Platform Stack Architectural Framework: An Introductory Guide

A Digital Twin Consortium White Paper

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Digital twins have the potential to revolutionize how we approach even the simplest of tasks, from managing stock in a warehouse to designing and maintaining a fleet of aircraft. To realize this transformative value, digital twin systems need to be designed and architected with best practices for scalability, interoperability, and composability.

This guide introduces these concepts for C-Suite and business leaders providing them with a foundational understanding before they dive into technology selection or development. It also provides a starting framework for system architects to facilitate the incorporation of best practices.

We introduce the central concepts of a digital twin system. What are the critical constituent parts of a digital twin system? What are the elements that take a solution from being a great model or simulation to “qualifying” as a digital twin?

A reference architecture can answer these questions by providing foundational building blocks. We review some commonly adopted technological approaches and standards and build up an architectural framework of key common elements of digital twin systems.

We also look at a range of case studies showcasing the value that digital twins can bring from decarbonizing the electricity grid to supporting cities with their net-zero targets or improving the operational efficiency of making coffee.

1 DIGITAL TWIN SYSTEM CENTRAL CONCEPTS AND CAPABILITIES

According to the Digital Twin Consortium’s definition of digital twin[1], digital twins are virtual representations of real-world entities and processes, synchronized at specified frequencies and fidelities. Two key concepts in this definition inform an architecture:

- Entities and processes: the approach needs to be applicable to building digital twins of both physical systems and logical processes and often needs to accommodate both.
- Synchronization: there needs to be a mechanism for enabling and controlling this key qualifying element.

The definition is further elaborated with three points:

- Digital twin systems transform business by accelerating holistic understanding, optimal decision-making and effective action.
- Digital twins use real-time and historical data to represent the past and present and simulate predicted futures.

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[1] *https://www.digitaltwinconsortium.org/glossary/glossary/#digital-twin*

- Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge and implemented in IT/OT (information technology and operations technology) systems.

The variety of data, simulation and IT and OT systems, introduces considerations for:

- the role of data and different types and sources,
- the role of simulation or machine learning for predictive modeling,
- the need for integration and interoperability and
- the role of both IT and OT in realizing these systems.

These considerations drive the need for certain underlying capabilities that make up digital twin systems.

1.1 CAPABILITIES OF DIGITAL TWIN SYSTEMS

The capabilities of digital twins can be broken into six key high level categories as shown in Figure 1-1:

- data services,
- integration,
- intelligence,
- user experience (UX),
- management and
- trustworthiness.

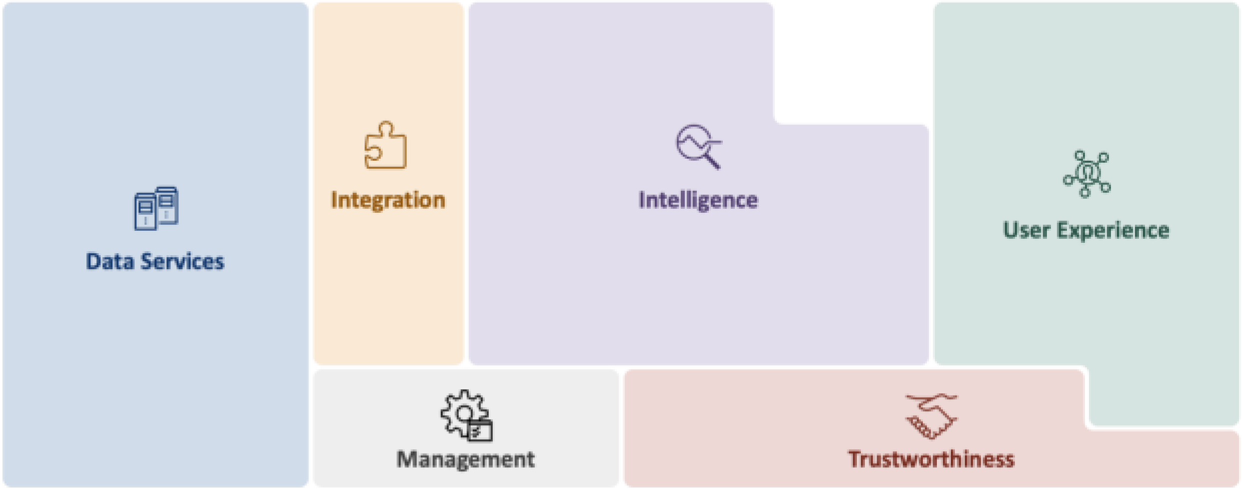
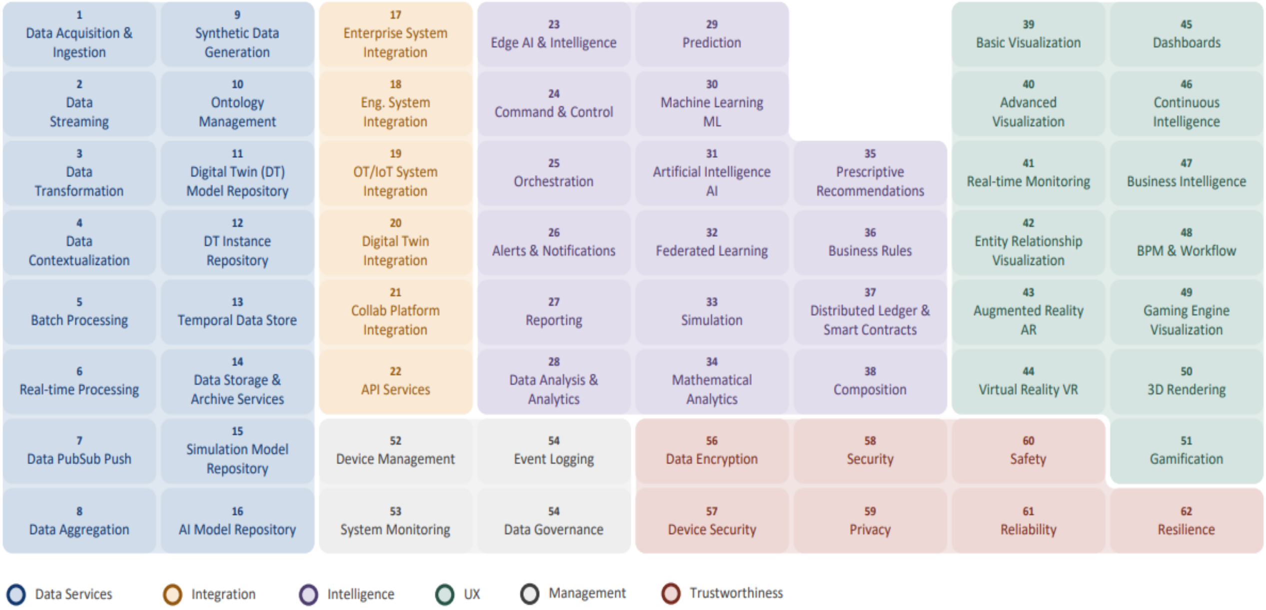


Figure 1-1: Diagrammatic view of capability categories. *(Source: Digital Twin Consortium.)*

Each of these categories further expands into 62 discrete top-level capabilities of a digital twin ecosystem as shown in Figure 1-2 below. The top-level capabilities can be further broken into additional capabilities. Only a subset (and different combinations) is likely to be required for any given deployment, and each represents the opportunity to make appropriate technology selections for a given use case. A full expansion of these capabilities can be found in the Digital Twin Consortium's Capabilities Periodic Table User Guide,[2] shown in Figure 1-2.



1 Data Acquisition & Ingestion	9 Synthetic Data Generation	17 Enterprise System Integration	23 Edge AI & Intelligence	29 Prediction		39 Basic Visualization	45 Dashboards
2 Data Streaming	10 Ontology Management	18 Eng. System Integration	24 Command & Control	30 Machine Learning ML		40 Advanced Visualization	46 Continuous Intelligence
3 Data Transformation	11 Digital Twin (DT) Model Repository	19 OT/IoT System Integration	25 Orchestration	31 Artificial Intelligence AI	35 Prescriptive Recommendations	41 Real-time Monitoring	47 Business Intelligence
4 Data Contextualization	12 DT Instance Repository	20 Digital Twin Integration	26 Alerts & Notifications	32 Federated Learning	36 Business Rules	42 Entity Relationship Visualization	48 BPM & Workflow
5 Batch Processing	13 Temporal Data Store	21 Collab Platform Integration	27 Reporting	33 Simulation	37 Distributed Ledger & Smart Contracts	43 Augmented Reality AR	49 Gaming Engine Visualization
6 Real-time Processing	14 Data Storage & Archive Services	22 API Services	28 Data Analysis & Analytics	34 Mathematical Analytics	38 Composition	44 Virtual Reality VR	50 3D Rendering
7 Data PubSub Push	15 Simulation Model Repository	52 Device Management	54 Event Logging	56 Data Encryption	58 Security	60 Safety	51 Gamification
8 Data Aggregation	16 AI Model Repository	53 System Monitoring	54 Data Governance	57 Device Security	59 Privacy	61 Reliability	62 Resilience

○ Data Services ○ Integration ○ Intelligence ○ UX ○ Management ○ Trustworthiness

Figure 1-2: Periodic table for digital twin ecosystem capabilities. *(Source: Digital Twin Consortium.)*

2 QUALIFYING A DIGITAL TWIN SYSTEM

This section provides an overview of the foundational elements to provide distinction between digital twins and digital twin systems. First, a digital twin system is defined as "a system-of-systems that implements a digital twin."[3] At a digital twin system level we are concerned about the integration with other systems as well as the composition of multiple digital twins together into more complex digital twins, often using a federated approach. As outlined below, without realizing the digital twin in a digital twin system, there is less ongoing value creation.

2.1 LEVELS OF MATURITY

Technical maturity affects the adoption of digital twins and Technology Readiness Levels[4] help understand technical maturity of a system:

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[2] *https://www.digitaltwinconsortium.org/capabilities-periodic-table-user-guide-form/*

[3] *https://github.com/digitaltwinconsortium/dtc-glossary/blob/main/glossary.md#digital-twin-system*

[4] *https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level*

Figure 2-1: Technology readiness levels. (*Source: TWI Global.*)[5]

These are summarized as research (TRL 1 ~ 3), development (TRL 4 ~ 6) and deployment (TRL 7 ~ 9).

They can be correlated to the building of digital twin systems in the following stages:

- Modeling and simulation, starting with theoretical models (TRL 1) and improving to being based on real-world data (TRL 3).
- Digital twins as individual components based on real data and being validated in the real world through a level of synchronization (TRL 3 ~ 6).

Digital twin systems taking this into production and operational environments with system integration and clearly defined synchronization at a specified frequency (TRL 6+).

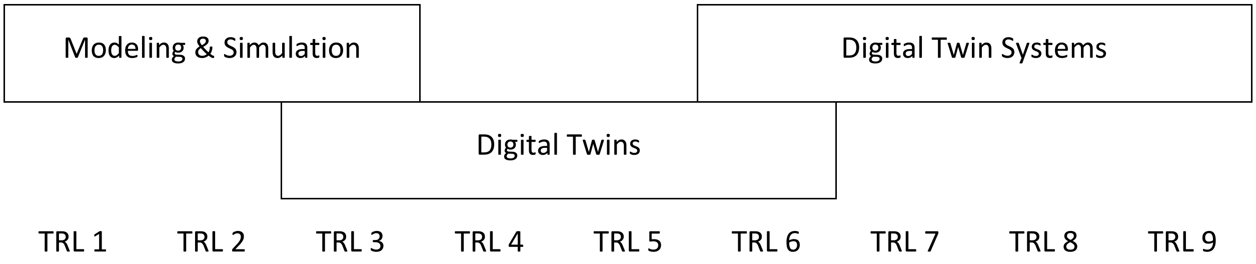

Figure 2-2: Correlation of TRL levels to levels of digital twin maturity.

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[5] *https://www.twi-global.com/technical-knowledge/faqs/technology-readiness-levels*

2.2 IS IT A DIGITAL TWIN?

Many solutions may qualify as simulations, or as digital twins rather than digital twin systems. This leads us back to the definition of a digital twin and digital twin systems with the key qualifying building blocks being a model or virtual representation, an ability to simulate and synchronize data between the digital twin and the real world.

Table 2-1 shows criteria that can be used to identify whether your system is a digital twin system and whether the digital twin reference architecture is applicable to your deployment. As you can see, simply having a model, or a simulation without real data, or a dashboard without feedback or control of a real entity is insufficient to be called a digital twin. You need all the criteria, as identified in the definition of a digital twin, to be categorized as a digital twin.

Criterion	Model	Simulation	Dashboard (or other Application)	Digital Twin	Digital Twin System
Virtual (Stored) Representation	✓			✓	✓
Virtual (Computational) Representation / Simulation & Forecasting		✓		✓	✓
Built on Data (Synchronization for Initialization)			✓	✓	✓
Synchronized (including Feedback & Control)			✓	✓	✓
System Integration			✓		✓

Table 2-1: Classification of models and simulations through to digital twins and digital twin systems.

3 REFERENCE ARCHITECTURES: AN OVERVIEW

A reference architecture provides a template for building solutions within a particular domain. A digital twin reference architecture identifies the foundational building blocks for practitioners, practices between them and a guide for building digital twin systems.

In this section we present the digital twin reference architecture, which abstracts several well-known reference architectures including the Service Oriented Architecture and multiple cloud reference deployment patterns from Microsoft Azure, Amazon Web Services and a multitude of other providers. These are further outlined in Chapter 5.

3.1 BUILDING SYSTEMS-OF-SYSTEMS WITH COMPOSABLE TWINS

The reference architecture includes the following elements as shown in Figure 3-1:

- security, trust and governance forming a foundation for everything else,
- the real world from which the digital twin is instantiated and with which it is synchronized,
- an IT/OT platform for implementing a digital twin system,
- the virtual representation,
- wrapped in service interfaces for integration and interoperability and
- applications where the digital twin value realization occurs.

This framework provides the guiding principles for building digital twins, digital twin systems, and relates them to systems of systems. Using this guide, it is possible to assess whether the solution being proposed is actually a digital twin and rapidly identify the elements of a proposed system architecture that may be required. Emphasis should be placed on the role of synchronization, integration and interoperability and the makeup of the virtual representation given their significance in the makeup of digital twins.

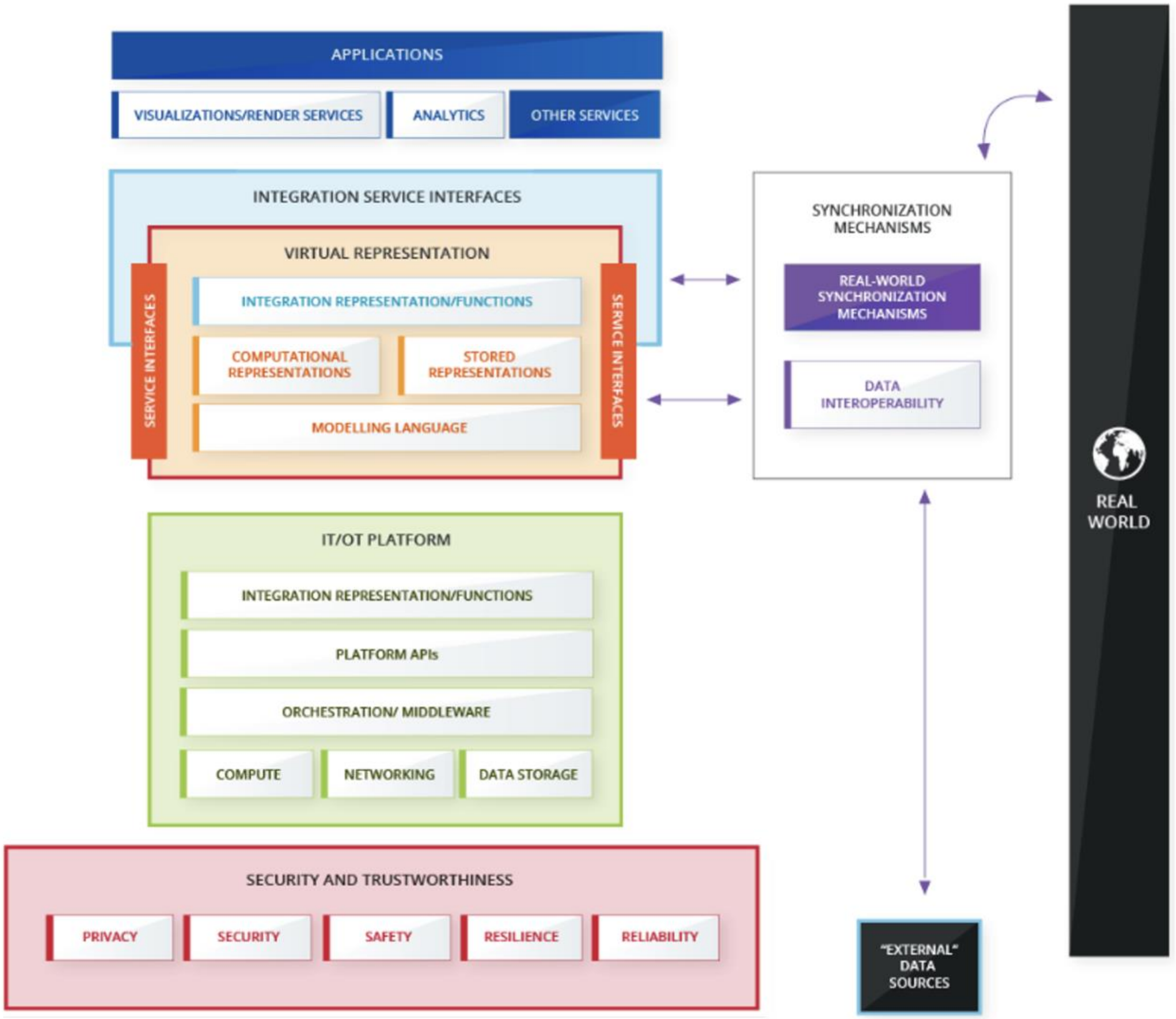

Figure 3-1: The Platform Stack Architectural Framework, including all elements and sub-systems.

The digital twin system architecture here provides the foundation to building systems of composable (built by a combination of capabilities) and federated (across organizational boundaries) digital twin systems. This approach to building composable digital twins provides an effective method to managing the complexity of digital twins. In the context of composable or federated digital twins we consider the integration service interfaces, synchronization mechanisms as well as the security, trust, and governance across the system boundaries of digital twin systems.

3.2 BUILDING THE PLATFORM STACK ARCHITECTURAL FRAMEWORK

The following sections expand on each of the elements of the framework in further detail.

3.2.1 THE IMPORTANCE OF SECURITY AND TRUSTWORTHINESS

Security, trust and governance are foundational concerns for a digital twin system.

Definition: Trustworthiness

> "The degree of confidence one has that the system performs as expected. Characteristics include safety, security, privacy, reliability and resilience in the face of environmental disturbances, human errors, system faults and attacks."[6]

Trustworthiness must consider the following concepts: privacy, physical and cyber-security, safety, resilience and reliability. These, shown in Figure 3-2, build trust in a system and demonstrate that the digital twin can be relied upon.

Although these are well-defined concepts with a long heritage (Avizienis, Algirdas, et al.)[7], they remain a challenge for most organizations. As digital twins can control and manage real critical assets, trustworthiness must be considered from the outset; it cannot be retrofitted.

Figure 3-2: Trustworthiness, a foundation for trust.

The subsystems include:

- Privacy: The right of individuals to control or influence what information related to them may be collected and stored and by whom and to whom that information may be disclosed. (*ISO/TS 17574:2009 2*)[8].
- *Security*: The property of being protected from unintended or unauthorized access, change or destruction ensuring availability, integrity and confidentiality.
- Safety: The condition of the system operating without causing unacceptable risk of physical injury or damage to the health of people, either directly, or indirectly as a result of damage to property or to the environment. (*ISO/IEC Guide 51:2014 3*)[9].
- *Resilience*: Ability of a system or component to maintain an acceptable level of service in the face of disruption.

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[6] *https://www.iiconsortium.org/pdf/Trustworthiness_Framework_Foundations.pdf*

[7] *https://www.nasa.gov/pdf/636745main_day_3-algirdas_avizienis.pdf*

[8] *https://www.iiconsortium.org/wp-content/uploads/sites/2/2022/04/Industry-IoT-Vocabulary.pdf*

[9] *https://www.iiconsortium.org/wp-content/uploads/sites/2/2022/04/Industry-IoT-Vocabulary.pdf*

- Reliability: Ability of a system or component to perform its required functions under stated conditions for a specified period of time. (*ISO/IEC 27040:2015 1*)[10]

A trust-assessment model suggests:[11]

"By strongly connecting the virtual and physical worlds, digital twins are an essential part of this [digital transformation] transition, but they need to operate at least as securely and safely as existing infrastructure. If they are to be adopted at scale, digital twins need an interoperable and understandable model for maintaining security and safety assurance that satisfies all stakeholders: technical, business and regulatory."

3.2.2 IT/OT FOUNDATIONS

Definition: IT/OT Platform

"The information technology and operational technology infrastructure and services on which the subsystems of a digital twin system are implemented."[12]

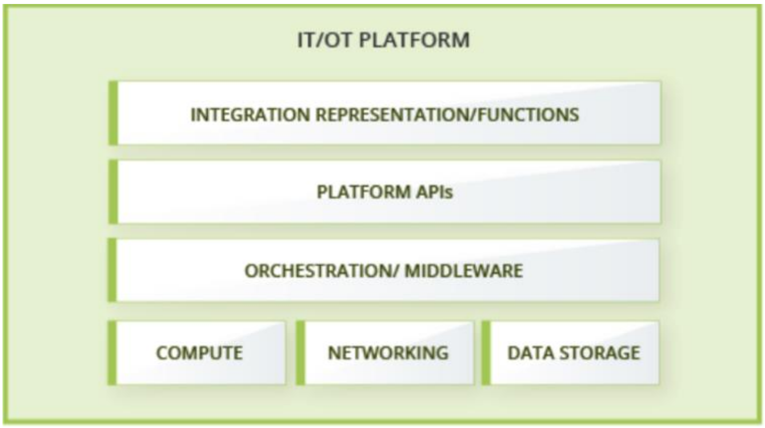

Figure 3-3: IT/OT Layer expanded to show sub-systems.

The IT/OT platform section of the Framework includes the foundational elements representing the convergence of IT and OT. These high level subsystem elements provide the link between the orchestration, operations and platform services and related functions to the physical/operational including compute, networking, and data storage. This convergence is at the heart of the digital twin and is also used to showcase the foundational elements in the context of real world use case mapping as described in the Digital Twin Consortium reference library[13].

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[10] *https://www.iiconsortium.org/wp-content/uploads/sites/2/2022/04/Industry-IoT-Vocabulary.pdf*

[11] *https://www.digitaltwinconsortium.org/assuring-trustworthiness-in-dynamic-systems-using-digital-twins-and-trust-vectors-form/*

[12] *https://www.digitaltwinconsortium.org/glossary/glossary/#itot-platform*

[13] *https://www.digitaltwinconsortium.org/initiatives/technology-showcase/*

The subsystems include:

- Computing, storage, networking infrastructure and orchestration middleware, which provide the foundational resources to support the operation of software and programs,
- Platform APIs (Application Program Interfaces) that provide access to the platform services and platform management, and
- Integration representation/functions, which are primarily for storage of data for the digital twin and transforming data between various systems.

Any of these systems could be in a remote data center, on-premises, edge, embedded, mobile, distributed or a hybrid of the above.

3.2.3 VIRTUAL REPRESENTATION

Definition: Virtual Representation

"A complex, cohesive digital representation comprising stored representations, computational representations and supporting data that collectively provide an information-rich "virtual" experience of their subject matter."[14]

The heart of the digital twin architecture is the virtual representation that provides the logical encapsulation for all data within and used by the digital twin. Digital twins run on/use the IT/OT platform and a software platform and related tools. This includes all types of digital twins and the appropriate breakdown of their components. Specifically, this includes digital models (reference and simulation), their supporting data, and services.

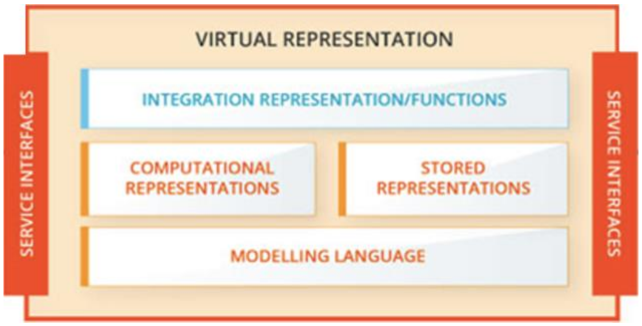

Figure 3-4: Virtual representation expanded to show the three sub-elements.

This part of the reference architecture comprises computational and stored representations and modeling languages used to express those representations. We can also consider the computational and stored representations as being the simulation and modeling elements of the

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[14] *https://www.digitaltwinconsortium.org/glossary/glossary/#virtual-representation*

digital twin. Around the digital twins are the service interfaces (i.e. integrations, APIs, and protocols) for use within particular domains or with other digital twins.

The computational representation can be defined as the “executable digital representation of computational algorithms and supporting data representing the subject matter from a dynamic perspective.” Examples of this would include simulations and predictive analytics where the subject matter is a process or real-world entity whose properties are a function of time. These computational representations typically take a stored representation as an input and produce them as outputs.

Stored representations can therefore be defined as “consisting of stored structured information, representing state of the subject matter.”

Stored representations can take the form of databases of all kinds including relational databases, graph databases and other NoSQL databases, Internet of Things (IoT) "data historians," specialized Computer Aided Design (CAD), Building Information Modeling (BIM), and Geographic Information System (GIS) repositories, 3D meshes derived from photogrammetry and/or point clouds, satellite or radar imagery, spreadsheets, intelligent 2D drawings and schematics.

Figure 3-5 depicts the difference between the stored and computational representations.

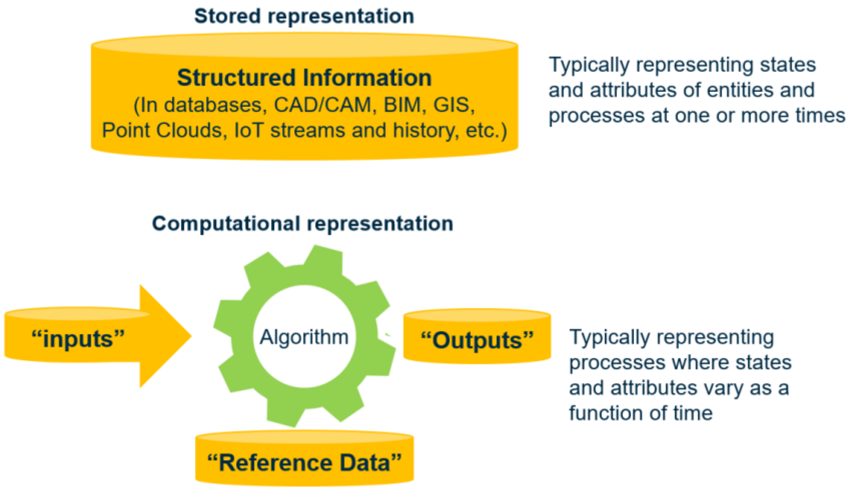

Figure 3-5: Comparison of stored and computational representations.

3.2.4 SERVICE LAYER FOR INTEGRATION, INTEROPERABILITY AND SYNCHRONIZATION

Definition: Service Interface

“A system’s *service interface* is a digitally addressable endpoint that implements a protocol through which other systems and services may interact with the system.”[15]

Once we have data, models and simulations (stored and computational representations), we need a way to combine these from a system-of-systems perspective into a digital twin system, ensuring interoperability between disparate systems and facilitating the synchronization of data between the real world entity and the digital twin. One of the key concepts in ensuring interoperability is consideration of the ontologies that represent the relationships of the interdependencies between the systems of interest.

3.2.4.1 INTEGRATION AND INTEROPERABILITY

As outlined at the introduction to this section, in order to deliver value digital twins must be considered as part of systems i.e. digital twin systems. This introduces the need for a systems perspective or “system-of-systems thinking”.[16]

Particularly relevant are the architectural approaches to building digital twin systems that themselves comprise of multiple digital twins or other digital twin systems in a composable or federated approach. The role of ontologies becomes more critical in ensuring the interoperability between these disparate systems in terms of communication frameworks as well as the semantics of the data and models for the digital twins.

Furthermore, a systems approach is required to architect digital twins and the systems they sit within successfully, with a clear understanding of the system boundaries, communication patterns and use cases between the digital twins and the IT/OT system of which they are part. An example would be the IEEE 1516-2010e High Level Architecture[17] approach for event-based co-simulation.

3.2.4.2 STANDARDS-BASED DATA AND SYNCHRONIZATION

To facilitate interoperability, data must be exchangeable and compatible. There are numerous standard data formats, but there will always be unique formats with their own challenges. This

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[15] *https://www.digitaltwinconsortium.org/glossary/glossary/#service-interface*

[16] *https://www.iiconsortium.org/wp-content/uploads/sites/2/2023/03/Patterns-System-of-Systems-Orchestrator-030923.pdf*

[17] *https://standards.ieee.org/ieee/1516/3744/*

is particularly the case with IoT or IIoT systems with disparate data formats and protocols that need to be integrated.

There are numerous efforts to provide unifying SDKs (software development kits) covering the most common of these formats and mappings between them. For example, within the geospatial sector the open source GDAL (The Geospatial Data Abstraction Library[18]) provides a comprehensive mapping between data formats. There are also numerous industrial bodies such as the Open Design Alliance[19], that provide SDKs for converting between well-known BIM formats.

Figure 3-6: Synchronization mechanisms.

Once the data is interoperable, there needs to be a mechanism for synchronizing the data. A common approach is to use publish/subscribe pattern, using the likes of the Data Distribution Service (DDS[20]), or message-queue systems with standards such as MQTT[21] or AMQP[22], or web-based approaches with RESTful[23] or GraphQL[24] APIs.

An important approach is the use of data modeling ontologies that provide a semi-structured approach for data within a given domain. However, the vast number of competing standards and ontologies within any given domain does introduce significant challenges to interoperability. This gives rise to a particular need to map between these different ontologies or data modeling languages.

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[18] *https://gdal.org/*

[19] *https://www.opendesign.com/*

[20] *https://opendds.org/*

[21] *https://mqtt.org/*

[22] *https://www.amqp.org/*

[23] *https://swagger.io/resources/articles/best-practices-in-api-design/*

[24] *https://graphql.org/*

3.2.5 REALIZING VALUE THROUGH APPLICATIONS

Digital twin services are functional subsystems of a digital twin system that provide value. To realize value with digital twins there needs to be business logic. Applications require services, such as visualization and rendering, analytics platforms and business management tools.

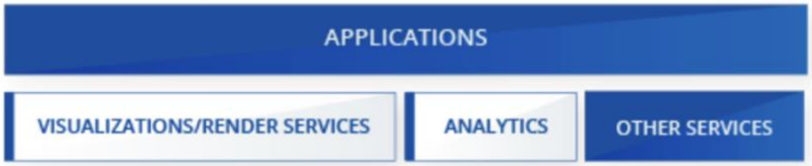


Figure 3-7: Application layer which consists of services such as visualization and analytics to deliver value.

There are numerous examples of open-source technology being adopted within the context of digital twins at this layer. The most prevalent are game engines for rendering, and web visualization libraries.

Business applications make it easier to compose digital twins within specific industry domains and combine visualization, analytics, monitoring into powerful performance management, financial modeling and optimization solutions.

4 DIGITAL TWIN USE CASES

Table 4-1 provides a summary of real world use cases that use the platform stack architectural framework to provide consistent context across industries. Each use case can also be found in Annex A, detailing the mapping from the architectural framework to its implementation in the use case.

Use Case	Objective	Value	Digital Twin Role	Solution Aspects
Buildings as Batteries	Develop and provide an energy infrastructure to enable rural and campus communities to achieve energy security and meet renewable energy goals.	Operational Resiliency Optimized Energy Consumption Economic Opportunity	Performs autonomous monitoring and analysis Provides prioritized real time optimization of energy consumption Enables efficient load balancing and storage	**Decentralized Power Grid** When deployed at scale, this evolution of the power grid will provide a fully decentralized energy infrastructure, allowing for unparalleled energy redistribution and operational resilience. **Scalability** This Use Case provides a digital twin system of

				systems blueprint to develop and operate, using a mass customization approach, a decentralized energy infrastructure. **Production Improvements** The digital twin is a creation and optimizer engine, allowing for real-world operation and optimizations under the conflicting constraints including • Safety and Security • Operational Efficiency • Economic Opportunity
Emergency Communication Services	Allow diverse teams distributed across the disaster area to interact in real time in a structured workflow as if they were in the same room	Establishes a practical approach for management of emergency and incident response with a common operating picture	Digital Twin provides advanced simulations, predictive analytics, and instant scenarios for decision process from the aggregated information layer to provide optimization of the communication structure for situational awareness collaboration	**Common Operating Picture** C4Map provides a globally distributed, synchronized and highly secure Ops Center, while being able to be scaled to any sized operation. Adaptable to any local or enterprise environment with multiple disparate entities. Fully scalable. **New Value to Old money** The solution is agnostic of hardware, software, network, or operating system; and is designed for seamless integration with standalone, virtualized, or pure data stream systems. Use of drone, AWS, and Digital Twin technologies further enhances C4MAP’s viability in even

				the most desperate situations. **Reliable and Secure** The processes and information passed throughout the communication network are backed by 24/7 automated diagnostics. Network Health and Cybersecurity as a service in the same platform.
Manufacturing Quality Control Via Remote Operator	Increase the flexibility of quality control on manufacturing lines	Introduces digital twins into the legacy manufacturing process, to bring it into alignment with post-Covid remote personnel requirements.	Provides a digital replica of the manufacturing cell, enabling manipulation and quality control inspection of manufacturing cells using Virtual Reality. The twin tracks energy efficiency, performance metrics, and maintainability of the manufacturing line.	**Virtual Reality Inspection** A digital twin of the manufacturing cell is created using to be experienced on VR headsets and deployed in a virtual environment, enabling real-time quality control. **Machine Learning Analysis** Process elements are measured and examined via the digital twin and passed onto machine learning technologies to provide actionable insights.
Scope 3 Carbon Reporting Emissions	Provide clear insights to a company's carbon footprint across the supply chain	Allows a first-time view at scope 3 emissions from the whole of a supply chain	The digital twin provides the standardized data model for carbon reporting as well as the standardized interface to access the carbon report	**Track Scope 3 Emissions** Using industrial digital twins (OPC UA – IEC 62541 and Asset Admin Shell - IEC 63278), reporting of carbon emissions along the supply chain is realized, allowing an end user to leverage open standards already established in

				the manufacturing industry. **Supply Chain Improvements** Factories can shift from providing custom forms of data to a more cohesive form, allowing better integration and the ability to monitor Scope 3 emissions. **Improve Industry Standards** To measure Scope 3 emissions, a standardized and platform-independent data sharing service must be introduced, and every actor along the supply chain needs to be able to report emissions and product carbon footprints.
Infectious Disease Management	Help teams to build intelligent digital twin solutions providing real-time 3D, XR and IOT support with a variety of deployment options.	Low initial costs support exploratory and iterative development to find valuable use cases which can scale up to enterprise grade deployments.	Link time, spatial and sensor data with existing enterprise data to enable new insights. This helps organizations better understand and predict the physical world in which they operate.	**Visualization of Current Disease Spread** Epidemiologists get an up-to-date view of the state of disease spread across more than 1,700 inpatients in 6 blocks across the campus, linking existing enterprise data sources with interactive 3D visualizations. **Visual Time Slicing to Understand Progression and Trends** Users can move a time slicer across 12+ months of data to see patient movements between

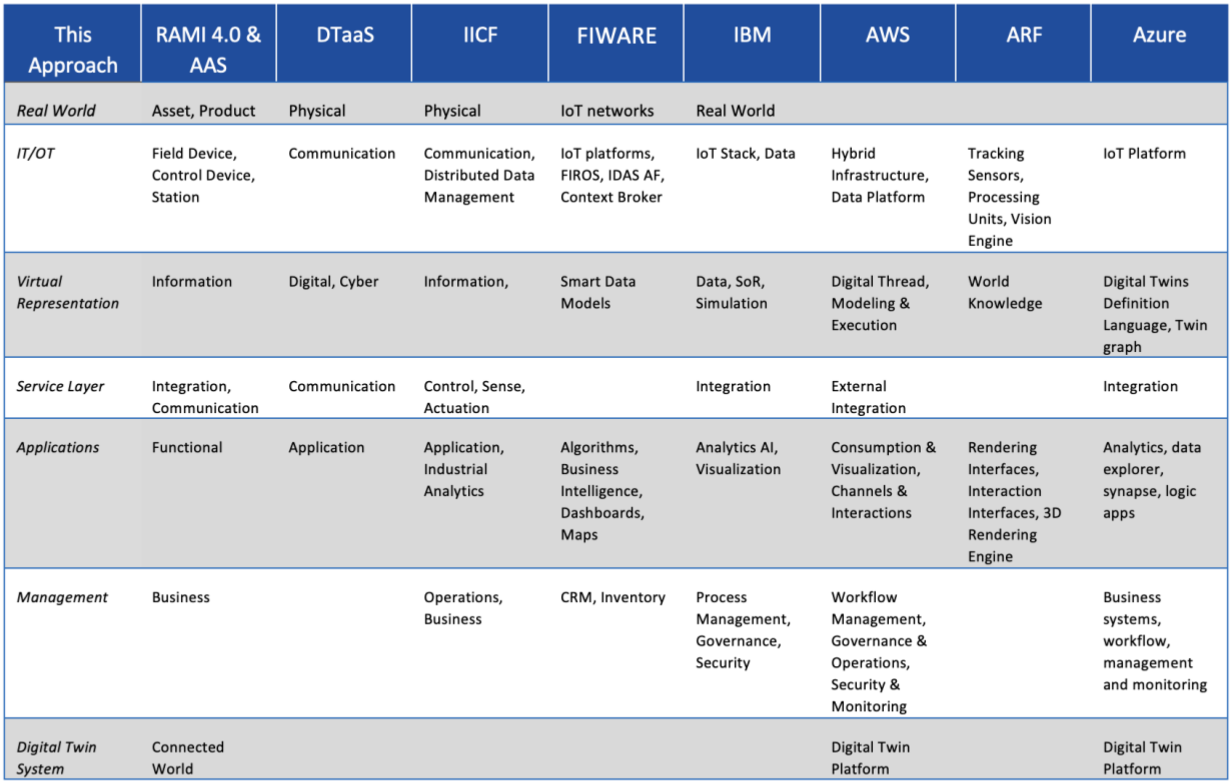
				beds along with their current and future disease state, providing an unprecedented level of contact tracing and investigation. **Risk Quantification, Prediction and Notifications** A risk quantification and prediction algorithm now uses both exposure time. and spatial distance to better predict likely secondary infections to better prioritize screening targets. Further integrations and notifications are in development.

Table 4-1: Summary of use cases.

5 PLATFORM STACK FRAMEWORK ALIGNED WITH OTHER APPROACHES

This chapter reviews other architecture approaches that currently exist along with their perspectives. General disclaimer: trademarks/copyrights belong to their respective organizations.

Table 5-1 highlights how the approach outlined in this paper relates to each of the digital twin reference architecture approaches as referenced in this section.



This Approach	RAMI 4.0 & AAS	DTaaS	IICF	FIWARE	IBM	AWS	ARF	Azure
Real World	Asset, Product	Physical	Physical	IoT networks	Real World			
IT/OT	Field Device, Control Device, Station	Communication	Communication, Distributed Data Management	IoT platforms, FIROS, IDAS AF, Context Broker	IoT Stack, Data	Hybrid Infrastructure, Data Platform	Tracking Sensors, Processing Units, Vision Engine	IoT Platform
Virtual Representation	Information	Digital, Cyber	Information,	Smart Data Models	Data, SoR, Simulation	Digital Thread, Modeling & Execution	World Knowledge	Digital Twins Definition Language, Twin graph
Service Layer	Integration, Communication	Communication	Control, Sense, Actuation		Integration	External Integration		Integration
Applications	Functional	Application	Application, Industrial Analytics	Algorithms, Business Intelligence, Dashboards, Maps	Analytics AI, Visualization	Consumption & Visualization, Channels & Interactions	Rendering Interfaces, Interaction Interfaces, 3D Rendering Engine	Analytics, data explorer, synapse, logic apps
Management	Business		Operations, Business	CRM, Inventory	Process Management, Governance, Security	Workflow Management, Governance & Operations, Security & Monitoring		Business systems, workflow, management and monitoring
Digital Twin System	Connected World					Digital Twin Platform		Digital Twin Platform

Table 5-1: Comparison of approaches to digital reference architectures.

5.1 RAMI INDUSTRIE 4.0

The Reference Architectural Model for Industrie 4.0 (RAMI 4.0)[25] has a three-dimensional perspective across IT, manufacturing and the product lifecycle. It references three standards to provide the basis for the layers.

1. IEC 62264 and IEC 61512 define control system integration and describe process controls that have been combined to provide the hierarchy levels with an addition of the “Product” at the lower end and “Connected World” at the upper.

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[25] *https://ec.europa.eu/futurium/en/system/files/ged/a2-schweichhart-reference_architectural_model_industrie_4.0_rami_4.0.pdf*

2. IEC 62890 provides the lifecycle stages representing data capture. The vertical axis provides a standard reference for IT layers often found in ERP systems moving up from the physical devices (assets) up through to business logic.

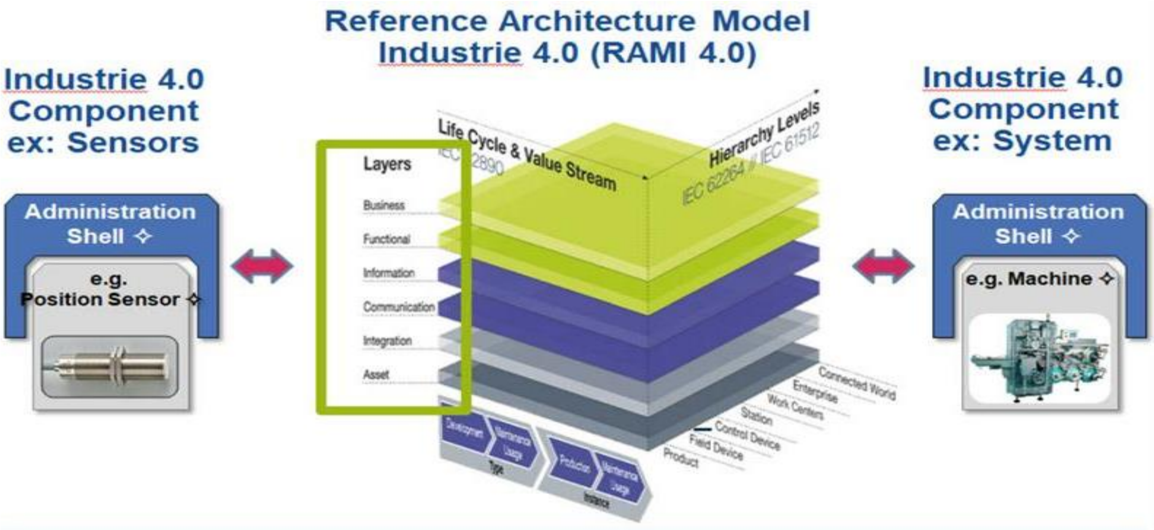

Figure 5-1: Industrie 4.0 Reference Architecture. (*Source: Industrie 4.0.)*

RAMI 4.0's asset administration shell is responsible for data storage and management, supporting functional behavior or business logic, providing network access to data and facilitating integration with communication protocols with other Industrie 4.0 systems or components.

5.2 DIGITAL TWIN AS A SERVICE IN INDUSTRIE 4.0

Another commonly adopted reference architecture comes from Aheleroff et al[26]. It closely aligns with RAMI 4.0, but suggests a digital thread (a flow of data from digital model to digital twin and then a predictive twin) instead of the hierarchy levels. This introduces a concept of digital twin maturity, which does have multiple subtle interpretations that we will expand on later.

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[26] *https://doi.org/10.1016/j.aei.2020.101225*

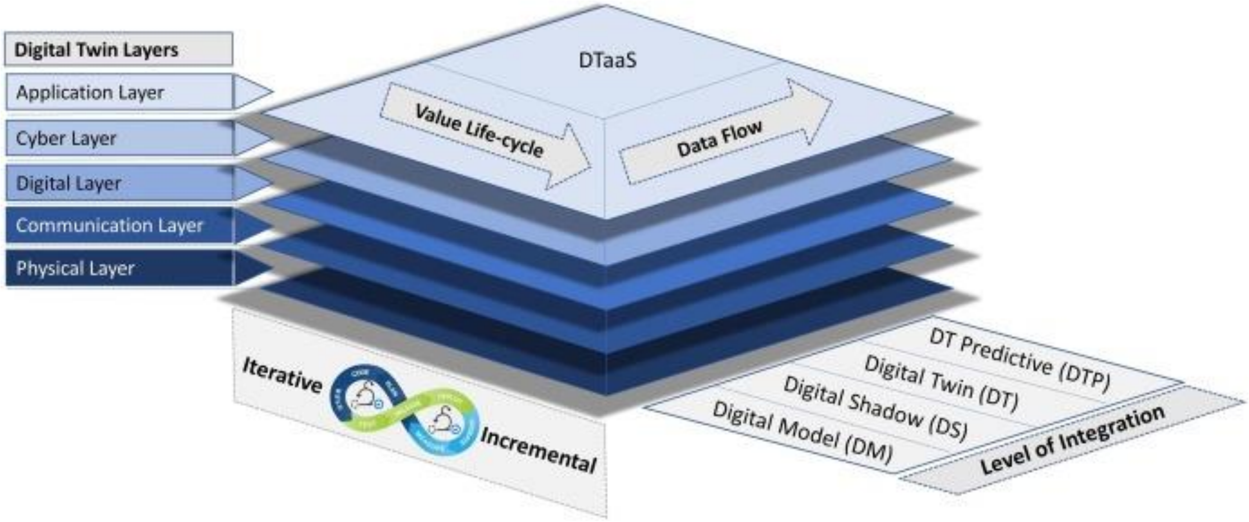

Figure 5-2: Digital Twin as a service architecture. (*Source: Industrie 4.0.*)

5.3 INDUSTRY IOT CONSORTIUM CONNECTIVITY FRAMEWORK

One of the purposes of the administration shell in RAMI 4.0 is to enable integration with other systems and components. This requires connectivity and interoperability frameworks.

The IIC's Industrial IoT Connectivity Framework (IICF)[27] builds from the physical device layer through network technologies such as Ethernet, wireless and internet protocols (a deeper dive specifically into the network framework can be found in the IIC's Industrial IoT Networking Framework)[28]. The connectivity framework highlights a useful set of middleware including Data Distribution Service (DDS), MQTT and OPC-UA. The last is used heavily in RAMI 4.0's asset admin shells.

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[27] *https://www.iiconsortium.org/wp-content/uploads/sites/2/2022/06/IIoT-Connectivity-Framework-2022-06-08.pdf*

[28] *https://www.iiconsortium.org/pdf/Industrial_Internet_Networking_Framework.pdf*

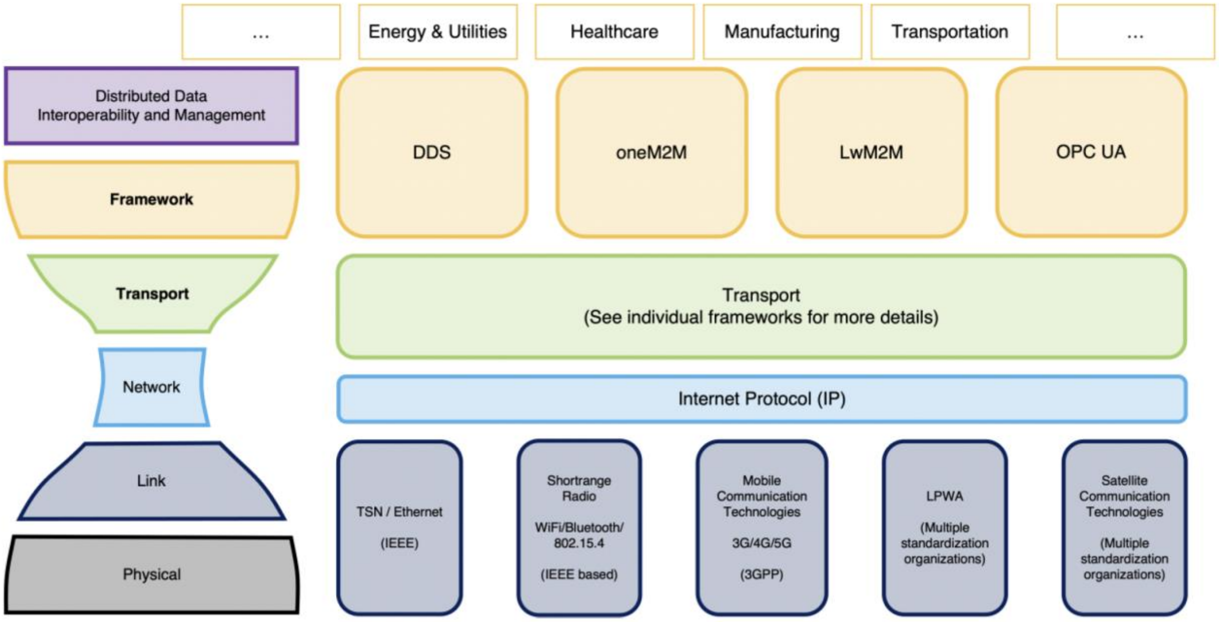

Figure 5-3: IIC Connectivity Framework. (*Source: Industry IoT Consortium.*)

The IIC's Industrial IoT Reference Architecture[29] defines stakeholder viewpoints from implementation up through to a business perspective, and a generalized lifecycle. Figure 5-4 summarizes the system characteristics and information flows.

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[29] *https://www.iiconsortium.org/pdf/IIRA-v1.9.pdf*

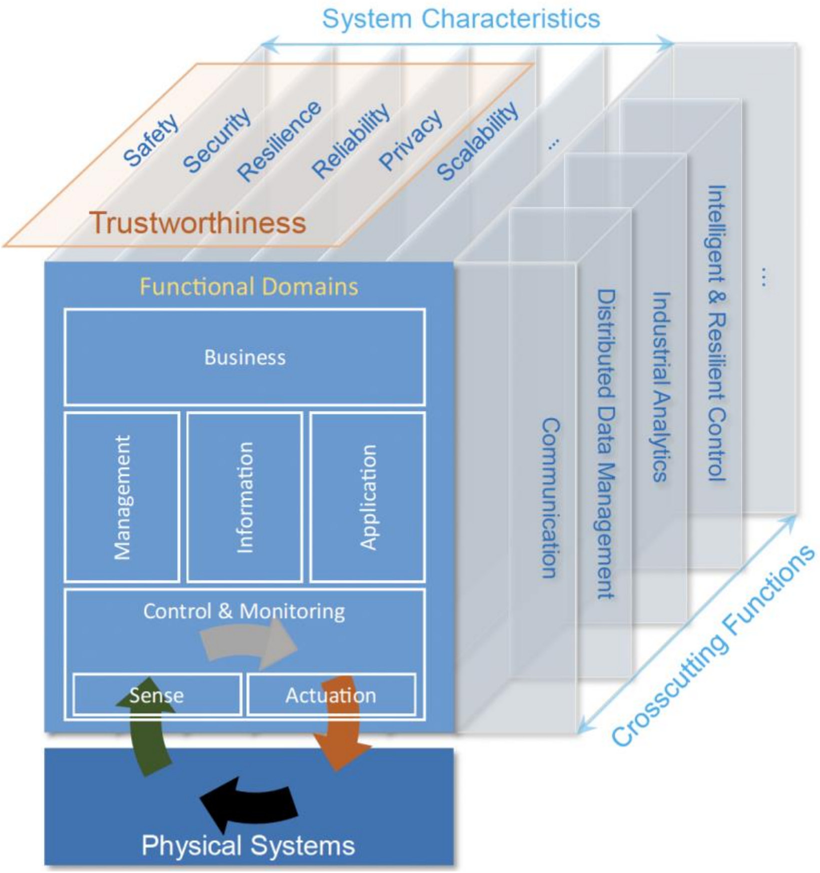

Figure 5-4: Industrial IoT Reference Architecture. (*Source: Industry IoT Consortium.)*

Along the top are the five characteristics of trustworthiness:

- safety,
- security,
- resilience,
- reliability and
- privacy.

Vertically on the right are cross-cutting functions including communication, data management and analytics. Cutting across these, at the front is the functional perspective with the information flows from the physical systems up to the business operations.

5.4 FIWARE ARCHITECTURE

FIWARE enables effective data integration across APIs to access digital twin data and the data models describing the attributes and semantics associated with them.

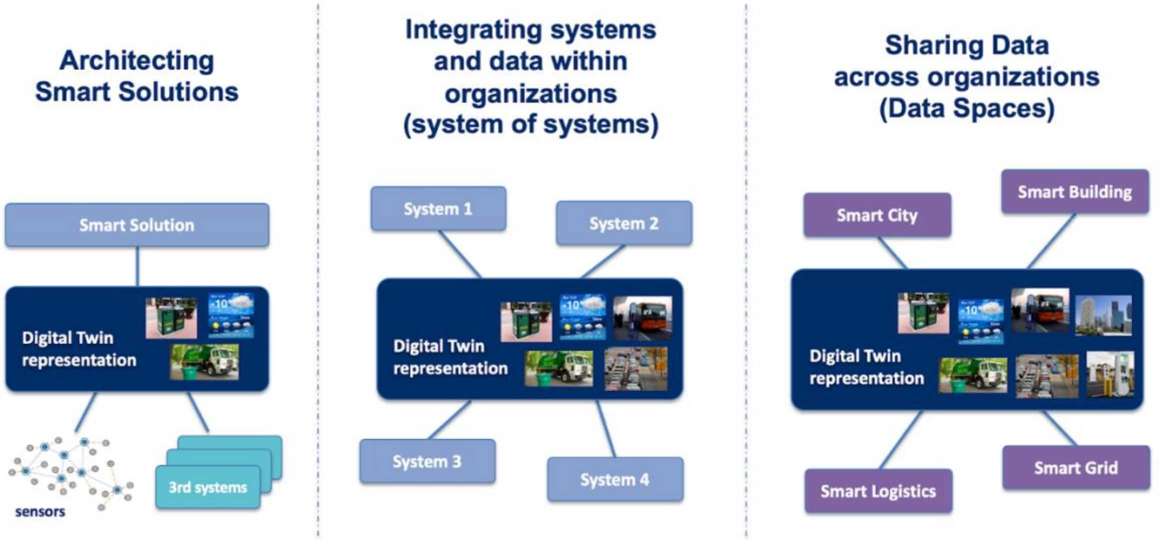

Figure 5-5: Levels of integration supported following the FIWARE digital twin approach.

The FIWARE community has driven and continues to drive standardization with both the NGSI API and their Smart Data Models program.

The NGSI API provides a simple yet powerful RESTful API for access to context and digital twin data. NGSI API specifications have evolved over time, driven by feedback from developers and implementation experiences. A first mature version of the API is the NGSIv2 API, which was defined by members of the FIWARE community and is currently used in many systems in production within multiple sectors. The NGSI-LD API is used as the data integration API and is implemented by the primary component of any “powered by FIWARE” architecture: the context broker component. Different alternative open-source implementations of a context broker are available within the FIWARE community.

The Smart Data Models program, launched by the FIWARE Foundation, provides a library of data models described in JSON/JSON-LD format, which are compatible with the NGSIv2/NGSI-LD APIs. It is also useful for defining other RESTful interfaces for accessing digital twin data. Data models published under the initiative are compatible with the schema.org ontology[30] and comply with other existing de facto sectoral standards where they exist. They solve one major issue developers face: a given data model specification may be mapped into JSON/JSON-LD in many different ways, all of them valid.

Thanks to the Smart Data Models program, developers can rely on concrete mappings into JSON/JSON-LD, compatible with the NGSIv2/NGSI-LD APIs, that are made available within this library, avoiding interoperability problems that arise from alternative mappings. More than 500

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[30] *https://schema.org/docs/datamodel.html*

data models have been published and the number of organizations contributing data model descriptions is growing.

Figure 5-6 depicts the reference architecture of a vertical smart solution powered by FIWARE. The example shows a smart solution for picking and palletizing products from a warehouse using robots.

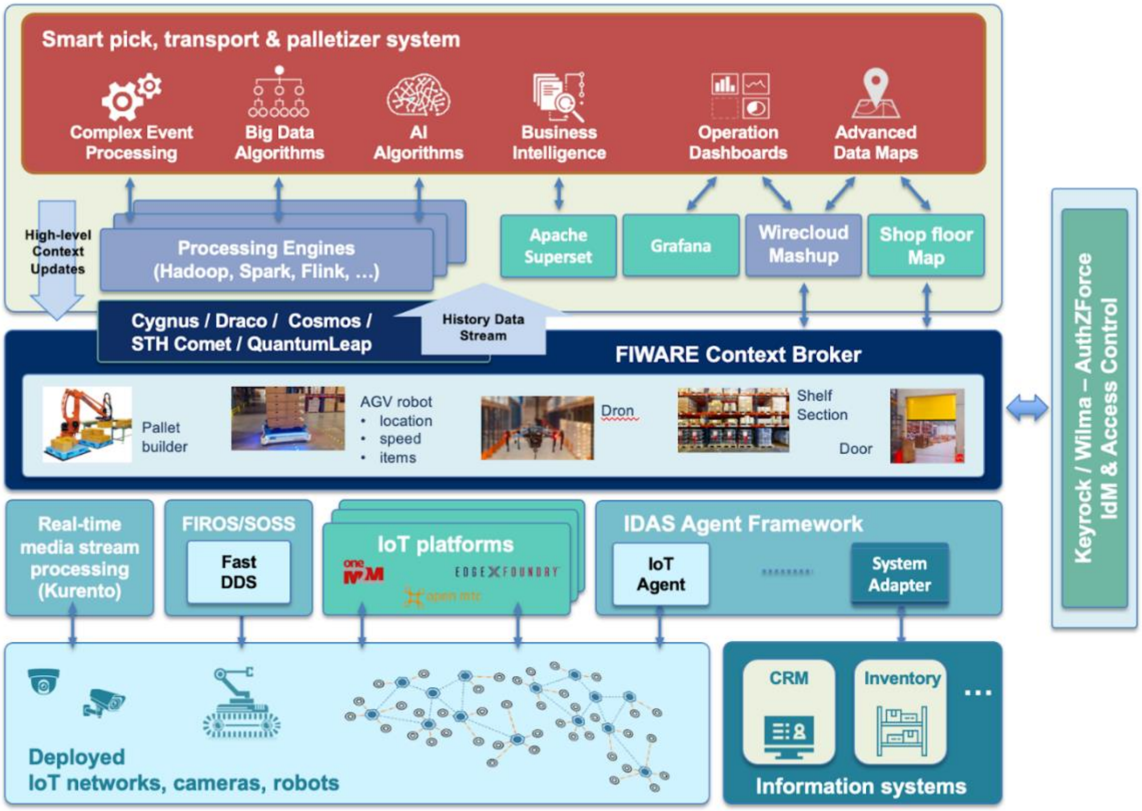

Figure 5-6: Smart solution for picking and palletizing products from a warehouse. (*Source: FIWARE.)*

This reference architecture is structured in three layers:

The *context broker* is at the heart of the architecture, keeping a digital twin representation of the real-world objects and concepts relevant to the specific problem: AGV robots, palletizer robots, shelf sections where products are stored in the warehouse, automatic doors AGV robots must pass, operators in the shop floor, items of stored products, orders generated from CRM, etc.

The context broker and the NGSI IoT agents are used for connections to robotic systems exporting the OPC-UA IoT protocol or to specific sensors or actuators, used, for example, to detect items in shelf sections or to be able to open the shop-floor doors. They perform the necessary conversions between IoT protocols and NGSI. System adapters based on the IDAS agent library cope with the connection to the CRM and the Warehouse Inventory Management system that the solution interfaces with. FIWARE components like FIROS/SOSS adapt to robotic systems based on

ROS/ROS2. The FIWARE component Kurento processes the video streams from cameras deployed in the shop floor, which are helpful to detect potential obstacles or risky situations.

Above the context broker, various tools support real-time big-data processing of the streams of data generated and as digital twin information evolves over time. A combination of open-source components from third-party products (Apache Superset/Grafana) and FIWARE (e.g., Wirecloud) support the creation of operational dashboards and advanced data maps for monitoring processes. A number of FIWARE data connectors (Cygnus, Draco, Cosmos, STH Comet and QuantumLeap) are available to facilitate transferring of historic context and digital twin information to these tools.

Transversal to all these layers, FIWARE components support identity and access management. They enforce the policies establishing what users can update, query or subscribe to changes on context and digital twin data. Applications can update context data, which triggers changes in the devices, robots or systems at the foot of the figure.

You are not required to use all the complementary FIWARE components; you can use third-party platform components to design a hybrid platform of your choice. For example, you may choose to use a concrete IoT platform instead of IDAS IoT agents to interface with sensors and actuators. As long as it uses the FIWARE context-broker technology to manage context information, your platform and solutions built on top, can be labeled as “powered by FIWARE.”

5.5 ASSET ADMINISTRATION SHELL

The IEC 61131 Asset Administration Shell is a result of the collaboration between the Platform Industrie 4.0 and the ZVEI in Germany. It is a cross-platform data sharing service with a defined data exchange and packaging format (part 1 of the specification) as well as a standardized REST interface for hosting Asset Admin Shells in a web server (part 2 of the specification).

In recent years, the Industrial Digital Twin Association (IDTA) has been founded and tasked with commercializing the Asset Admin Shell and creating additional content for it (for example, marketing material or Asset Admin Shell templates that end users can use to create Asset Admin Shells more easily by themselves). There is also a significant open-source initiative on GitHub focused on Asset Admin Shells reference implementations and tools, now driven by the IDTA and currently getting moved to a top-level Eclipse Foundation project. The IDTA membership has steadily and linearly increased since its inception.

5.6 CLOUD STACKS

Digital twins are typically only possible if significant connectivity and computing power is available. As a result, computing in a data center is vital. We outline three common architectures for building large-scale digital twin systems.

5.6.1 IBM DIGITAL TWIN REFERENCE ARCHITECTURE

IBM proposes an approach outlined in Figure 5-7.

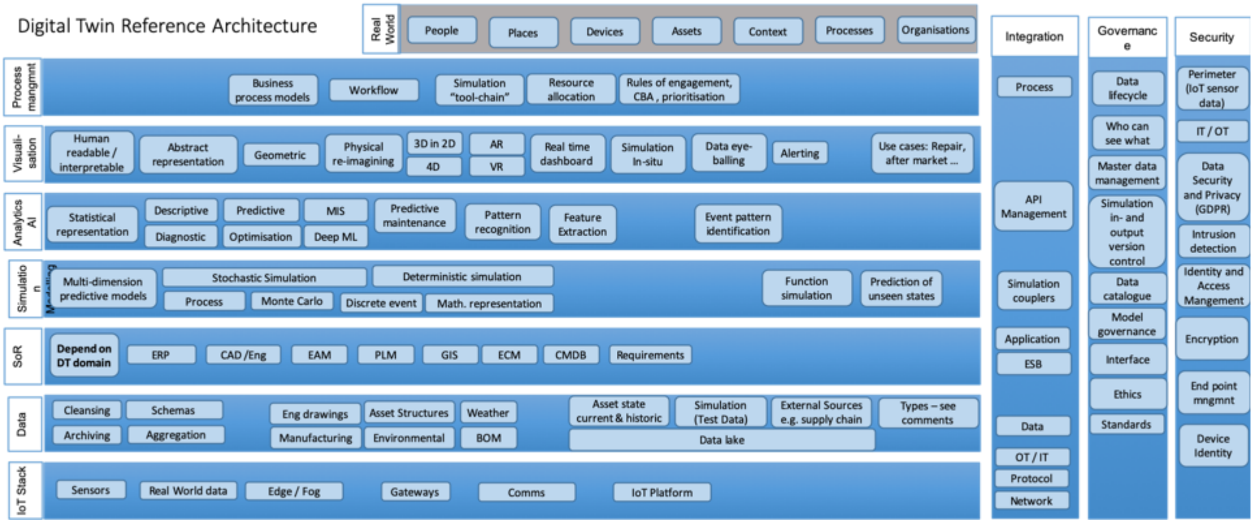

Figure 5-7: IBM digital twin reference architecture. (*Source: IBM*.)

This comprises the following primary layers:

- IoT stack, with everything from the hardware and sensors up to the edge platforms for managing these devices and the flow of data from them into and out of the data center.
- Data layer, dependent on the domain, with data schemas, data cleaning and archiving and mechanisms for data storage, such as databases and data lakes.
- Information management layer (or systems of record) with PLM and ERP systems and domain-specific systems, such as managing engineering data through CAD.
- Modeling & simulation, with stochastic or deterministic simulations including process models, Monte Carlo, discrete event, discrete time, computational fluid dynamics and finite element analysis.
- An analytics layer focused on machine-learning.
- Visualization, everything from dashboards to virtual or augmented reality.
- A management layer for an organizational or business perspective driving or deriving value from the system.

This is supported by three cross-cutting columns for integration, governance and security.

5.6.2 MICROSOFT DIGITAL TWIN REFERENCE ARCHITECTURE

Microsoft's Digital Twin Reference architecture is depicted below:

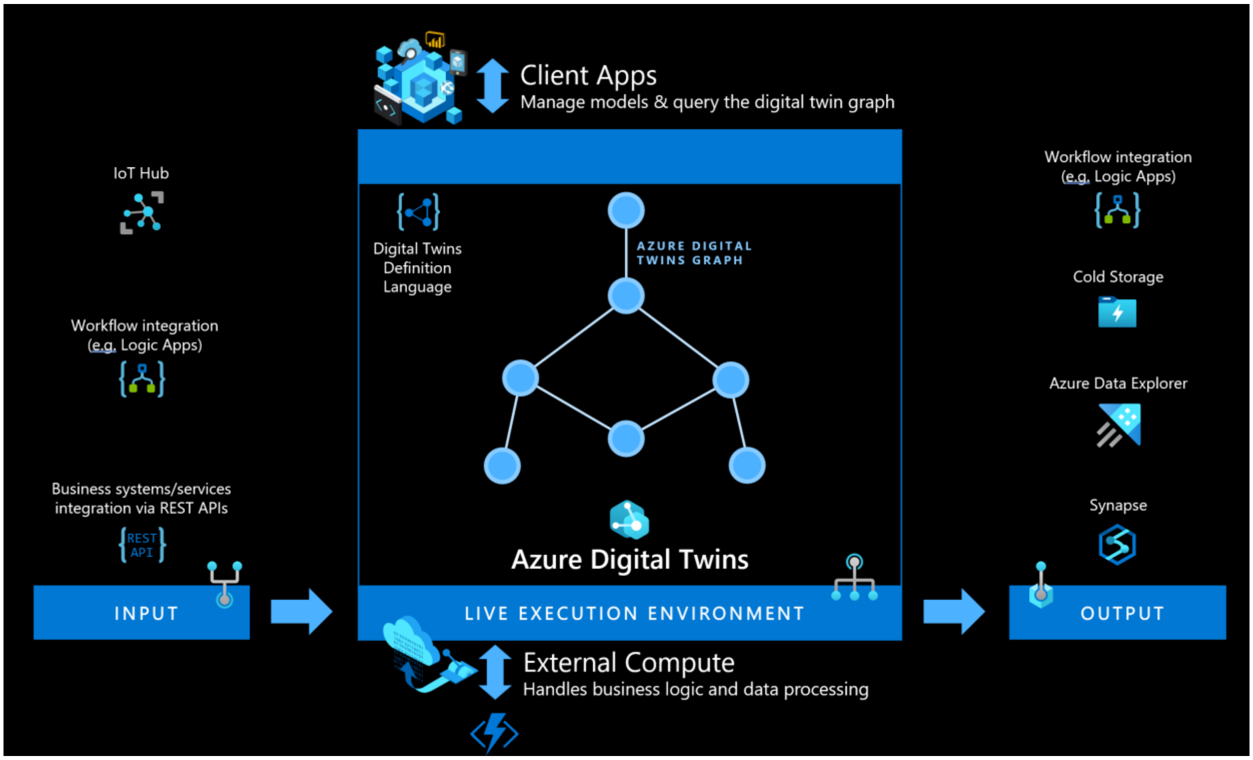

Figure 5-8: Microsoft digital twin reference architecture. *(Source: Microsoft.)*

Data is sent to the Azure Digital Twins (ADT) service via different sources. ADT provides a REST API and SDK to enable this with low engineering effort. The digital twin data sent to ADT is in Digital Twin Definition Language (DTDL) format, an open, JSON-LD-based format.

Additionally, Azure Digital Twin Service can be configured to historize the data to Azure Synapse, Azure Storage or to the Azure Data Explorer service for further analytics. Azure Logic Apps are also supported for custom input and output to ADT. Both Azure Digital Twins service and Azure Data Explorer service have built-in PaaS dashboards for user interaction, as well as an API to run queries against the digital twins as well as their associated models contained in the services.

5.6.3 AWS SOFTWARE STACK

Figure 5-9 shows the equivalent stack from Amazon Web Services. It is comprised of three elements:

- the digital twin platform itself,
- integrations with third-party systems including IoT devices, enterprise ERP systems and
- channels for visualization and user interaction including mobile devices, applications.

The digital twin platform then has five horizontal layers:

- data platform for data ingestion, storage and transformation,
- a digital thread is an information layer providing semantics to the data platform,

- modeling and execution layer for analytics, simulation and machine learning,
- visualization and API layer, and
- a workflow management layer for overall orchestration of the system.

This is crosscut by governance, operations and security.

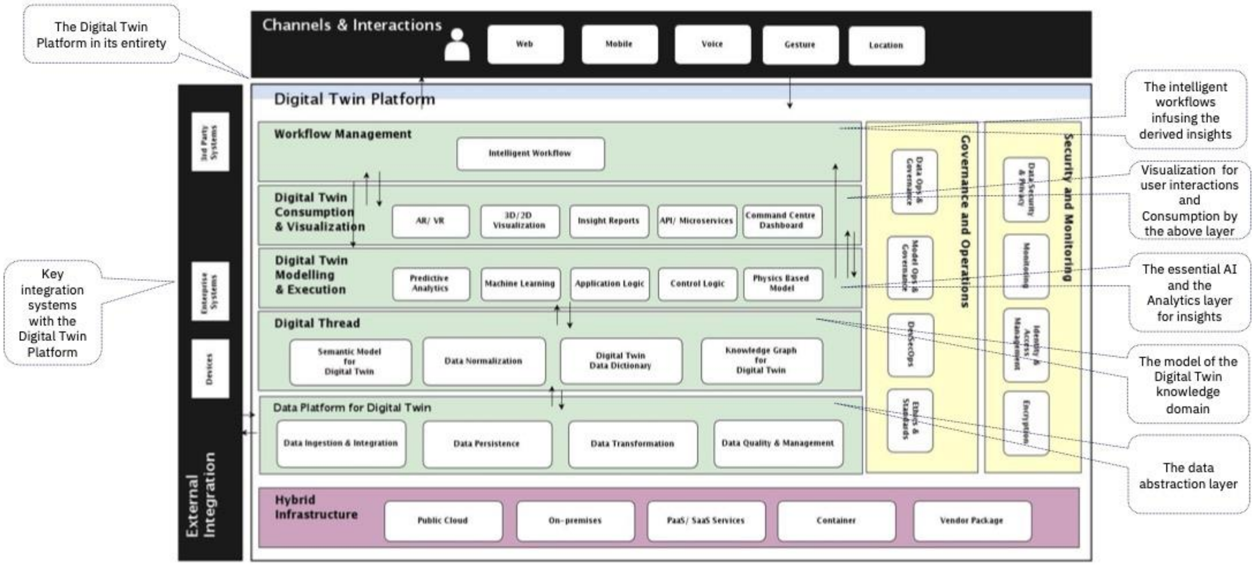

Figure 5-9: AWS digital twin platform architecture. *(Source: Amazon Web Services.)*

5.7 AUGMENTED REALITY FRAMEWORK

The ETSI Augmented Reality Framework (ARF) architecture comprises three layers: hardware, software and data with different elements suitable for data center deployment, edge deployment or on local devices. A "vision engine" manages the mapping of data while a "rendering engine" handles interactive aspects.[31]

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[31] *https://www.etsi.org/committee/1420-arf?jjj=1688653881682*

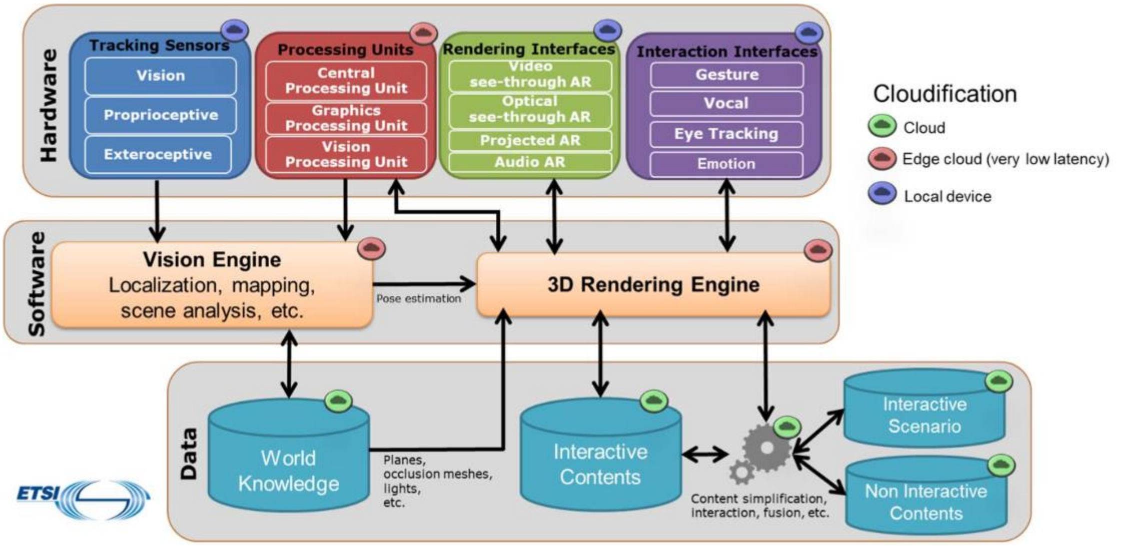

Figure 5-10: Augmented reality framework (ARF) architecture. (*Source: ETSI.)*

5.8 ONTOLOGIES

The Microsoft Azure reference architecture outlines a similar stack to those above, however it is focused more on the semantics of modeling languages and specifically the Digital Twin Definition Language (DTDL)[32]. A comprehensive review, focusing on the built environment, can be found in work by Centre for Digitally Built Britain (CDBB)[33].

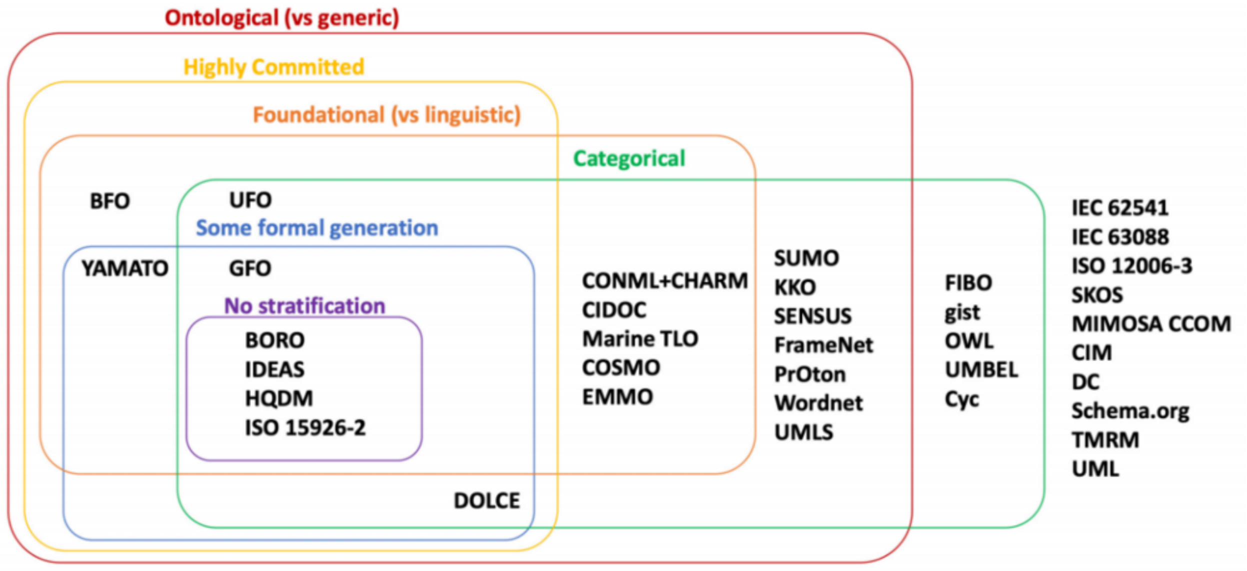

Figure 5-11: Venn diagram showing classifications of top-level ontologies for built environment. *(Source: CDBB.)*

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[32] *https://github.com/Azure/opendigitaltwins-dtdl*

[33] *https://www.cdbb.cam.ac.uk/*

DTDL provides one approach that can be applied across multiple domains, although it has been primarily applied within the built environment. Figure 5-12 shows an example mapping between DTDL, NGSI from FIWARE, the geoSPARQL approach by the Open Geospatial Consortium and the building SMART IFC standard.

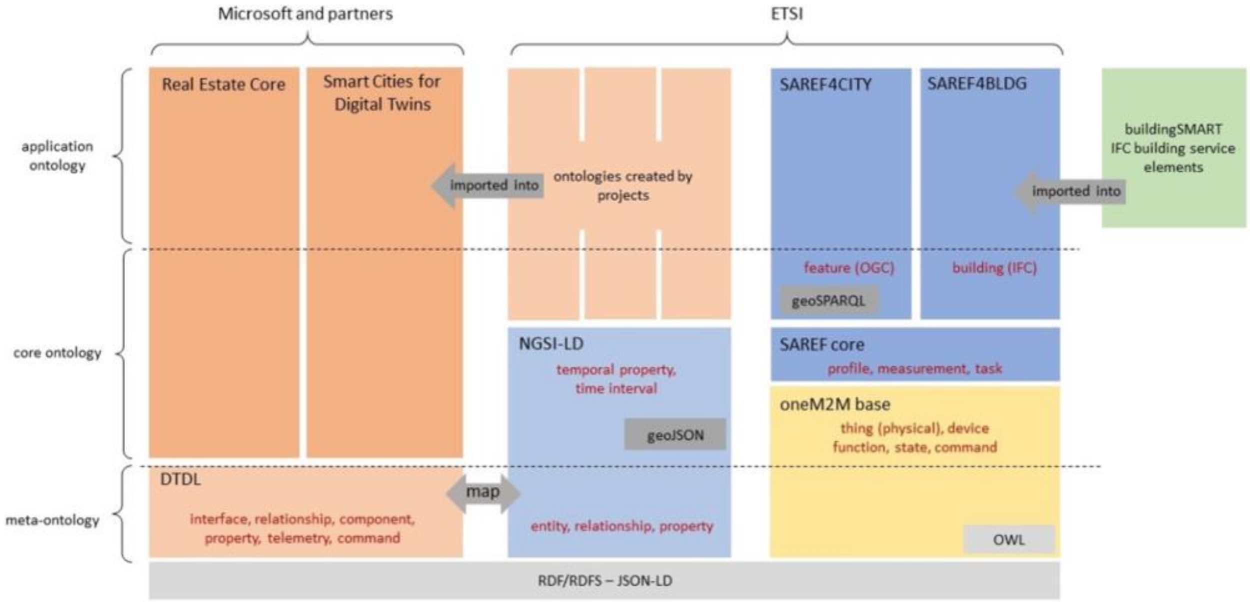


Figure 5-12: Digital twin ontologies mapped by CDBB. *(Source: CDBB.)*

6 SUMMARY

Digital twin systems have the potential to accelerate digitization as they enable organizations to operate more efficiently than ever before. Digital twins could uniquely help us tackle some of the most pressing challenges facing our world.

To build these systems, we need to define best practices. In this paper we have outlined the central parts of any digital twin system including the IT/OT infrastructure, the virtual representation, service interfaces, applications for delivering value, mechanisms for synchronization and data from the real world. This provides a pattern we can work from to explore use cases and continue to encourage the development of more open and interoperable systems.

In Annex A. we have correlated these against five use cases of varying levels of maturity providing examples of how this architecture can be used in practice. These use cases looked at everything from energy systems in buildings to emergency response for natural disasters to carbon reporting and net zero planning.

7 AUTHORS & LEGAL NOTICE

This document is a work product of the Digital Twin Consortium Open Source, Standards and Platform Stacks Subgroup, chaired by David McKee (Slingshot Simulations).

Authors: The following people contributed substantial written content to this document: David McKee (Slingshot Simulations).

Contributors: The following persons contributed valuable ideas and feedback that significantly improved the content and quality of this document: Casey Mullen (Bentley), Koya Mori (Nippon Telegraph and Telephone Corporation), Sean Olcott (Gafcon Digital), Anto Budiardjo (Padi), Chafia Aouissi (Microsoft), Said Tabet (Dell) and Alberto Abella (FIWARE).

Technical Editor: Dan Isaacs (DTC CTO) oversaw the process of organizing the contributions of the above Authors and Contributors into an integrated document.

Annex A DIGITAL TWIN USE CASE EXAMPLES

A.1 USE CASE 1: BUILDINGS AS BATTERIES

VALUE

- Operational Resiliency
- Optimized Energy Consumption
- Economic Opportunity

PLANNED DEPLOYMENT

Brooklyn Navy Yard

Solution Description

Decentralized Power Grid

When deployed at scale, this evolution of the power grid will provide a fully decentralized energy infrastructure, allowing for unparalleled energy redistribution and operational resilience.

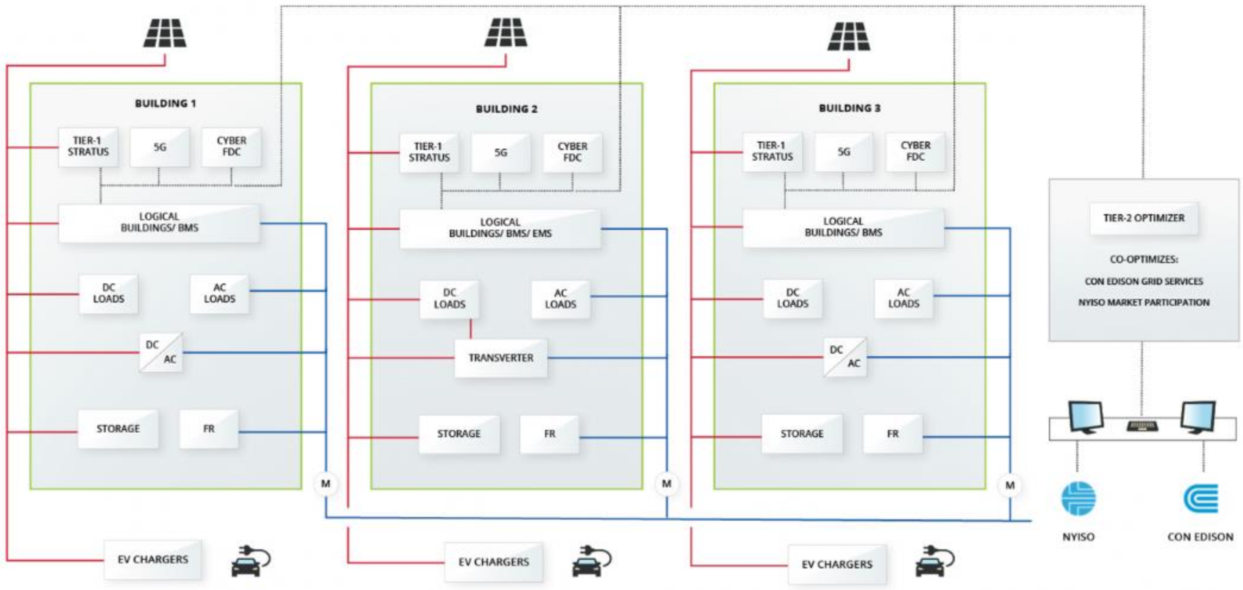
Scalability

This Use Case provides a digital twin system of systems blueprint to develop and operate, using a mass customization approach, a decentralized energy infrastructure.

Production Improvements

The digital twin is a creation and optimizer engine, allowing for real-world operation and optimizations under the conflicting constraints including

- Safety and Security
- Operational Efficiency
- Economic Opportunity



The above figure depicts the architecture of Buildings as Batteries case study that is composed of EV charges external to the buildings and the electrical and connectivity/intelligence systems within the buildings. The latter are connected to tier 2 optimizers for integration with broader systems such as markets and the electrical grid.

The mapping to the platform stack architectural framework is shown below, where the buildings are acting as data sources external to the twin and the tier-1 management system and connectivity systems provide the mechanisms for synchronization. The tier 2 optimizer provides the management and governance systems.

For complete information on the Buildings as Batteries use case, please visit the Digital Twin Consortium website.[34]

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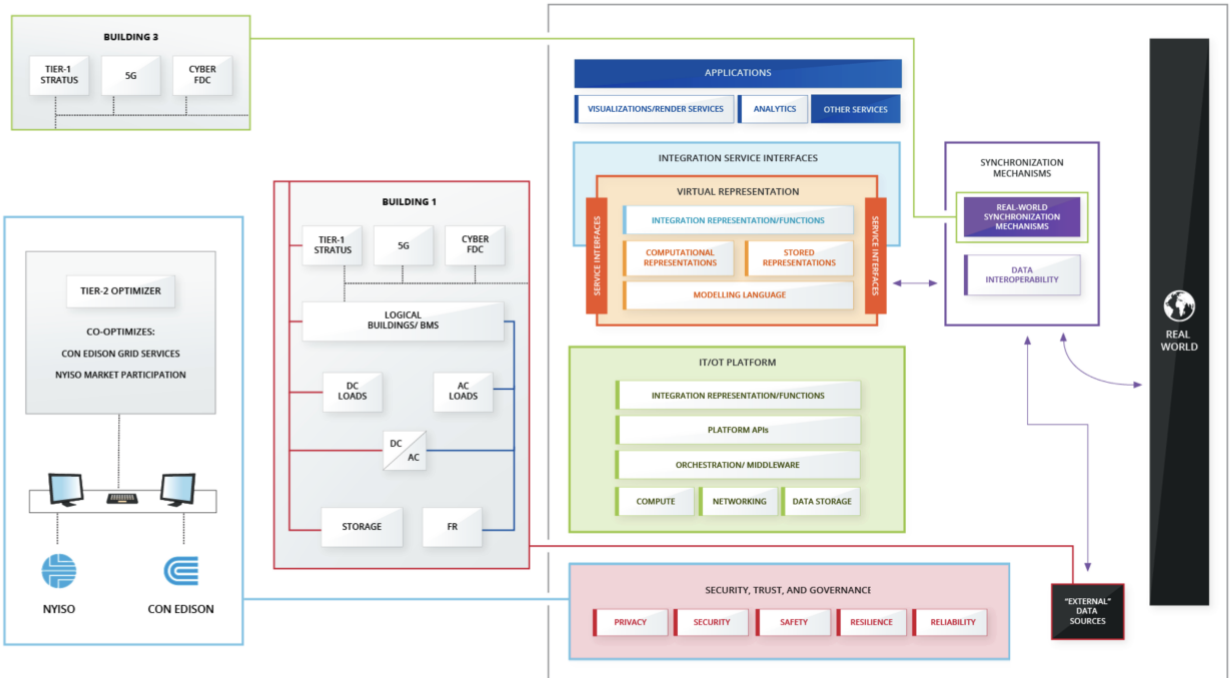
[34] *https://www.digitaltwinconsortium.org/initiatives/technology-showcase/buildings-as-batteries/*


BUILDING 3
TIER-1 STRATUS
5G
CYBER FDC
TIER-2 OPTIMIZER
CO-OPTIMIZES:
CON EDISON GRID SERVICES
NYISO MARKET PARTICIPATION
NYISO
CON EDISON
BUILDING 1
TIER-1 STRATUS
5G
CYBER FDC
LOGICAL BUILDINGS/ BMS
DC LOADS
AC LOADS
DC
AC
STORAGE
FR
APPLICATIONS
VISUALIZATIONS/RENDER SERVICES
ANALYTICS
OTHER SERVICES
INTEGRATION SERVICE INTERFACES
VIRTUAL REPRESENTATION
SERVICE INTERFACES
INTEGRATION REPRESENTATION/FUNCTIONS
COMPUTATIONAL REPRESENTATIONS
STORED REPRESENTATIONS
MODELLING LANGUAGE
SERVICE INTERFACES
IT/OT PLATFORM
INTEGRATION REPRESENTATION/FUNCTIONS
PLATFORM APIs
ORCHESTRATION/ MIDDLEWARE
COMPUTE
NETWORKING
DATA STORAGE
SECURITY, TRUST, AND GOVERNANCE
PRIVACY
SECURITY
SAFETY
RESILIENCE
RELIABILITY
SYNCHRONIZATION MECHANISMS
REAL-WORLD SYNCHRONIZATION MECHANISMS
DATA INTEROPERABILITY
"EXTERNAL" DATA SOURCES
REAL WORLD

A.2 USE CASE 2: EMERGENCY COMMUNICATION SERVICES

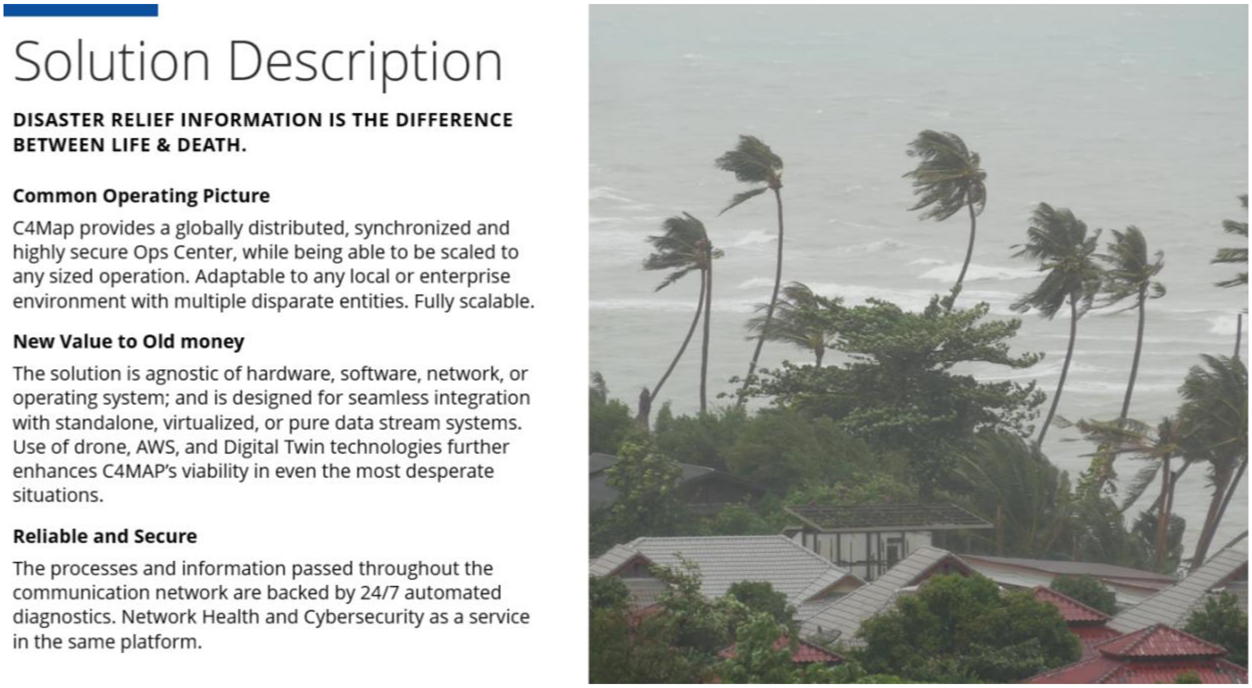
Emergency Communication Services

OBJECTIVE

Allow diverse teams distributed across the disaster area to interact in real time in a structured workflow as if they were in the same room.

VALUE

Establishes a practical approach for management of emergency and incident response with a common operating picture.



Solution Description

DISASTER RELIEF INFORMATION IS THE DIFFERENCE BETWEEN LIFE & DEATH.

Common Operating Picture

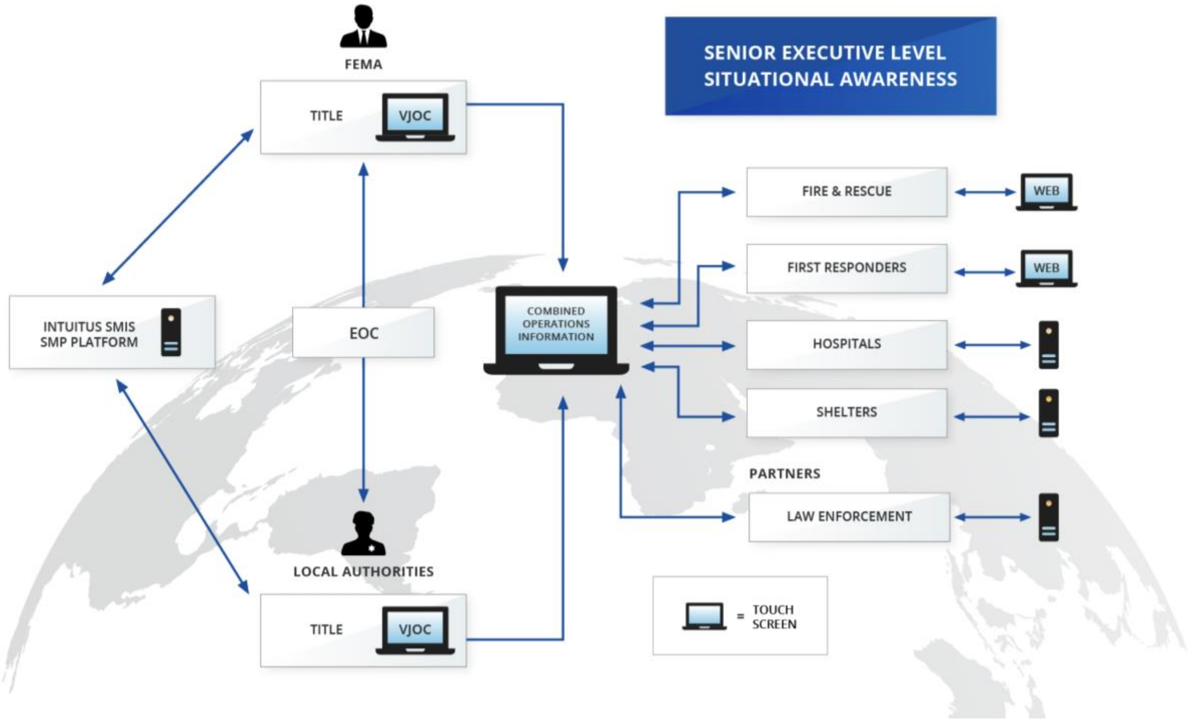
C4Map provides a globally distributed, synchronized and highly secure Ops Center, while being able to be scaled to any sized operation. Adaptable to any local or enterprise environment with multiple disparate entities. Fully scalable.

New Value to Old money

The solution is agnostic of hardware, software, network, or operating system; and is designed for seamless integration with standalone, virtualized, or pure data stream systems. Use of drone, AWS, and Digital Twin technologies further enhances C4MAP's viability in even the most desperate situations.

Reliable and Secure

The processes and information passed throughout the communication network are backed by 24/7 automated diagnostics. Network Health and Cybersecurity as a service in the same platform.



For complete information on the Emergency Communications Services use case, please visit the Digital Twin Consortium website.[35]

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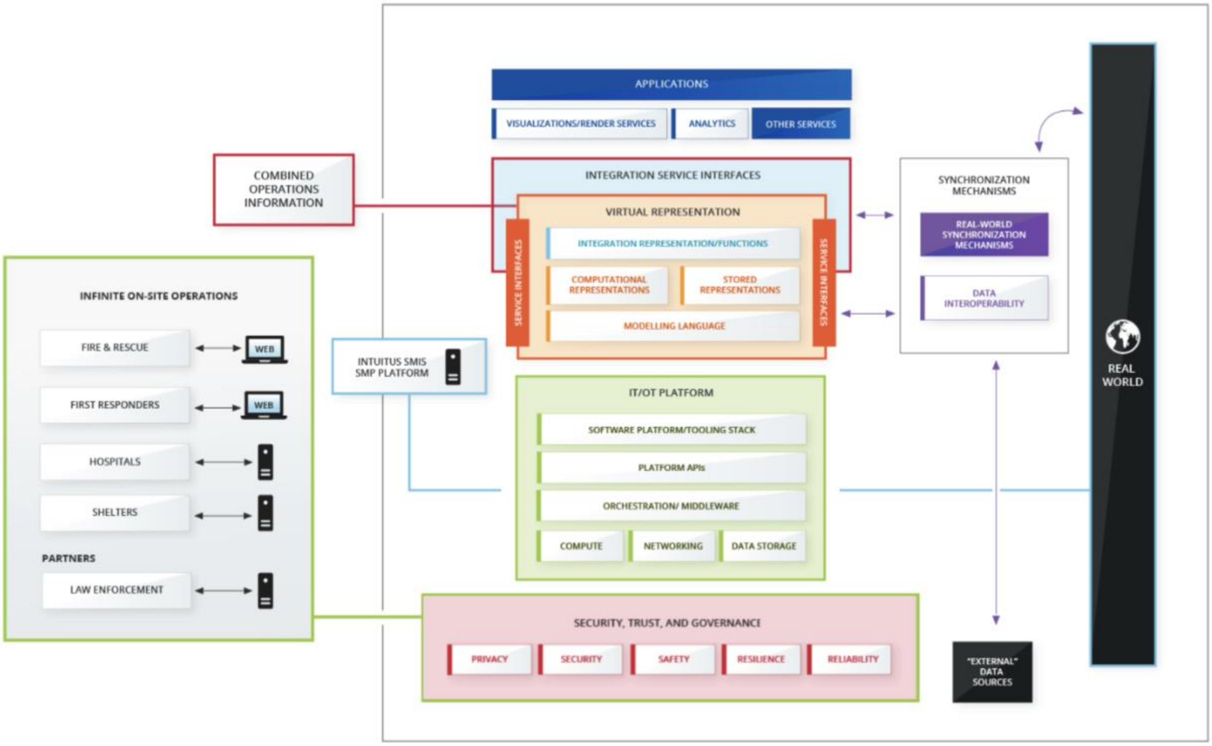
[35] *https://www.digitaltwinconsortium.org/initiatives/technology-showcase/emergency-communication-services/*


APPLICATIONS
VISUALIZATIONS/RENDER SERVICES
ANALYTICS
OTHER SERVICES
COMBINED OPERATIONS INFORMATION
INTEGRATION SERVICE INTERFACES
VIRTUAL REPRESENTATION
SERVICE INTERFACES
INTEGRATION REPRESENTATION/FUNCTIONS
COMPUTATIONAL REPRESENTATIONS
STORED REPRESENTATIONS
MODELLING LANGUAGE
SERVICE INTERFACES
SYNCHRONIZATION MECHANISMS
REAL-WORLD SYNCHRONIZATION MECHANISMS
DATA INTEROPERABILITY
REAL WORLD
INFINITE ON-SITE OPERATIONS
FIRE & RESCUE
WEB
FIRST RESPONDERS
WEB
HOSPITALS
SHELTERS
PARTNERS
LAW ENFORCEMENT
INTUITUS SMIS SMP PLATFORM
IT/OT PLATFORM
SOFTWARE PLATFORM/TOOLING STACK
PLATFORM APIs
ORCHESTRATION/ MIDDLEWARE
COMPUTE
NETWORKING
DATA STORAGE
SECURITY, TRUST, AND GOVERNANCE
PRIVACY
SECURITY
SAFETY
RESILIENCE
RELIABILITY
"EXTERNAL" DATA SOURCES

A.3 USE CASE 3: MANUFACTURING QUALITY CONTROL VIA REMOTE OPERATOR

Manufacturing Quality Control Via Remote Operator

OBJECTIVE

To increase the flexibility of quality control on manufacturing lines.

VALUE

Introduces digital twins into the legacy manufacturing process, to bring it into alignment with post-Covid remote personnel requirements.

vicomtech
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

Vicomtech is a technological non-profit foundation. Their main mission is to respond to the developmental needs of businesses and institutions, enabling them to confront new financial and social challenges.

aingura IIoT

Aingura IIoT designs and develops cutting edge IIoT solutions for the industry based on data acquisition, pre-processing, processing and managing decision support actionable insights in industrial environments.

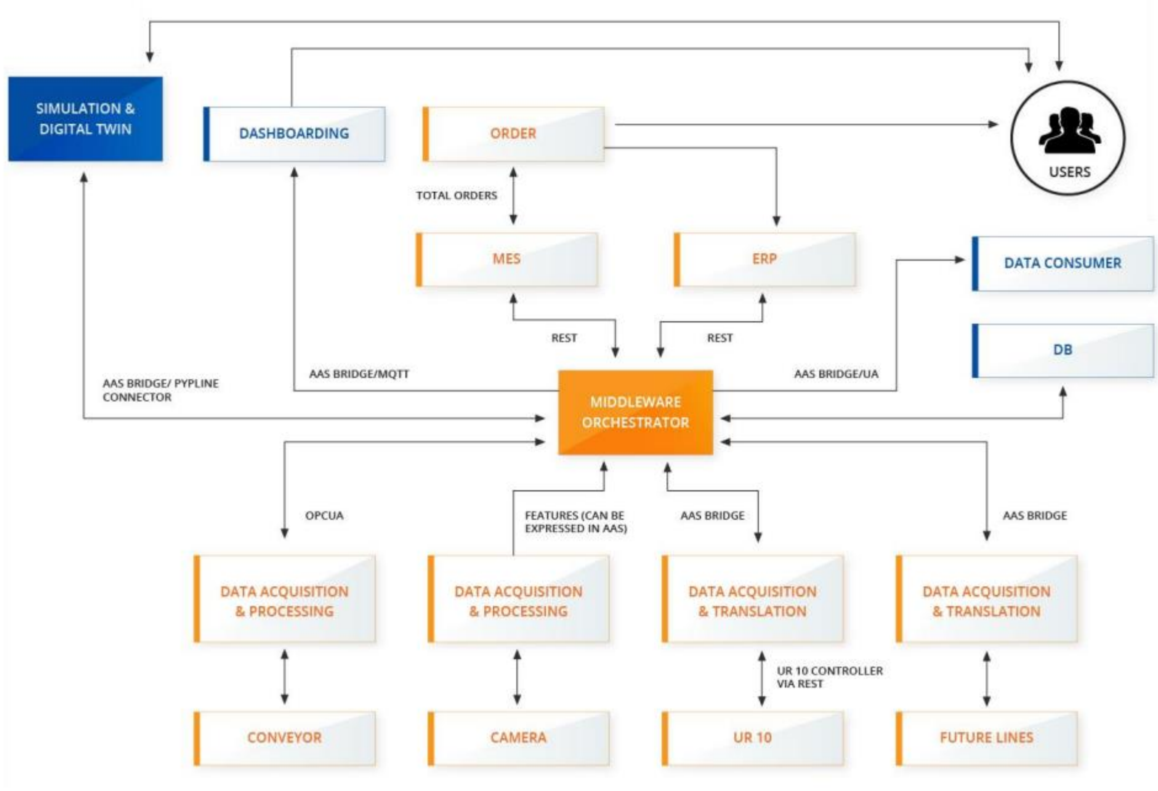
THE SOLUTION

This showcase replicates a real manufacturing line and its components, in the following sequence:

- An Enterprise Resource Planning (ERP) system which sends the order to a Manufacturing Execution System (MES). The MES launches the manufacturing process, including a conveyer that moves parts and a remote-controlled robot.
- A remote operator decides if the part is valid, viewing a live camera image over 5G, and the robot finishes the manufacturing process.
- A Data Acquisition Module communicates with the elements of the manufacturing line to store relevant traceability and process data at a High-Performance Computer (HPC).
- This data feeds an Assets Administration Shell (AAS) based digital representation of the line elements that are the input for the twin. The twin, including the dashboard, is deployed in a virtual environment viewed by AR goggles.

DIGITAL TWIN ROLE

- Provides a digital replica of the manufacturing cell, enabling manipulation and quality control inspection of manufacturing cells using Virtual Reality.
- Tracks energy efficiency, performance metrics, and maintainability of the manufacturing line.



In this manufacturing use case, the above architecture is mapped into the platform stack reference framework as shown below. Data acquisition systems acquire external data from cameras to conveyor belts and more acting as the inbound synchronization mechanism. An orchestrator uses a range of communication approaches within the IT system and an Asset Admin Shell bridge is used to connect to the simulation aspect of the digital twin paired with using MQTT to publish results to dashboards.

For complete information on the Manufacturing Quality Control use case, please visit the Digital Twin Consortium website.[36]

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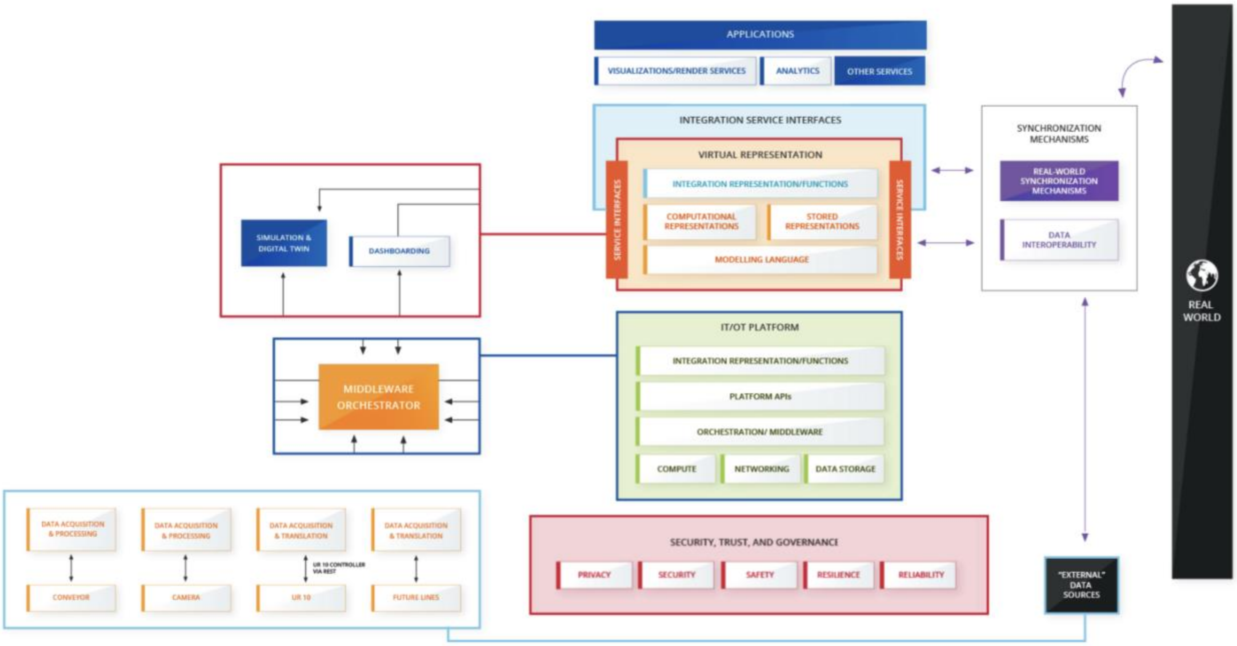
[36] *https://www.digitaltwinconsortium.org/initiatives/technology-showcase/ai-quality-control/*


APPLICATIONS
VISUALIZATIONS/RENDER SERVICES
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SIMULATION & DIGITAL TWIN
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MIDDLEWARE ORCHESTRATOR
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PLATFORM APIs
ORCHESTRATION/ MIDDLEWARE
COMPUTE
NETWORKING
DATA STORAGE
DATA ACQUISITION & PROCESSING
DATA ACQUISITION & PROCESSING
DATA ACQUISITION & TRANSLATION
DATA ACQUISITION & TRANSLATION
UR 10 CONTROLLER VIA REST
CONVEYOR
CAMERA
UR 10
FUTURE LINES
SECURITY, TRUST, AND GOVERNANCE
PRIVACY
SECURITY
SAFETY
RESILIENCE
RELIABILITY
"EXTERNAL" DATA SOURCES

A.4 USE CASE 4: SCOPE 3 CARBON EMISSIONS REPORTING

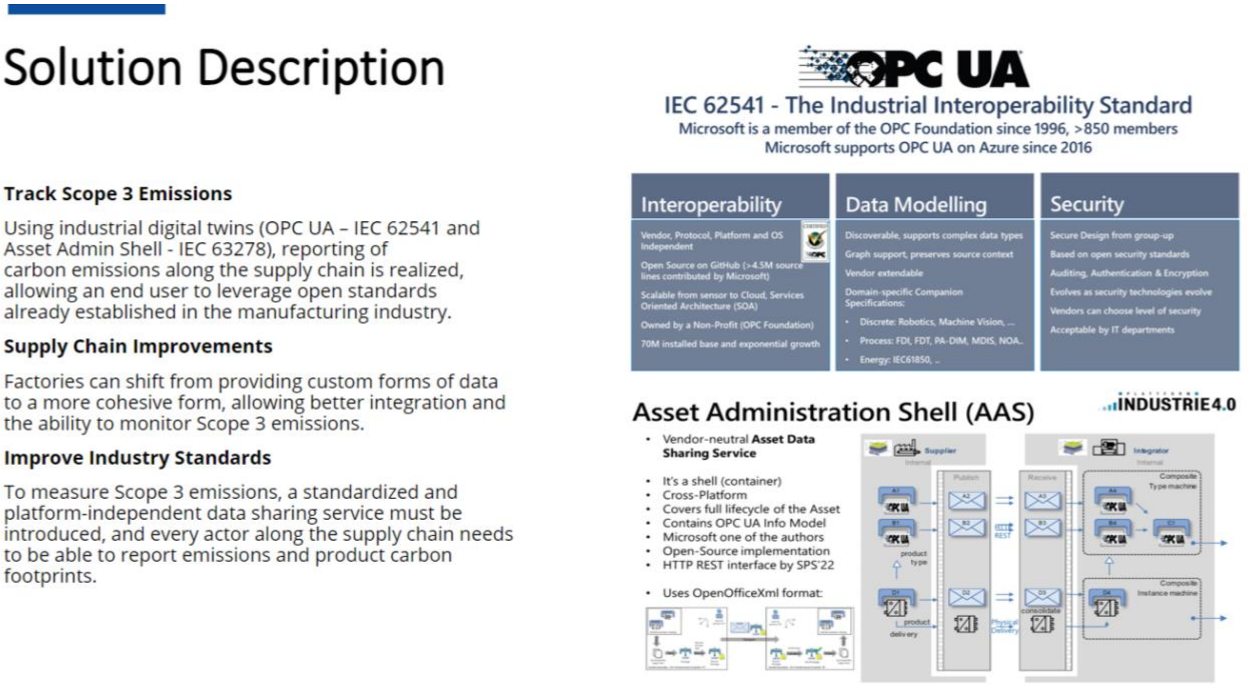
Scope 3 Carbon Emission Reporting

Objective

Provide clear insights to a company's carbon footprint across the supply chain

Value

Allows a first-time view at scope 3 emissions from the whole of a supply chain



Solution Description

Track Scope 3 Emissions

Using industrial digital twins (OPC UA – IEC 62541 and Asset Admin Shell - IEC 63278), reporting of carbon emissions along the supply chain is realized, allowing an end user to leverage open standards already established in the manufacturing industry.

Supply Chain Improvements

Factories can shift from providing custom forms of data to a more cohesive form, allowing better integration and the ability to monitor Scope 3 emissions.

Improve Industry Standards

To measure Scope 3 emissions, a standardized and platform-independent data sharing service must be introduced, and every actor along the supply chain needs to be able to report emissions and product carbon footprints.

OPC UA

IEC 62541 - The Industrial Interoperability Standard

Microsoft is a member of the OPC Foundation since 1996, >850 members
Microsoft supports OPC UA on Azure since 2016

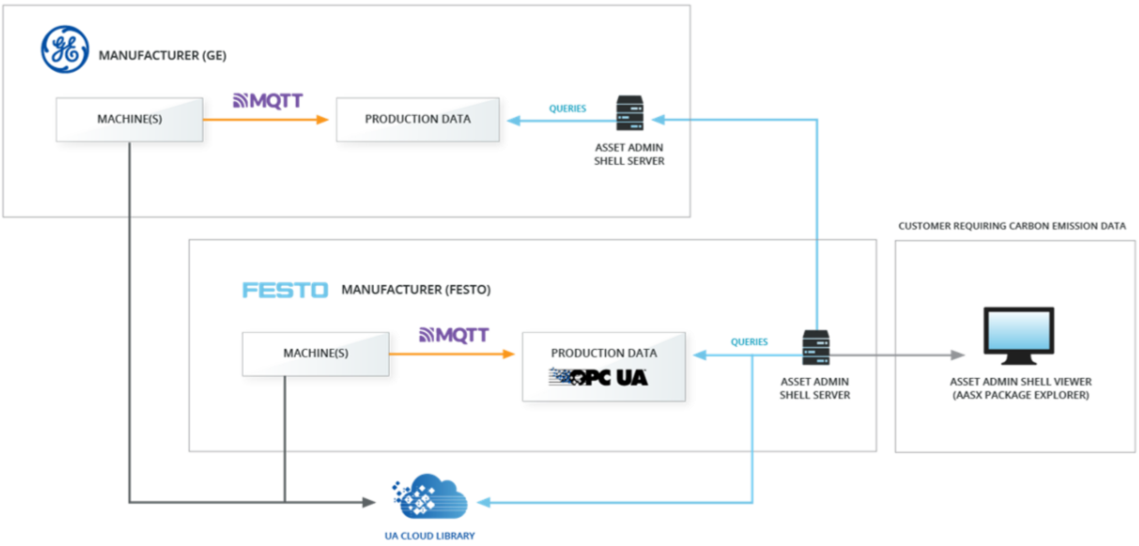
Interoperability	Data Modelling	Security
Vendor, Protocol, Platform and OS Independent Open Source on GitHub (>4.5M source lines contributed by Microsoft) Scalable from sensor to Cloud, Services Oriented Architecture (SOA) Owned by a Non-Profit (OPC Foundation) 70M installed base and exponential growth	Discoverable, supports complex data types Graph support, preserves source context Vendor extendable Domain-specific Companion Specifications: • Discrete: Robotics, Machine Vision, ... • Process: FDI, FDT, PA-DIM, MDIS, NOA.. • Energy: IEC61850, ..	Secure Design from group-up Based on open security standards Auditing, Authentication & Encryption Evolves as security technologies evolve Vendors can choose level of security Acceptable by IT departments

Asset Administration Shell (AAS)

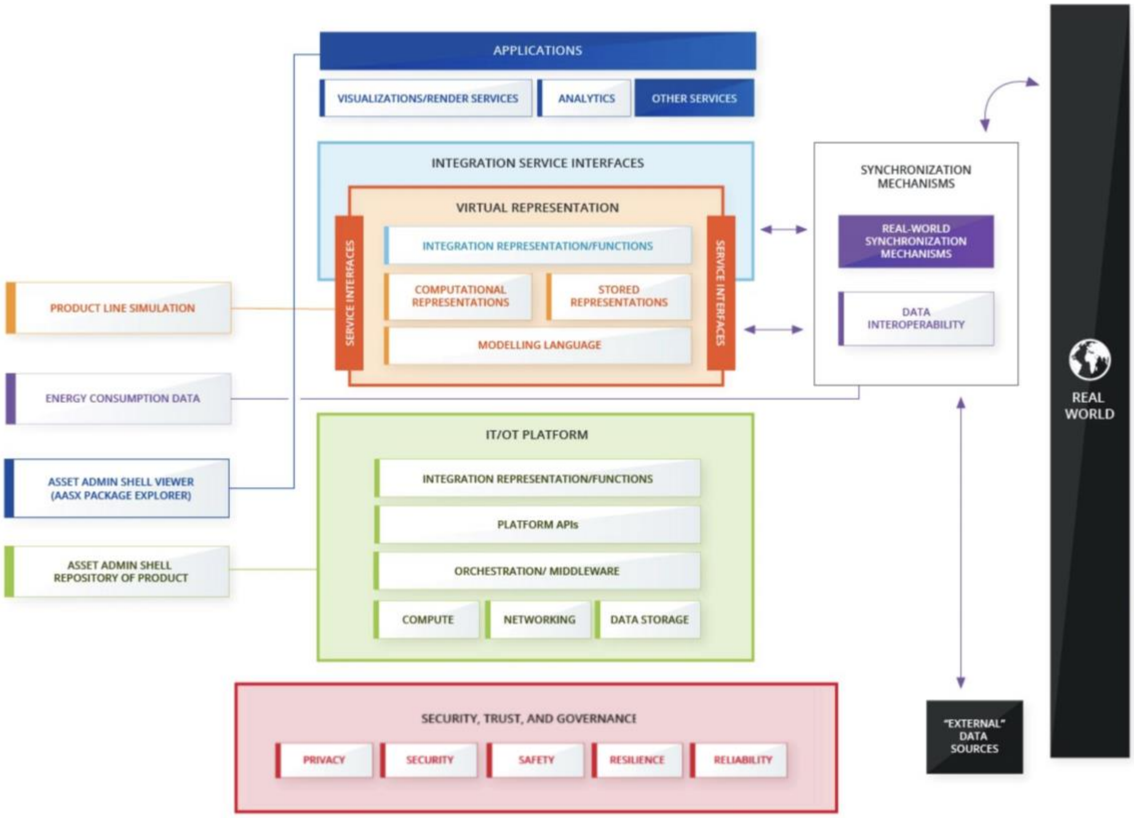
- Vendor-neutral **Asset Data Sharing Service**

- It's a shell (container)
- Cross-Platform
- Covers full lifecycle of the Asset
- Contains OPC UA Info Model
- Microsoft one of the authors
- Open-Source implementation
- HTTP REST interface by SPS'22

- Uses OpenOfficeXml format:



This carbon reporting use case uses OPC UA to synchronize data into the system and emission data is provided via the Asset Admin shell and package viewer for exploration and download. For complete information on the Carbon Emissions Reporting use case, please visit the Digital Twin Consortium website.[37]



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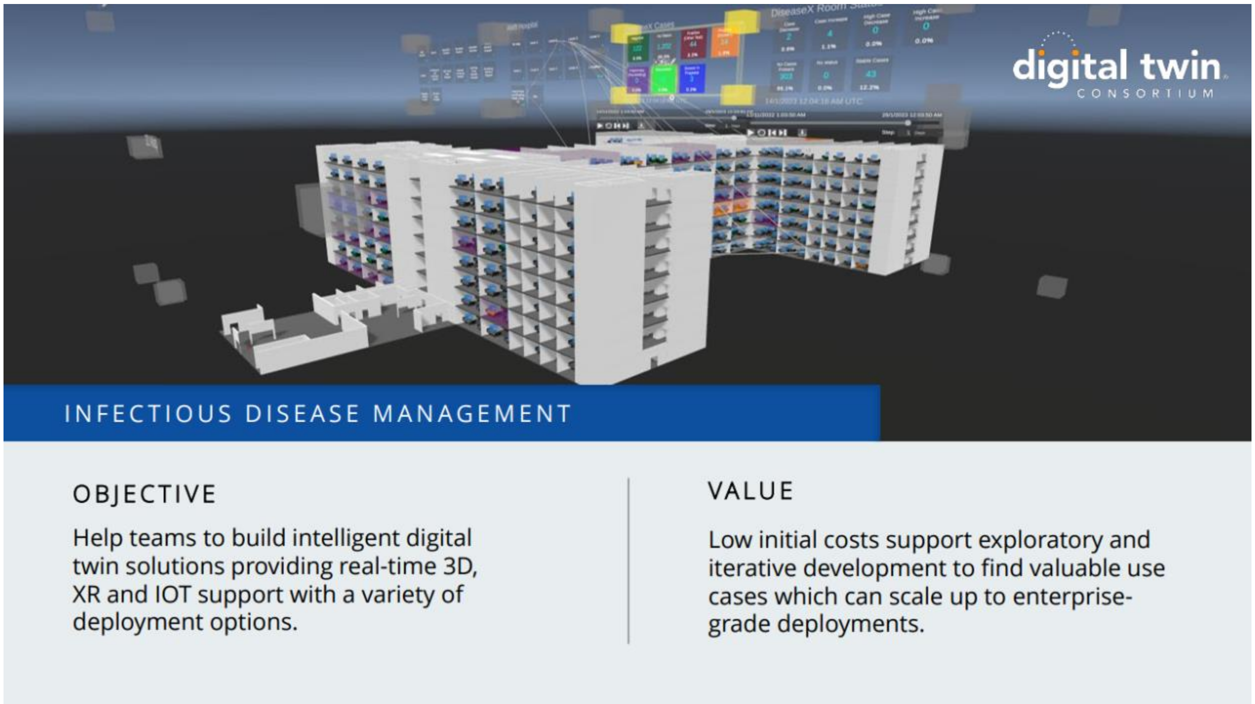
[37] *https://www.digitaltwinconsortium.org/initiatives/technology-showcase/carbon-reporting/*

A.5 USE CASE 5: INFECTIOUS DISEASE MANAGEMENT



INFECTIOUS DISEASE MANAGEMENT

OBJECTIVE

Help teams to build intelligent digital twin solutions providing real-time 3D, XR and IOT support with a variety of deployment options.

VALUE

Low initial costs support exploratory and iterative development to find valuable use cases which can scale up to enterprise-grade deployments.

Live Project –Solution Components

Infectious disease management at an acute care hospital

Visualization of Current Disease Spread

Epidemiologists get an up-to-date view of the state of disease spread across more than 1,700 inpatients in 6 blocks across the campus, linking existing enterprise data sources with interactive 3D visualizations.

Visual Time Slicing to Understand Progression and Trends

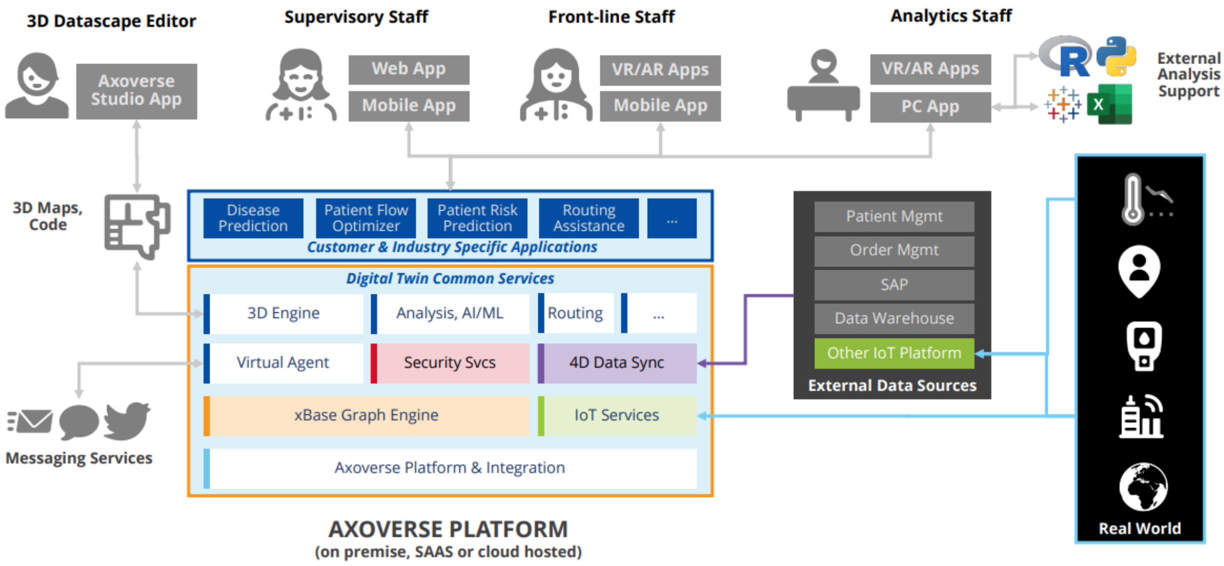
Users can move a time slicer across 12+ months of data to see patient movements between beds along with their current and future disease state, providing an unprecedented level of contact tracing and investigation.

Risk Quantification, Prediction and Notifications

A risk quantification and prediction algorithm now uses both exposure time and spatial distance to better predict likely secondary infections to better prioritize screening targets. Further integrations and notifications are in development.

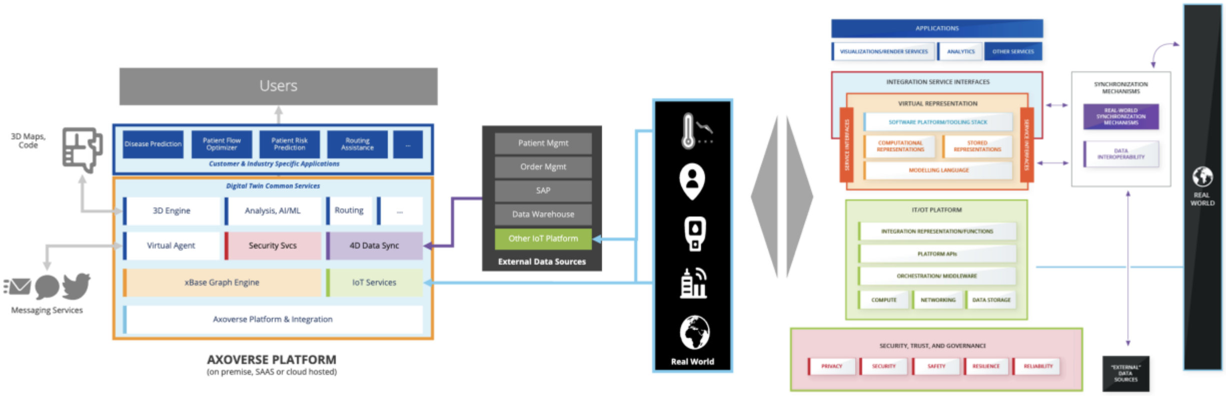
PROJECT HIGHLIGHTS:

- Large acute care hospital with 1,700+ inpatient beds across 6 blocks
- Commenced in January 2022 as a COVID response
- Built from 2D CAD maps, some of which were 20+ years old.
- Imports data from multiple data sources and fuses it into the 3D model.
- Now tracking over 15 pathogens, including viruses and multi-drug resistant organisms



As shown above, the healthcare use case for infectious diseases within hospitals has a range of services and components. External data sources include patient record systems and IoT platforms. Within the IT platform data stored within the Axoverse platform and the stored aspect of the virtual representation uses the xBase Graph Engine. There are then a range of services that cross the boundary of the digital twin up to the application layer with a range of use case specific apps.

For complete information on the Infectious Disease Management Use Case, please visit the Digital Twin Consortium website.[38]



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[38] *https://www.digitaltwinconsortium.org/initiatives/technology-showcase/infectious-disease-management/*