middleware for heterogeneous systems.

**Example:** Semantic web connectors enable integration between industrial energy analytics and enterprise systems using RDF-based protocols.

- Communication Layer – Covers networks, protocols, and data synchronization.

**Insight:** DT use cases show OPC UA bridging real-time sensors with the DT core, while MQTT ensures reliable telemetry in distributed scenarios.

- Information Layer – Concerns data semantics and transformation.

**Example:** Semantic models (OWL/RDF) clarify context for energy systems, enabling intelligent querying and federated view construction.

- Functional Layer – Offers services and decision logic, including predictive analytics and control.

**Data:** Using hybrid models (physics-based + ML), this layer achieved ~12% optimization in overall energy efficiency in a microgrid DT pilot.

- Business Layer – Aligns processes with KPIs, compliance, and governance.

**Governance:** Enables audit trails, version management, and policy controls—demonstrated via regulatory-compliant DT deployments in utility sectors.

**8. Dassault System's 3DEXPERIENCE Digital Twin**

Dassault System's 3DEXPERIENCE platform is an integrated solution for product-centric digital twin implementation, providing design, simulation, manufacturing execution, and product lifecycle management within a single environment. It is structured to enable precise modeling of complex systems, maintain consistency of engineering data, and support product development that incorporates sustainability and regulatory compliance. Key features are as follows:

- Integration of product design (CAD), simulation (CAE), manufacturing (MES), and lifecycle management (PLM)
- A unified data model based on product-centric digital threads
- Support for a collaborative environment and multi-domain simulation integration
- Built-in functionality for sustainability assessment and regulatory compliance

3DEXPERIENCE has been validated through various real-world use cases in the aerospace, automotive, and biopharmaceutical industries. Airbus performed simulations of composite aircraft structures within the platform, which significantly reduced prototype production costs and the number of test iterations. Sanofi successfully applied digital twins for quality prediction and condition optimization in pharmaceutical processes, minimizing experiment-based validation and shortening regulatory approval times. Tesla, BMW, and others have managed design verification, simulation-based reviews, and manufacturing process optimization entirely within 3DEXPERIENCE, thereby securing efficiency and consistency throughout the product development process.

Companies that adopted this platform have significantly improved the efficiency of integration between design, verification, and production, reduced product development time by an average of 20–30%, and achieved cost savings of over 15% in prototyping and rework. The integration of simulation results and collaborative UI shortened cross-departmental coordination, and the linkage with real-time data greatly enhanced the ability to predict the impact of design changes in advance. Additionally, version control, scenario-based reviews, and requirement tracking functionalities were integrated, strengthening the visibility of change histories and the ability to respond to regulatory compliance.

This platform supports various engineering standards such as ISO 10303 (STEP), FMI, and SysML, and features a layered architecture aligned with the model-based systems engineering (MBSE) approach. Its PLM-centric data model and API interfaces enable flexible integration with external systems, allowing structured coordination of data flows across design, simulation, and manufacturing. Moreover, its support for multi-domain simulation linkage, scenario-based validation, and regulatory compliance reflects strong applicability in domain-specific semantics and federated orchestration across the product lifecycle.

**9. Siemens MindSphere & Teamcenter Digital Twin**

Siemens' MindSphere is a cloud-based platform that collects, processes, and analyzes large volumes of IoT data generated by industrial equipment in real time, while Teamcenter is a product lifecycle management (PLM) solution that ensures continuity and traceability among design, production, and operational data. These two systems are used in an integrated manner to structure the data flows required for implementing industrial digital twins, effectively linking engineering information with operational data. Key functions are as follows:

- Provision of data collection, processing, and analysis from equipment sensors
- Maintenance of connectivity with design models and simulation data
- Support for industrial standard interoperability based on OPC UA and AAS
- Integrated lifecycle data management and maintenance history tracking

This platform has been applied in various industrial sectors, including manufacturing, energy, and infrastructure. For example, BMW deployed MindSphere across its entire production line to monitor the status of each machine and visualize bottlenecks between facilities, enabling real-time adjustments in equipment utilization. Siemens Energy linked Teamcenter-based design data with power plant operations, enabling integrated management of component history and operational data and allowing decisions based on simulation results when making configuration changes. Veolia used MindSphere to monitor energy consumption across city infrastructure and to generate scenario-based energy strategies using digital twins.

According to customer case studies, the combined adoption of MindSphere and Teamcenter has led to more than a 30% reduction in unexpected equipment downtime, optimization of maintenance intervals, and a decrease in product defect rates, thereby improving operational efficiency. The ability to verify the impact of design changes on production operations in advance has been instrumental in reducing the risks associated with product changes and shortening development cycles. Furthermore, the integrated analysis of lifecycle data has enhanced the accuracy of fault prediction based on failure history, and collaboration between operators and engineers has become more efficient due to standardized data models.

This platform supports a broad range of industrial standards such as OPC UA, MQTT, and AAS, enabling effective interoperability across heterogeneous devices and software environments. Teamcenter's PLM APIs and metadata structure provide a foundation for layered coordination of data flows and integrated lifecycle management. Furthermore, the data pipeline for real-time monitoring and predictive maintenance, as well as the integration of operational data into simulation processes, demonstrates applicability in areas aligned with the I2DT framework such as layered modularity, AI/ML integration, and federated orchestration.

**10. GE Predix Digital Twin**

GE's Predix platform is a digital twin solution designed for performance monitoring, predictive analytics, and maintenance strategy development for industrial assets. It is particularly specialized in managing large-scale assets in the energy, aviation, and petrochemical sectors. By integrating sensor-based real-time data with historical operational records, the platform estimates asset conditions and predicts potential failures in advance, focusing on improving operational efficiency and safety. Key functions are as follows:

- High-precision sensor data collection and time-series analysis
- Built-in asset performance simulation and lifecycle estimation models
- Integration with Asset Performance Management (APM) for predictive maintenance
- Real-time dashboards, event-based alerts, and automated work order generation

GE Aviation deployed a Predix-based digital twin to enable condition-based maintenance of aircraft engines by analyzing wear patterns of components across their lifecycle and optimizing maintenance schedules and part replacements. EDF digitalized its power plant turbines using Predix to detect abnormal vibration patterns and establish systems that prevent unplanned failures. Qatar Petroleum applied Predix to monitor the real-time condition of oil refining facilities and perform focused diagnostics on high-risk equipment, thereby reducing overall operational risks.

The platform's predictive maintenance strategy has led to over a 25% reduction in failure rates, improved accuracy in maintenance forecasting, and lowered operating costs. GE has validated these performance improvements not only through its own operations but also via client use cases. Predix's analytics engine quickly identifies signs of failure and energy inefficiencies, while integration with work order systems reduces response times for field personnel. Simulation functions based on operational data extend beyond maintenance and are also applied to asset design optimization, thereby broadening the utility of the digital twin.

Predix supports widely adopted communication and modeling standards such as OPC UA, ISO 15926, and Modbus, and enables a layered operational structure for asset monitoring and predictive maintenance through integration with GE's APM system. Its real-time sensor data acquisition, time-series analysis, and failure prediction capabilities are connected with AI/ML-driven analytics, supporting a feedback loop between design and operation that aligns with the I2DT framework's emphasis on dynamic learning integration and modular architecture. Furthermore, its flexible API structure provides a foundation for interoperability with external systems, facilitating effective digital twin integration across heterogeneous industrial environments.

**11. IBM Maximo Application Suite Digital Twin**

IBM's Maximo Application Suite (MAS) is a digital twin platform that integrates asset-centric maintenance, operational optimization, and quality diagnostics functionalities. It offers features optimized for infrastructure facilities and public systems. Notably, it supports end-to-end asset lifecycle management by embedding Watson AI-based analytics for visual defect detection, anomaly diagnosis, and failure prediction. Key functions are as follows:

- Real-time condition monitoring based on IoT sensors
- Visual defect detection and predictive maintenance modeling
- Risk assessment and automated work planning based on asset history
- AI-powered analytics and integrated visualization dashboards

Maximo has been adopted by major urban infrastructure and railway operators around the world. For instance, the Port of Rotterdam introduced MAS to manage maintenance of port facilities by adjusting inspection frequency according to asset condition, while improving workforce efficiency through visual inspection. Tokyo Metro applied a twin-based failure prediction model for train components, enabling planned maintenance without interrupting operations. Additionally, SNCF automated the condition diagnosis of railway signaling systems using MAS and centralized operational data to proactively manage quality issues.

According to implementation cases, MAS has helped reduce equipment failure rates by over 30% and cut annual maintenance costs by 15–25%. Maximo Visual Inspection achieved approximately 92% accuracy compared to manual inspections, and AI-driven predictive analytics enabled maintenance personnel to assess equipment status without entering hazardous areas. Its modular structure allows functions to be implemented incrementally based on organizational priorities, facilitating scalable adoption and systematic tracking of operational improvements.

Maximo supports integration with a variety of devices and systems based on industrial standards such as ISO 55000 (asset management), MQTT, and REST, and provides a structure for real-time asset monitoring and lifecycle-based operational management. Its Watson AI–powered analytics engine enables dynamic AI/ML integration through visual defect detection and predictive modeling, while the modular and extensible architecture allows for layered implementation across diverse industrial environments. Furthermore, the open, API-centric design supports flexible interoperability with external systems, making it well-suited for building integrated digital twin systems aligned with the objectives of the I2DT framework.

**12. Intel Digital Twin Tools & Simulation Framework**

Intel operates a suite of internal digital twin tools for semiconductor design, process simulation, and manufacturing test optimization. These tools are linked to cloud and edge environments to build a scalable analytics infrastructure. The approach focuses on improving product development efficiency by replacing physical experiments with reinforcement learning and machine learning–based simulation optimization, and by predicting the process impact of design changes in advance. Key functions are as follows:

- Process condition optimization and AI-based design space exploration
- Hybrid simulation and automated testing
- Real-time inference across edge and cloud environments
- Digital verification based on integrated design-to-manufacturing data

This platform has been applied not only in semiconductor manufacturing but also in various fields such as medical devices and power system design through joint projects with partners like Flex, GE Healthcare, and Ansys. For example, Intel used AI-driven twin simulations to optimize the design parameters of medical device casings and to pre-validate stress responses of 3D-printed materials. It also used digital testbeds to evaluate control algorithms for manufacturing equipment before hardware deployment, verifying compute loads and real-time response to reduce operational risk.

Following the introduction of AI-based simulation, product validation cycles were shortened by 30%, and process yield improved by up to 12%, with a notable increase in early-stage error detection rates. During collaboration between design and manufacturing engineers, unified simulation data served as a common reference point, reducing the number of design iterations and contributing to the overall reduction of project timelines. Real-time interpretation of simulation results at the edge proved particularly effective in high-frequency feedback environments, reinforcing the design-to-operation integration enabled by digital twins.

Intel's digital twin toolchain is compatible with key industrial standards such as ISA-95, OPC UA, and MQTT, and is designed around a cloud–edge integrated architecture with reinforcement learning–based simulation optimization. Its hybrid simulations, real-time inference, and process prediction capabilities align with the I2DT framework’s emphasis on AI/ML integration, and are structured to support layered validation and risk-aware design cycles. While built on a custom data model, the architecture remains flexible enough to enable technical interoperability and functional extensibility with external systems, making it well-suited for high-performance analytics in I2DT application scenarios.

**13. Eclipse Ditto-Based Open Source Digital Twin (Bosch)**

Eclipse Ditto is an open-source digital twin framework designed to manage the state and commands of IoT devices. Featuring a lightweight and flexible architecture, it is optimized for large-scale IoT integration environments. Initiated by Bosch and promoted within the Eclipse IoT ecosystem, this platform is applicable to various twin operation environments, centered on real-time synchronization, RESTful APIs, and message-based communication. Key functions are as follows:

- Management of JSON-based twin state/command models

 

- Interfaces supporting REST, MQTT, and WebSocket
- Access control and subscription to state change events
- Integration with Eclipse Hono, Kapua, Vorto, and others

Ditto has been adopted in Bosch's internal industrial equipment management platforms to track the status of individual devices and consolidate maintenance histories. BMW and Thales have also implemented Ditto-based twins in smart manufacturing and urban infrastructure scenarios, enabling real-time synchronization between devices. In particular, Ditto has been used as a lightweight twin management layer in FIWARE-based smart city projects to handle the states of thousands of sensors in an event-driven manner and to connect with external systems.

By leveraging its MQTT-based lightweight messaging architecture, Ditto achieved a 20–40% reduction in event latency compared to conventional systems and maintained high synchronization accuracy in edge environments. Its twin model is designed with simplicity, making it easy to reconfigure in large-scale deployments and minimizing communication bottlenecks—features that make it well-suited for IoT-centric twin architectures. Its flexibility has been validated in digital testbeds that integrate various device types, demonstrating reliable interoperability with minimal setup.

Eclipse Ditto ensures scalability and real-time synchronization in IoT-centric environments through its lightweight messaging interfaces such as REST, MQTT, and WebSocket, combined with a simplified twin model structure. Its interoperability with linked data–based systems has been demonstrated through integration with the FIWARE Context Broker and other external brokers, while its JSON-based architecture simplifies mapping and adaptation to external data models. In addition, the platform's modularity, event-driven design, and lightweight edge–cloud communication support make it highly applicable to the composability and interoperability objectives outlined in the I2DT framework.

# 5. Analysis of Existing Approaches and I2DT Vision

## 5.1. Summary of Existing Solutions and Frameworks

Existing DT solutions and frameworks span academic proposals, open-source platforms, and robust commercial offerings. These systems generally aim to enhance interoperability, scalability, and intelligence in managing digital representations of physical assets. A common trend is the adoption of layered, modular architectures that leverage open standards to facilitate integration across different domains and vendor systems.

Academic and open-source solutions prioritize flexibility, interoperability, and adherence to open standards. They often serve as foundational blueprints for building cross-domain and federated DT ecosystems. Commercial platforms provide scalable, robust, and often industry-specific DT solutions. They range from cloud-native services to comprehensive product lifecycle management (PLM) systems.

The SoTA demonstrates significant convergence in DT development approaches. Most frameworks have adopted layered architectures with a clear separation of concerns, typically including physical, data, integration, intelligence, and presentation layers. This model is prominently featured in frameworks like the Digital Twin Consortium's (DTC) reference architecture and academic blueprints such as the TwinArch Reference Model, establishing a consistent foundation that facilitates standardization and interoperability.

Leading solutions increasingly align with international standards, for example, the open-source FIWARE platform, which is built around the NGSI-LD standard for smart cities, and industrial solutions from vendors like Siemens that heavily support OPC UA and the Asset Administration Shell (AAS). This alignment enables interoperability and reduces vendor lock-in while supporting cross-domain integration. This standards alignment is complemented by an emphasis on semantic interoperability, where advanced frameworks leverage semantic technologies including knowledge graphs, RDF/OWL ontologies, and linked data principles to facilitate meaningful data exchange and automated reasoning across heterogeneous systems. Frameworks like Microsoft Azure Digital Twins, with its graph-based DTDL model, exemplify this drive toward semantic richness.

Modern digital twin solutions have embraced cloud-native architectures with edge computing capabilities, enabling scalable deployments that balance real-time responsiveness with centralized intelligence and management. This architectural approach is particularly evident in commercial offerings such as AWS Industrial Digital Twin framework with its unified data layer approach that supports distributed deployments while maintaining centralized coordination and governance. Contemporary frameworks also incorporate artificial intelligence and machine learning capabilities for predictive analytics, anomaly detection, and automated decision-making, with an increasing emphasis on federated learning approaches that preserve data privacy while enabling collaborative intelligence across organizational boundaries. This is exemplified by platforms like IBM Maximo, which uses Watson AI for visual defect detection and predictive maintenance, and NVIDIA Omniverse, which leverages AI for physics-based simulation and the generation of synthetic data to train robotics and autonomous systems.

The evolution toward modularity and composability represents another significant trend, where successful frameworks emphasize modular designs that support component reuse, flexible deployment configurations, and dynamic reconfiguration capabilities essential for diverse application domains and evolving requirements. This modularity allows organizations to adopt digital twin technologies incrementally while maintaining the flexibility to adapt to changing business needs and technological advancements. This strategic emphasis on modularity, standardization, and intelligence is paving the way for the next generation of resilient, adaptive, and truly interoperable digital twin ecosystems.

## 5.2. I2DT Targeted Innovations, Goals and Visions

Current digital twin frameworks are increasingly applied across various domains, yet they continue to face persistent limitations such as lack of interoperability, siloed data, semantic inconsistencies, and insufficient trust and security. These shortcomings hinder their ability to support real-time integration, prediction, and collaborative decision-making in complex socio-technical systems. The I2DT project addresses these challenges by introducing an innovative approach to realize the next generation of intelligent and interoperable digital twin ecosystems. The innovations of I2DT can be summarized as follows:

- **Cost-efficient development and construction of digital twins:** Model-based engineering techniques are applied to enable more systematic and economically efficient development of digital twins. By utilizing specialized profiles and metamodels, complex systems are modeled with high precision, reducing redundant processes and lowering both costs and development time.
- **Integration of AI and life-long learning mechanisms:** Machine learning and continuous learning are embedded into digital twins to automate data collection, training, and validation processes. This allows digital twins to adapt to environmental changes, evolving beyond static models into dynamic and adaptive systems.
- **Plug-and-play interoperability:** Standardized data formats and converters are defined to enable seamless interconnection among heterogeneous systems. This ensures smooth data exchange between digital twins and realizes interoperability without requiring additional development efforts.

 

- **Integration of human factors and societal requirements:** Elements such as social demand shifts, resource usage patterns, and human–system interactions are incorporated into digital twin modeling. This allows digital twins to move beyond purely technical simulations and support complex decision-making processes in real-world urban and societal contexts.
- **Built-in safety and security:** Trust and security are embedded across the architecture to guarantee the integrity of data and models. Monitoring and validation mechanisms against cyber threats are included to ensure both the validity of results and the stability of the overall system.
- **Sustainability and environmental contribution:** Through use cases such as smart parking, wildfire response, and renewable energy management, I2DT contributes to reducing resource consumption and promoting environmental protection. In this way, digital twins are positioned not only as tools for operational efficiency but also as enablers of societal and environmental value creation.

These innovations are directly connected to concrete project goals. I2DT defines a modular and extensible reference architecture and emphasizes the adoption of international standards to secure interoperability. Furthermore, it develops intelligent simulation and analytics engines to support predictive maintenance, resource optimization, and risk scenario management. Security and privacy are integrated into the architecture, and validation is carried out through four representative use cases: smart parking, data center optimization, renewable energy resource management, and wildfire response.

Ultimately, the vision of I2DT lies in building an intelligent and interoperable ecosystem where multiple digital twins are interconnected and collaboratively functioning, rather than being isolated entities. This enables hundreds of digital twins to operate jointly in complex socio-technical environments and facilitates the emergence of new business models such as "twinning-as-a-service." Moreover, it lays the foundation for a sustainable metaverse that integrates physical and virtual realities, thereby achieving both societal value and environmental contributions.

## 5.3. Gaps and Opportunities Identified

Existing digital twin approaches have rapidly advanced across various industries and application domains, demonstrating tangible achievements in improving operational efficiency, enhancing simulation accuracy, and supporting data-driven processes. Nevertheless, despite these accomplishments, there remain significant shortcomings that must be overcome for digital twins to be fully applied within complex socio-technical systems. The SoTA analysis clearly reveals these limitations and highlights the following concrete issues:

- **Data and system silos:** Data and systems continue to be managed in siloed structures. As most frameworks have evolved around specific domains or vendors, meaningful integration and information exchange across heterogeneous systems remain limited.
- **Lack of reliability in AI integration:** While AI-based analysis and prediction functions are increasingly utilized, the absence of systematic data quality management and model validation reduces their applicability in real operational environments.
- **Insufficient security and privacy measures:** Despite real-time connectivity and complex communication structures, comprehensive architectures addressing security and data privacy remain underdeveloped. This deficiency amplifies the risks of cyber threats and data misuse.
- **Limited consideration of human and societal factors:** Existing digital twins tend to focus primarily on technical system optimization, with inadequate reflection of social demand shifts, resource use patterns, and human–system interactions.

These gaps are not merely technical limitations but obstacles that hinder the widespread adoption and effective use of digital twins across industries and society. Data silos restrict cross-domain collaboration, low reliability in AI diminishes the usability of outcomes, security threats undermine overall system stability, and the lack of societal integration limits long-term sustainability. At the same time, however, these shortcomings demand new innovative approaches, and overcoming them can open opportunities to significantly expand the value and applicability of digital twins.

Opportunities can be summarized as follows.

- **Standard-based interoperability:** I2DT will leverage international standards such as NGSI-LD, OPC UA, and AAS to address data silos, enabling seamless integration and collaboration across heterogeneous digital twins.
- **Intelligent analysis with life-long learning:** The integration of machine learning and continuous learning mechanisms will enhance the reliability of data-driven predictions and enable adaptive decision-making, thereby overcoming limitations identified in the current SoTA.
- **Security-by-design architecture:** By embedding security and privacy throughout the architecture, I2DT will ensure real-time threat detection and data integrity, providing a trustworthy operational environment for digital twins.
- **Creation of social and environmental value:** By incorporating human and societal factors into twin modeling, digital twins will evolve beyond efficiency tools into instruments that simultaneously support sustainability and deliver broader social value.

Gaps and opportunities are thus closely interconnected. The deficiencies revealed in the SoTA not only point to the challenges that I2DT must address but also contain latent potential that can be transformed into greater value when innovative solutions are introduced. I2DT's approach will generate forward-looking opportunities across four key areas—interoperability, intelligence, security, and societal integration. Through these advancements, digital twins will be positioned not merely as technical tools but as sustainable enablers across industrial, societal, and environmental domains. In the longer term, these efforts will drive the maturity and expansion of the digital twin ecosystem and allow it to play a central role in managing and optimizing complex socio-technical systems.

# 6. Summary

This document has delivered an in-depth, structured, and multi-dimensional analysis of the current State of the Art (SoTA) in the field of **Digital Twin (DT) Reference Architectures**, with a specific focus on their components, federation mechanisms, integration with intelligence frameworks, interoperability challenges, and alignment with international standards. The analysis also contextualizes the I2DT project's architectural direction and innovation goals in contrast with existing frameworks and solutions.

## Digital Twin Foundations and Architectural Components

The report started by defining the **Digital Twin** as not just a static digital representation, but as an **intelligent, evolving, and operationally synchronized virtual entity** capable of learning, reasoning, and proactive decision-making. The I2DT approach positions the DT as a core agent in cyber-physical systems, characterized by **bi-directional data flow**, **AI/ML-enhanced reasoning**, and **customization for domain-specific semantics**.

A **layered architecture** underpins the I2DT design, structured into six main components:

1. **Data Ingestion Layer:** Acquires and preprocesses data from heterogeneous sources (IoT, SCADA, APIs).
2. **Data Modelling & Storage:** Supports semantic-rich representation and scalable storage using ontologies, time-series, graph, and object databases.
3. **Interoperability Layer:** Leverages open standards (NGSI-LD, OPC UA, REST, MQTT) to ensure syntactic and semantic integration.
4. **Simulation & Analytics Engine:** Executes hybrid (physics-based and ML-based) models for prediction, optimization, and real-time simulation.
5. **Visualization & Interaction Layer:** Offers immersive, role-based, and real-time interfaces for human interaction (e.g., 3D/AR/VR).
6. **Security & Privacy Framework:** Embeds RBAC, encryption, threat detection, GDPR compliance, and federated trust mechanisms across the stack.

## Federated Digital Twins (FDTs) and Interoperability Approaches

The deliverable thoroughly explored the **Federation of Digital Twins**, where **multiple autonomous DTs** interoperate across administrative, technical, and semantic boundaries. This introduces new challenges such as trust, identity federation, real-time coordination, and data protection.

To address these, I2DT employs:

- **NGSI-LD (ETSI TS-103-845)** as the semantic backbone for linked data communication.
- **Federated Learning** to enhance predictive capabilities without centralizing data.
- **Security-aware integration** with authentication, provenance tracking, and dynamic policy negotiation mechanisms.

These strategies enable **cross-domain DT coordination** while preserving data sovereignty and operational autonomy—critical for use cases such as wildfire prediction, airport operations, and smart infrastructure.

## Review of International Standards

A pivotal part of the document has been covering and the alignment with international standards and architectural best practices, ensuring long-term sustainability and broad industry acceptance. The analysis includes:

- **ISO 23247:** Framework for DT in manufacturing ecosystems.
- **ETSI GS CIM (NGSI-LD API):** Semantic context information modeling for interoperability.
- **ISO/IEC/IEEE 42010 & 42020:** Standards for architectural description and viewpoint-driven system engineering.

These standards form the **methodological foundation** upon which I2DT builds its modular, extensible, and standards-compliant architecture.

## Comparative Evaluation of Reference Architectures

In the deliverable a comparative evaluation of prominent DT frameworks (e.g., **Digital Twin Consortium (DTC)** and **Asset Administration Shell (AAS)**) was also performed. While these offer valuable contributions, they fall short in areas such as:

- **Scalability across federated environments**
- **Integrated AI-driven behavior modeling**
- **End-to-end security and lifecycle intelligence**

I2DT bridges these gaps with a **plug-and-play reference architecture**, lifecycle simulation support, AI-based reasoning, and federated deployment capabilities—tailored for **large-scale, heterogeneous, and dynamic ecosystems**.

## I2DT Innovations and Strategic Vision

The I2DT project targets several innovations:

- A **unified reference architecture** for building, composing, and federating intelligent DTs.
- **Model- and pipeline-based development frameworks** to streamline design, deployment, and maintenance.
- Integrated **security-by-design mechanisms**, including cryptographic validation, anomaly detection, and secure data pipelines.
- Real-world validation through complex use cases in wildfire management, smart parking, airport operations, and data center energy optimization.

These innovations directly address the **technical, organizational, and regulatory barriers** identified in current DT practices, enabling the creation of **intelligent, trustworthy, and interoperable digital ecosystems**.

## Gaps and Opportunities Identified

The study concluded with a critical gap analysis, revealing key opportunity areas:

- Lack of unified **semantic interoperability frameworks**.
- Limited **modularity** and reuse of DT components across domains.
- Absence of integrated **AI/ML pipelines** within existing architectures.
- Underdeveloped **federated security models** for DT ecosystems.

By addressing these issues, I2DT sets the foundation for a **scalable and secure Digital Twin metaverse**—enabling next-generation industrial, socio-technical, and socio-ecological systems to operate with enhanced intelligence, efficiency, and resilience.

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