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Digital Twins and Standardization Opportunities in ETSI

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Smart Machine-to-Machine communications (SmartM2M).

Modal verbs terminology

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Executive summary

The present document provides an overview of the potential of Digital Twins (DTs) in the context of the Internet of Things (IoT) and Industrial IoT (IIoT). The present document focuses also on collecting, identifying, and defining use cases for various industries and applications, in order to fully leverage the potential of DTs. This can help to identify potential requirements, such as interoperability, data security and privacy, scalability, and real-time processing, that need to be addressed to fully realize the benefits of DTs in these domains. In summary, the present document provides a comprehensive understanding of the requirements and challenges of DTs, their major characteristics and architectures, major functionalities, candidate communication functionalities for standardization, and the importance of collecting, identifying, and defining use cases. It is essential reading for anyone interested in leveraging the full potential of digital twins in the IoT and industrial IoT domains.

Introduction

Digital Twins (DTs) are computerized representations of physical objects or systems that can digitalize their behaviour and performance in a virtual environment. In order to effectively utilize digital twins, it is important to analyse their major characteristics and architectures, which may differ depending on the specific applications and use cases. Additionally, identifying major functionalities and selecting candidate communication functionalities for standardization is crucial for achieving interoperability and seamless integration with other systems. To fully leverage the potential of digital twins in the context of the Internet of Things and Industrial IoT, it is important to collect, identify, and define use cases for various industries and applications. This can help to identify potential requirements, such as interoperability, data security and privacy, scalability, and real-time processing, that need to be addressed to fully realize the benefits of digital twins in these domains.

1 Scope

The present document shows in a structured and comprehensive way the main requirements for the definition of interoperable and standardized Digital Twins within the context of challenging cyber-physical use cases and application scenarios. The main objectives can be summarized as follows:

- Analysis the major requirements and challenges of cyber-physical systems and the identified use cases.
- Analysis of the main requirements, characteristics, and architecture of DTs.
- Identification of DTs major functionalities and responsibilities.
- Selection of the candidate communication approaches for standardization.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or nonspecific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

NOTE: While any hyperlinks included in this clause were valid at the time of publication ETSI cannot guarantee their long term validity.

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

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[i.10] SAREF extension for Smart City, European Telecommunications Standards Institute (ETSI).

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3 Definition of terms, symbols and abbreviations

3.1 Terms

For the purposes of the present document, the following terms apply:

Digital Twin (DT): comprehensive software representation of properties, conditions, relationships, events, and behaviours of an individual Physical Object (denoted also as Physical Twin)

3.2 Symbols

Void

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

AI Artificial Intelligence
API Application Programming Interface
AR Augmented Reality
CDN Content Delivery Network
CDT Composed Digital Twin
DevOp Development and Operations

DT	Digital Twin
DTD	Digital Twin Description
GPS	Global Positioning System
IIC	Industrial Internet Consortium
IIoT	Industrial Internet of Things
IIRA	Industrial Internet Reference Architecture
IoT	Internet of Things
LPWAN	Low-Power WAN
MEC	Multi-access Edge Computing
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
NDT	Network Digital Twin
NFV	Network Function Virtualization
ODT	Operator Digital Twin
OPC	Open Platform Communications
PA	Physical Asset
PT	Physical Twin
QoE	Quality of Experience
QoS	Quality of Service
REST	REpresentational State Transfer
SAREF	Smart Applications REFerence ontologies
SDK	Software Development Kit
SDN	Software-Defined Networking
TR	Technical Report
UA	Unified Architecture
V2X	Vehicle to Everything
VRU	Vulnerable Road User

4 Smart City Use Case

4.0 Foreword

Clause 4 delves into the analysis of a reference Smart City use case, examining its key characteristics, open challenges, and exploring the integration and adoption opportunities for DTs. By providing a comprehensive understanding of the built cyber-physical city environment, the objective is to enable efficient resource allocation, real-time monitoring, and predictive analysis, empowering city stakeholders to make informed decisions and deliver enhanced services. However, as with any transformative technology, there are challenges to be addressed, including data privacy, interoperability, and scalability. Clause 4 explores these challenges in the context of reference use case and interaction patterns and discuss the integration and adoption opportunities that DTs bring to create smarter, more sustainable, and resilient cities.

4.1 Smart City Use Case Introduction

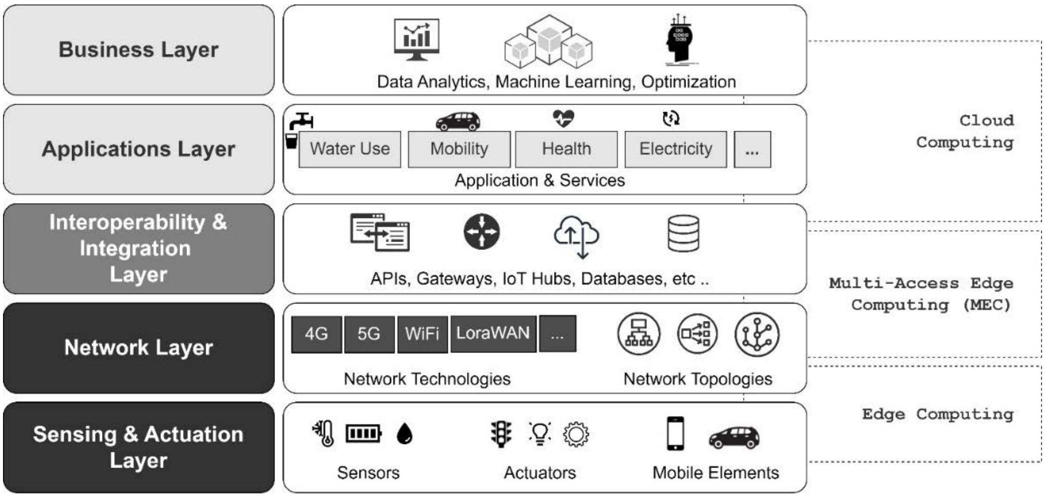

Figure 1: High level representation of the key architectural layers that constitute a Smart City ecosystem together with their possible deployment option across an Edge, MEC and Cloud computational continuum

Smart Cities are increasingly becoming a reality in today's world, with cities around the globe investing in technologies that can help optimize their operations and improve the quality of life for their citizens. One of the key objectives in building a smart city is the need to integrate a wide range of physical devices, subsystems, and application scenarios, each with its own set of requirements and standards. The fragmentation of these systems can make it difficult to create a unified, interoperable cyber-physical ecosystem that can support the diverse needs of a Smart City. Furthermore, the massive amount of big data generated by these systems can be overwhelming, and it requires effective integration and analysis to extract valuable insights and inform decision-making.

Furthermore, in a Smart City use case (as depicted in Figure 1), multiple different architectural layers are involved key building the city ecosystem, together with their possible deployment options across a distributed computational continuum involving Edge Computing, Multi-Access Edge Computing (MEC), and Cloud Computing. From bottom to top, the layers include:

- **Sensing & Actuation Layer:** This foundational layer encompasses a vast network of sensors, actuators, and devices spread across the city. These smart devices gather real-time data from the urban environment, capturing information related to traffic flow, air quality, energy consumption, and more. The data is then processed and used to control various actuators to trigger responses, such as adjusting traffic lights, managing street lighting, or regulating irrigation systems.

- **Network Layer:** The network layer serves as the backbone of the Smart City infrastructure, facilitating seamless data communication and exchange between sensors, devices, and control centres. It encompasses a combination of wired and wireless communication technologies, including Wi-Fi®, cellular networks, LoRaWAN, and others. The network layer ensures reliable and low-latency data transmission across the city.

- **Interoperability & Integration Layer:** Situated above the network layer, the interoperability layer plays a vital role in harmonizing the diverse data formats, communication protocols, and standards used by various smart devices and systems. It facilitates data integration, enabling cross-domain collaboration and data sharing. This layer ensures that data from different sources can be easily combined and analysed to provide a comprehensive view of the city's operations.

- **Applications Layer:** The applications layer represents the heart of the Smart City ecosystem, housing a myriad of intelligent applications and services designed to optimize urban operations and enhance the quality of life for citizens. These applications leverage the data collected from the lower layers to provide real-time insights, support data-driven decision-making, and deliver smart services. Examples of applications include smart traffic management, waste management optimization, and public safety monitoring.

- **Business Layer:** At the top of the architectural stack, the business layer governs the overall strategy, policies, and regulations for the Smart City implementation. It involves city authorities, service providers, and other stakeholders collaborating to define the city's objectives and aligning the Smart City initiatives with the broader urban development goals. The business layer ensures that the Smart City projects are aligned with long-term sustainability, economic efficiency, and citizen-centric values.

With respect to the interoperability and integration responsibilities, Smart City has the need have a standardized and structured representation of the multiple domains and sub-domains involved in the city ecosystem (e.g. energy, mobility, health-care, etc.). In this context, the use of Ontologies plays a pivotal role in achieving seamless interoperability and efficient data exchange among diverse smart devices, systems, and applications. Ontologies provide a standardized and structured representation of the domain knowledge and relationships between various entities, enabling a common understanding of data across different stakeholders. This common understanding is crucial for effective data integration, enabling data-driven decision-making, and supporting the development of advanced smart services and applications. One notable example of a reference ontology for Smart City applications is the ETSI Smart Applications REFerence (SAREF) ontology providing a comprehensive and extensible vocabulary for describing smart appliances and their capabilities ([i.9] and [i.10]). By integrating and adopting SAREF as a reference ontology within the integration and interoperability, Smart City initiatives can achieve harmonization of data and promote the development of innovative and standardized smart applications that can seamlessly interact with a wide range of devices and services.

The deployment of these architectural layers across the Edge, MEC, and Cloud computational continuum offers a flexible and scalable approach to Smart City implementations. Edge computing brings data processing and analytics closer to the data source, reducing latency and enabling real-time decision-making for time-sensitive applications. MEC further enhances edge capabilities by leveraging cloud services at the network edge. The Cloud, on the other hand, provides vast storage, computational power, and data processing capabilities, making it ideal for handling large-scale data analysis and resource-intensive applications. The Smart City ecosystem benefits from the strategic placement of these layers across the continuum, effectively harnessing the strengths of each deployment option to create a resilient, intelligent, and citizen-centric urban environment.

Typically, there are several actors, services, and stakeholders involved, including as the most important:

- **City government:** responsible for the overall planning, policy making, and management of the city. They work closely with other stakeholders to ensure that the city is equipped with the necessary infrastructure and services to support a smart and sustainable future.

- **Service providers:** responsible for providing the necessary technology and services to support smart city initiatives. This can include providers of IoT devices, sensors, networking equipment, cloud computing services, and more.

- **Citizens & People:** represent the heart of any smart city initiative. They are the end users of the services and technologies that are deployed, and their needs and preferences should be considered when planning and designing smart city solutions.

- **Private sector:** plays an important role in smart city initiatives by providing funding, expertise, and resources. Private sector stakeholders may include technology companies, startups, and other businesses that are involved in the development and deployment of smart city solutions.

In this complex and fragmented ecosystem, deployed physical assets (e.g. smart cameras, pollution monitoring, energy metering systems, etc.) can represent shared core cyber-physical sub-systems that are not useful only as siloed verticals but that can be useful for different applications and services in different ways according to their goals and business logic. For example, a real-time mobility application can be interested in receiving smart camera metadata in real-time to enable vehicle-to-vehicle communication, while on the other hand, a statistical analysis application might need data from multiple cameras associated with the same physical location without real-time requirements but with the need of aggregating data over a target time-window for statistical and privacy reasons to support long-term city mobility planning.

This peculiar and fragmented scenario creates a cyber-physical ecosystem where different actors, services, and stakeholders might be interested in different levels of digitalization and abstraction of the same physical asset. For instance, a municipality might be interested in having a real-time monitoring system for traffic flow in a specific area to optimize mobility and reduce congestion, while a public transportation company might be interested in a different level of abstraction to monitor the availability and status of bus and metro stations. Therefore, the level of digitalization and abstraction required for a physical asset will depend on the specific needs of the applications and services involved. It is important to identify and analyse these needs to design and implement a digital abstraction layer that meets the requirements of all stakeholders involved in the Smart City ecosystem.

The main services involved in a Smart City use case can vary depending on the specific application scenario, but may include as challenging and reference ones:

- **Mobility services:** This can include intelligent transportation systems, parking management, and public transit optimization.
- **Energy management services:** This can include smart grid management, renewable energy integration, and energy efficiency programs.
- **Environmental services:** This can include air and water quality monitoring, waste management, and sustainability initiatives.
- **Public safety and security services:** This can include surveillance systems, emergency response services, and disaster management.
- **Citizen engagement services:** This can include community engagement platforms, open data initiatives, and digital services that enable citizens to participate in city decision-making.

Overall, all these sub-systems and service should collaborate within a Smart City involving multiple abstraction layers and a hierarchical management to effectively support a diverse range of actors, services, and stakeholders who have to work together to build a sustainable, equitable, and livable city of the future.

4.2 Smart City Requirements

With respect to the Smart City use case and the described challenging context, clause 4.2 highlights some reference requirements useful to drive the design and definition of a DT based architecture and technological requirements associated with the design of a Smart City cyber-physical layer:

- **Interoperability:** The ability to integrate multiple vendors, service providers, and devices into a uniform, interoperable ecosystem, despite the fragmentation and the heterogeneity that natively characterize deployed physical devices and cyber-physical subsystems.
- **Data management:** The ability to manage, integrate, and analyse massive amounts of Big Data generated by various sources in real-time, including both live and non-real-time applications, and edge and cloud services.
- **Abstraction:** The ability to support multiple abstraction levels and sequence data aggregation and analysis from field devices from the edge to the cloud and vice versa. This includes translating high-level commands into direct actions on physical objects, as well as aggregating and analysing data at different abstraction and responsibility layers for intelligent decision-making.
- **Security:** The ability to ensure the security and privacy of data, devices, and communications, and to prevent cyber-attacks or unauthorized access to the system. With respect to cyber-physical systems there is the need to segregate and create a fine-grained access control solution for core physical assets even if they are shared across multiple digital applications and consumers.
- **Scalability:** The ability to scale the system to handle large volumes of data and support the addition of new devices and services enabling the possibility to augment digital services with respect to the same physical deployment without generating malfunctioning and performance degradation.
- **Resilience:** The ability to maintain the continuity and integrity of services and applications, even in the face of disruptions, failures, or natural disasters.
- **Real-time responsiveness:** The ability to support real-time applications with low latency and high reliability, such as in mobility or emergency response scenarios.

- **Edge-Cloud Continuum:** On the one hand, the ability to perform computation, storage, and analysis at the edge of the network, close to the physical devices and sensors, to reduce latency and bandwidth requirements and improve performance. On the other hand, the ability to store, process, and analyse data in the cloud, to support high-level applications and services, and to provide scalability and flexibility. This compute continuum and the associated complexity should be decoupled by the applications that should be focused only on their application goal while a Smart City digital abstraction layer should take care of this complexity.

- **Standardization:** The use of standardized protocols, interfaces, and data formats to ensure compatibility, interoperability, and sustainability of the system.

- **Human-centric design:** The design of user-friendly interfaces, applications, and services that are accessible, inclusive, and responsive to the needs and preferences of citizens, stakeholders, and end-users.

- **Sustainability:** The design of energy-efficient, eco-friendly, and cost-effective solutions that minimize the environmental impact and maximize the economic and social benefits of the system.

4.3 Smart City Challenges

As presented in clause 4.2 earlier, Smart Cities offer a range of benefits such as improved efficiency, reduced costs, and enhanced decision-making capabilities. However, to fully realize their potential, several technical challenges have to be addressed. These challenges are directly related to Smart City requirements and includes:

- **Fragmentation of physical devices and cross-domain integration:** Smart cities involve multiple domains such as mobility, energy, and environment, which are typically managed by different vendors and service providers. This leads to a high degree of fragmentation, making it challenging to integrate and manage multiple physical devices across different domains. For example, in the mobility domain, connected vehicles and roadside units may use different communication protocols, making it difficult to exchange data and coordinate actions between them.

- **Heterogeneity of communication protocols and data formats:** Connected devices in a Smart City may use different communication protocols and data formats, creating interoperability issues. This makes it difficult to exchange data between devices and systems. For example, a smart traffic light may use a different communication protocol than a connected vehicle, making it difficult to exchange data between them.

- **Scalability and real-time processing of big data:** Smart City applications generate vast amounts of data that have to be processed in real-time to support real-time decision-making and coordination. This requires scalable, real-time data processing infrastructure, which can be challenging to design and manage. For example, traffic data generated by connected vehicles and sensors have to be processed in real-time to support real-time traffic management and coordination.

- **Data privacy and security:** Smart City applications rely on sensitive data such as personal information and location data. This creates significant privacy and security risks, which have to be addressed through robust security and privacy measures. For example, data generated by connected vehicles has to be securely transmitted and stored to protect the privacy of drivers and passengers.

- **Multiple Abstraction Points:** Managing multiple and hierarchical abstraction layers is a major challenge in designing a Smart City cyber-physical layer. This challenge arises because different stakeholders and applications require different levels of abstraction to interface with the physical world. For example, a street lighting system might be controlled by a high-level application that only needs to know whether the lights are on or off, while a maintenance system might require detailed information about the status of each individual light. To address this challenge, a dedicated cyber-physical management system is needed to manage the different levels of abstraction and ensure that the data and control signals are properly routed to the appropriate endpoints. This management system should be able to dynamically adapt to changes in the underlying physical infrastructure and the requirements of the various applications and stakeholders.

- **Reliability and resilience:** Smart City applications have to be highly reliable and resilient to ensure that critical services such as emergency response and traffic management are always available. This requires robust infrastructure and redundancy measures to ensure that services can continue to operate in the event of failures or outages. For example, emergency response services have to always be available to ensure the safety and security of citizens.

- **Interoperability and standardization:** Smart City applications involve multiple domains and stakeholders, each with their own standards and requirements. This creates significant interoperability challenges that have to be addressed through the development of common standards and frameworks. For example, common communication protocols and data formats have to be established to ensure that connected devices can exchange data and coordinate actions.
- **Integration of edge and cloud services:** Smart City applications require a mix of edge and cloud services to ensure that data is processed and analysed in real-time while also enabling long-term storage and analysis. This requires the integration of edge and cloud services, which can be challenging to manage. For example, edge devices such as connected vehicles and sensors have to be integrated with cloud services to enable real-time and long-term data analysis.
- **Longevity and sustainability:** Smart City applications require long-term planning and sustainability measures to ensure that they can continue to operate and evolve over time. This requires robust infrastructure and maintenance measures to ensure that services remain available and effective. For example, maintenance schedules have to be established to ensure that connected devices remain operational and secure over their lifetime.

4.4 Smart City Digital Twins

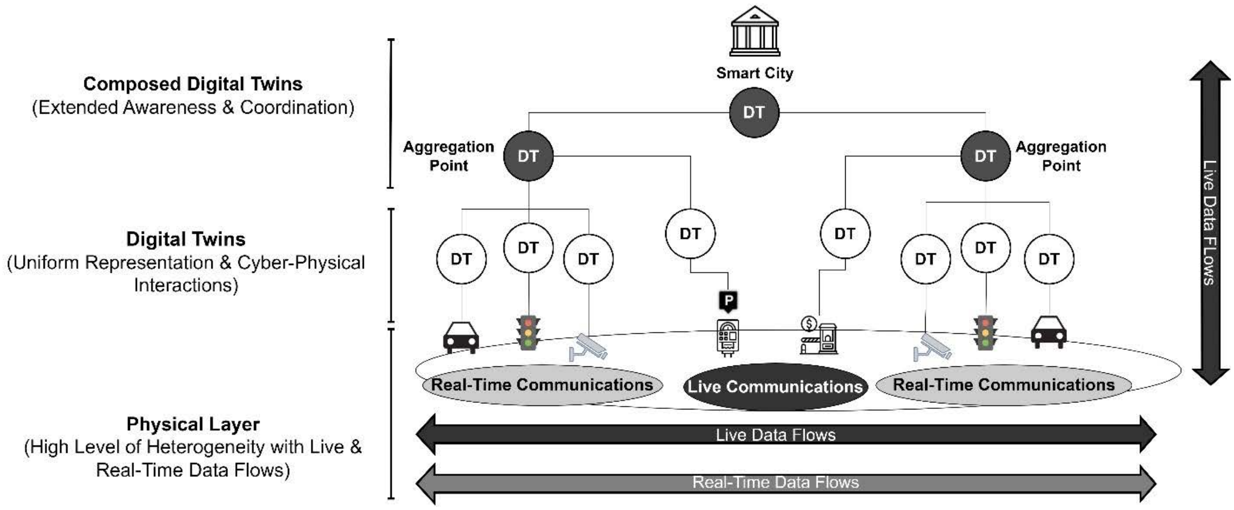

Figure 2: High-Level Smart City Application Scenario: Digital Twins Enabling Real-Time and Live Data Flow with Multi-Level Aggregation

As illustrated and analysed, Smart Cities are becoming increasingly complex and interconnected cyber-physical systems, the challenges they face are also growing in scale and complexity. To tackle these challenges DTs have emerged as a promising technology to address some of the open issues and opportunities. Clause 4.4 explores the match between Smart City requirements and challenges, and the benefits and characteristics of DTs.

DTs can provide benefits to simplify interaction with the physical layers by embedding the responsibility of interacting with connected devices through standard and custom protocols and technologies. Each DT will provide a common shared interface and description allowing external cyber-physical applications to see a uniform and homogeneous digital layer to interact with for reading data and executing actions. Multiple DTs of the same physical asset can be defined to support applications with different requirements and provide the right abstraction to each target application, hiding the management complexity from the digital application/service. DTs can be classified hierarchically, allowing the creation of graphs of DTs interconnected among each other and then to their physical counterpart. DTs can be used to support the hierarchical abstraction and mapping of the physical world and can be composed to aggregate properties and functionalities into a high-level DT. DTs can support interoperability both with respect to the physical world and at the digital layer, providing multiple ways to talk with existing and/or new digital services through a combination of reusable digital adapters. DTs can also be used to augment physical capabilities and properties in terms of data aggregation and analysis, introducing intelligent capabilities, and extending the interaction functionalities with the physical world. An important architectural and design element is that a DT operates only in its context determined as the digitalization of any existing physical asset without the responsibility to include external behaviours out of its operational environment. Digital applications may integrate and may cooperated with deployed DTs to implement high level and coordination behaviours reading data and interacting with multiple twins at the same time.

As illustrated in Figure 2, Smart City application scenario can be empowered through the adoption of DTs in particular with respect to the Integration and Interoperability layer previously introduced. Twins serve as virtual representations of physical assets, handling and facilitating both real-time and live data flow between the physical and digital realms. Furthermore, through multiple aggregation points, the DTs can be intelligently composed, providing a higher-level view and abstraction of the underlying physical assets. This composability allows for efficient data aggregation, sophisticated analysis, and seamless interaction between various applications, fostering a more interconnected and intelligent urban environment.

DTs benefits and main high-level characteristics can be summarized as follows:

- **Simplifies interaction with the physical layer:** DTs can interact with connected devices through standard and custom protocols and technologies, thus simplifying the interaction with the physical layers through the creation of a digital abstraction layer on top of the physical world.
- **Provides a common shared interface and description:** Each DT provides a uniform and homogeneous digital layer for external cyber-physical applications to interact with both for reading data and executing actions.
- **Supports multiple DTs of the same physical asset:** Multiple DTs of the same PT can be defined to support applications with different requirements (e.g. monitoring a device with different granularities). DTs provide the right abstraction to each target application without increasing the complexity of the physical object and hiding the management complexity from the digital application/service.
- **Enables Edge-Cloud deployment options:** Multiple DTs (also associated with the same object) can be deployed on the correct computational facility according to application requirements and business logic.
- **Supports hierarchical abstraction:** DTs can support hierarchical abstraction and mapping of the physical world. Multiple DTs can be composed into a Composed DT (CDT) to aggregate properties and functionalities into a high-level DT.
- **Supports interoperability:** DTs support interoperability both with respect to the physical world and at the digital layer, providing multiple ways to talk with existing and/or new digital services through a combination of reusable digital adapters.
- **Augments physical capabilities and properties:** DTs can augment physical capabilities and properties in terms of data aggregation and analysis, introducing intelligent capabilities, and extending the interaction functionalities with the physical world.
- **Operates only on its context:** The DT operates only on its context determined as the digitalization of any existing physical asset. The DT can only augment with functionalities and features associated with its physical counterpart(s) and cannot be the digital hub for other services and application logics.

Relying on these fundamental starting points, Smart City open challenges can be addressed and re-analysed to investigate how DTs can provide concrete solutions for each of the highlighted open issue:

- **Fragmentation of physical devices and cross-domain integration:** DT technology can help manage the integration of multiple physical devices across different domains by creating a virtual representation of the physical world. This can enable different domains to be integrated more easily by creating a common platform for data exchange and coordination. For example, a DT of a Smart City neighbourhood can help integrate mobility, energy, and environment domains by collecting data between different physical devices and providing a unified digital representation higher application layer and/or CDTs interested to monitor that specific district.
- **Heterogeneity of communication protocols and data formats:** DTs can enable interoperability between connected devices by creating a common platform for data exchange and translation. DTs can act as an intermediary between different devices and systems, translating data between different communication protocols and data formats. For example, a DT of a smart traffic light can translate data to and from a connected vehicle, enabling communication between the two devices and or participate to feed the neighbourhood to build the knowledge about mobility flows.

- **Scalability and real-time processing of big data:** DTs can support real-time data processing by providing a platform for data analysis and decision-making. By simulating the behaviour of physical devices in real-time, DT can provide insights into the behaviour of systems and enable real-time decision-making. For example, a DT of a traffic management system can provide real-time insights into traffic patterns and enable real-time decision-making to optimize traffic flow.
- **Data privacy and security:** DTs can provide a secure platform for data exchange and storage by implementing robust security and privacy measures isolating the PT and overseeing exposing the right data and functionalities only to authorized external entities. By digitalizing the physical world, DTs can also provide a safe environment for testing and validating security and privacy measures or incoming actions and requests on the PT before they are deployed or forwarded to the physical world. For example, a DT of a connected vehicle can be used to ensure security and privacy measures before they data are going out of the vehicle and/or action are executed on the local physical environment.
- **Multiple Abstraction Points:** DTs can be used to build and manage multiple abstraction layers by providing a common platform for data exchange and coordination. By creating a virtual representation of the physical world, DTs can provide a unified platform for different stakeholders and applications to interface with the physical world at different levels of abstraction. For example, a DT of a street lighting system can provide a high-level interface for a maintenance system that only needs to know the on/off status of each light, while also providing detailed information to a control system that requires information about each individual light.
- **Reliability and resilience:** DTs can support reliability and resilience by providing a platform for testing and validation before deployment in the physical world. Furthermore, the possibility to execute multiple DTs at the same time opens to the possibility to dynamically balance computational and data load and protect the direct load on physical assets. Nevertheless, DTs can also be used as aggregation and abstraction points without the need to directly interact with the PT to obtain the same information. For example, a digital application interested in accessing mobility statistics of a target district can directly talking with the neighbourhood DT in charge of keeping an history of the data without the need to interact with deployed smart cameras and sensors to get and analyse raw data.
- **Interoperability and standardization:** DTs can support interoperability and standardization by providing a common platform for data exchange and coordination. By creating a virtual representation of the physical world, DTs can provide a common platform for different stakeholders and applications to interface with the physical world using common standards and protocols. For example, a DT of a Smart City can provide a common platform for different domains and stakeholders to exchange data using common standards and protocols.
- **Integration of edge and cloud services:** Smart City applications require a mix of edge and cloud services to ensure that data is processed and analysed in real-time while also enabling long-term storage and analysis. This requires the integration of DTs both on the edge and in the cloud with seamless integration and communication. For example, edge DTs associated to devices such as connected vehicles and sensors have to be integrated and synchronized with cloud DTs services to enable at the same time real-time actionability and long-term data analysis.
- **Longevity and sustainability:** Smart City applications require long-term planning and sustainability measures to ensure that they can continue to operate and evolve over time. This requires an effective decoupling between cyber and physical layers and robust infrastructure and maintenance measures to ensure that services remain available and effective. In this challenging context, DTs can provide significant benefits in terms of decoupling the responsibility of cyber-physical management. For example, an "old" device can be extended and integrated with its DT as a secure and certified digital counterpart allowing the extension of operational functionalities (e.g. extend and integrate security requirements) without the need to adaption and changes on digital services.

4.5 Vulnerable Road Users Application

Vulnerable Road Users (VRUs) encompass a diverse group of individuals, including pedestrians, cyclists, and motorcyclists, who are at increased risk of road accidents and injuries due to their exposure to traffic. As urban areas evolve into smart cities, there is a growing need to prioritize the safety and well-being of VRUs. To achieve this, the next generation of Smart Cities has to focus on developing smart digital applications that cater to the unique requirements and challenges faced by VRUs ([i.11] and [i.12]). VRUs have specific safety requirements that distinguish them from other road users. Unlike vehicles, VRUs are exposed to more unpredictable and dynamic situations, such as sudden changes in traffic patterns and interactions with other road users. Moreover, VRUs lack the physical protection that vehicles offer, making them more vulnerable to accidents and serious injuries. Additionally, VRUs often have distinct mobility needs, such as accessible pedestrian pathways, bike lanes, and safe crossing points. These requirements call for a specialized approach to ensure the safety and seamless integration of VRUs into the urban transportation ecosystem.

In the next generation of Smart Cities, the implementation of smart digital applications can significantly enhance the support and safety of VRUs. These applications can leverage cutting-edge technologies like IoT, AI, and Edge Computing to create a responsive and adaptive urban environment. Smart digital applications can collect and analyse real-time data from various sources, including sensors, cameras, and connected vehicles. By analysing traffic patterns, pedestrian movement, and cyclist behaviour, these applications can identify potential hazards and proactively respond to ensure VRU safety. Utilizing AI and ML algorithms, smart digital applications can predict VRU behaviour and movement patterns. By anticipating potential conflicts or accidents, the applications can optimize traffic flow and implement preventive measures to avoid hazardous situations. They can cater to the unique requirements of VRUs by providing personalized services. For instance, pedestrian-friendly applications can offer real-time updates on safe pedestrian crossings, while cyclist-oriented applications can suggest the best routes with dedicated bike lanes. Furthermore, incorporating V2X communication capabilities, applications can enable seamless communication between VRUs, vehicles, and infrastructure. This facilitates timely alerts and warnings to all road users, ensuring they are well-informed about potential risks and hazards. The advancement of smart digital applications is paramount in ensuring the safety and efficient integration of VRUs in the next generation of Smart Cities. By tailoring solutions to VRU requirements and leveraging emerging technologies, cities can create a more inclusive and secure transportation environment for all road users. Implementing these smart digital applications will pave the way for a safer, smarter, and more sustainable urban landscape in the future.

Creating a real VRU application in the context of Smart City IoT poses significant challenges due to the massive fragmentation and heterogeneity of IoT applications and subsystems. Smart cities often involve a multitude of IoT devices, sensors, and data sources, each deployed and managed independently, resulting in a highly fragmented ecosystem. This fragmentation leads to interoperability issues, making it challenging to seamlessly integrate VRU support systems with various existing infrastructure and applications. Additionally, the diverse nature of IoT devices and data formats introduces complexity in data handling and processing, hindering the development of a unified VRU application. Overcoming these challenges requires a concerted effort to establish standardized communication protocols, data models, and integration frameworks that promote interoperability and streamline the aggregation and processing of heterogeneous IoT data. Only through a holistic approach and collaborative efforts, can real VRU applications effectively leverage Smart City IoT to ensure the safety and well-being of vulnerable road users.

In this challenging scenario, the adoption of DTs in the context of creating intelligent VRU applications holds significant potential for enhancing VRU safety and support. Digital Twins provide a virtual representation of physical assets, such as road infrastructure, vehicles, and VRUs, in real-time. This allows for comprehensive data collection and analysis, enabling a deeper understanding of the complex interactions between VRUs and their surroundings. By leveraging Digital Twins, intelligent VRU applications can efficiently handle interoperability and heterogeneity management. As various sensors and data sources may come from different manufacturers and platforms, twins provide a unified framework to integrate and harmonize these diverse inputs. This ensures seamless communication and data sharing between different components, enabling a holistic view of the urban environment and enhancing the accuracy of VRU support systems.

Moreover, DTs offer multiple aggregation and composition points, such as neighbourhoods, roundabouts, and highways, where data from multiple sensors and sources can be collected and processed. These aggregation points act as strategic nodes for data fusion and analysis, allowing the application to recognize complex traffic scenarios and VRU behaviours in real-time. By leveraging the power of DTs, intelligent VRU applications can proactively identify potential hazards and implement safety measures to mitigate risks effectively. In summary, the adoption of multiple twins in intelligent VRU applications brings a new dimension of data-driven insights and decision-making capabilities. By handling interoperability and heterogeneity management and providing multiple aggregation and composition points, DTs empower VRU support systems to create a safer and more responsive urban environment for vulnerable road users.

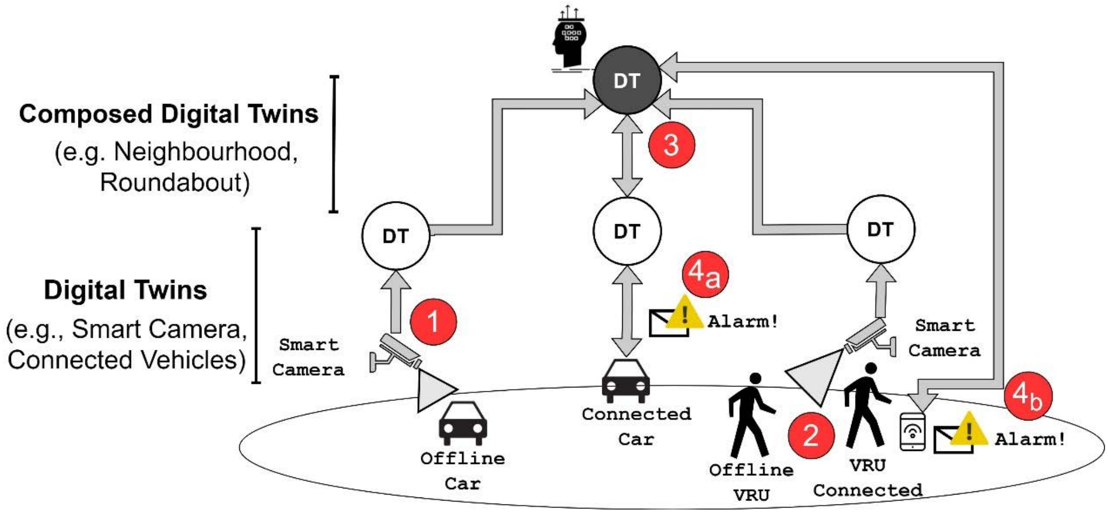

Figure 3: Schematic representation of a VRU Smart Application based on multiple DTs

Figure 3 depicts a schematic representation of a target application scenario where DTs are exploited to implement a VRU smart application architecture aiming to enhance the safety of vulnerable road users by leveraging on the management of data flows coming from connected vehicles, users, and smart cameras. On the one hand, DTs of connected vehicles represent their physical counterpart in the surrounding environment continuously collecting and updating data from car, including GPS positioning, speed, and direction, and building a digital representation of that entity in the target monitored area. The DTs provide a virtual representation of the vehicles' physical state, enabling the application to assess their movements and behaviours and augmenting also provided features with the prediction of movement directions according to collected data, streets map and speed. On the other hand, smart cameras positioned strategically in the urban landscape are an integral part of the architecture. These cameras capture real-time video streams, and through edge processing, they analyse the scenes to detect VRUs, such as pedestrians and cyclists. The analysis generates anonymized metadata, including VRU location and movement patterns. This metadata is associated with the Digital Twins of connected vehicles to assess potential collision risks and alert situations.

Analysing the reference Figure 3, the following interactions and subsequent events in the use case timeline can be highlighted:

1) The DT overseeing a smart camera in a Smart City is tasked with identifying the presence of one or multiple vehicles, simultaneously creating a digital representation of the monitored area. Additionally, it estimates the geographic coordinates of the detected objects.

2) Following the same principle and approach a second DT associated with a camera covering a closer area of interest detects a potential pedestrian and VRU.

3) The information collected, along with the associated metadata, is relayed from the respective DTs to a Composed DT responsible for constructing and maintaining a comprehensive perspective of mobility patterns, identifying potential risk situations based on the movements and trajectories of vehicles and VRUs.

4) Upon the detection of a dangerous scenario by the Composed DT, notifications are dispatched to connected entities capable of responding to the message. In this scenario, it is envisioned that two distinct categories of recipients will be notified: connected vehicles, utilizing their internal infotainment systems (4a), and connected VRUs, facilitated through wearable devices (4b). These real-time alerts pertain to collision warnings and, more broadly, mobility-related safety notifications, enabling prompt and appropriate responses.

Both DTs are then aggregated and composed into an additional DT responsible of digitalizing the target are of interest (e.g. a neighbourhood or a roundabout). This Composed DT is in charge of implementing the VRUs smart application logic and algorithms by communicating with vehicles and smart cameras DT together with potentially connected users (e.g. through their smartphones) analysing received data from with the aim to identify situations where VRUs are at risk, such as pedestrians crossing the road near moving vehicles or cyclists in the blind spots of connected vehicles. When a potentially dangerous situation is detected, the Composed DT smart notifications and alerts are sent to both the connected vehicles and connected VRUs directly or through their associated twins. Connected vehicles receive real--time alerts through their onboard infotainment systems or heads-up displays, warning the drivers about the presence of nearby VRUs and potential collision risks. Simultaneously, connected VRUs equipped with smart devices or wearables receive alerts, notifying them of potential hazards in their vicinity. The alerts provide timely information to VRUs, prompting them to take necessary precautions or avoid risky situations.

The analysis and implementation of the described VRU smart application faces several technological challenges, that should be considered for the design of effective DT-driven solution and approaches particularly related to physical heterogeneity and real-time communication capabilities:

- **Physical Heterogeneity:** The system needs to handle the diverse and heterogeneous nature of road users and vehicles. Different types of vehicles, ranging from cars and trucks to bicycles and scooters, have varying communication capabilities and sensor configurations. Additionally, VRUs come in different forms, such as pedestrians and cyclists, each with unique movement patterns and behaviour. Integrating data from these diverse sources making them homogenous and interoperable and ensuring seamless communication between them is a significant challenge.

- **Real-Time & Live Communication:** To effectively support VRUs, the system requires both real-time and live communication capabilities and an extended awareness of the relationships and links between cyber and physical world over time. The application has to process and analyse data from connected vehicles and smart cameras in real-time to detect potential risks and generate alerts promptly. Achieving low-latency communication between the components is crucial to provide timely warnings to both VRUs and connected vehicles, enabling them to respond quickly to potential hazards. Furthermore, a detailed monitoring of communication and network performance is crucial to build trustworthy DTs aware of their entanglement level with their physical counterparts.

- **Edge Processing and Analytics:** Edge processing and analytics are essential for efficiently handling the massive volume of data generated by smart cameras and connected vehicles. To ensure DTs real-time and live communication and decision-making, data processing and analysis should be performed at the network edge, close to the data source for example on dedicated Edge Nodes or MEC computation facilities. The challenge lies in implementing DTs that are easily deployable on different computing capabilities and also dynamically migrated when required in order to enable fast and accurate processing and algorithm execution according to the detected context.

- **Data Privacy and Security:** As the system collects and processes real-time data from connected vehicles and smart cameras, data privacy and security become critical concerns. Ensuring that the data is anonymized, protected, and transmitted securely is essential to maintain user trust and comply with data protection regulations.

- **Scalability and Interoperability:** For successful implementation, the system should be scalable and interoperable with existing infrastructure and technologies. As the number of connected vehicles and smart cameras increases, the architecture has to handle the growing data volume efficiently without compromising performance. Ensuring seamless integration with various IoT devices and communication protocols is crucial for a robust and adaptable system.

- **Environmental Factors:** The system needs to account for environmental factors that can impact data accuracy and communication reliability. Adverse weather conditions, physical obstructions, and varying road conditions can affect data quality and communication performance. The application and the deployed DTs have to be resilient and monitored in order to be aware of dynamic context variation and properly react to these challenges to ensure consistent and reliable support for VRUs.

5 Industrial Use Case

5.0 Foreword

Clause 5 presents the analysis of a reference Industrial use case, examining its main characteristics, open challenges, and exploring the integration and adoption opportunities for DTs. Recently, the Industry sector is undergoing a significant transformation through the adoption of advanced cyber-physical technologies and digitalization approaches aiming to enable real-time monitoring, predictive analytics, and optimization of industrial processes. The implementation of DT in this complex and dynamic sector is not without challenges and interoperability, security, and scalability are among the key considerations that need to be addressed. Clause 5 explores these challenges within the context and discuss the opportunities for integrating DTs as a strategic technological approach for accelerating the digitalization process and enabling the creation of new intelligent services.

5.1 Introduction

In the context of modern industrial environments, the complexity of physical assets and devices continues to increase with the adoption of new technologies such as IoT, automation, and robotics. These devices generate massive amounts of data that can be utilized to improve productivity, efficiency, and quality in manufacturing processes. However, the heterogeneity and fragmentation of these devices, as well as the different protocols and data formats used to communicate between them, make it difficult to develop and deploy digital applications and services that can effectively manage and utilize this data.

To address these challenges, a digital abstraction layer is required to decouple physical complexity management from digital applications and high-level services. This layer serves as a bridge between the physical and digital worlds, providing a standardized and unified interface for digital applications and services to interact with the physical assets and devices. By abstracting the complexity of the physical layer, digital applications and services can focus on their core functions and goals, without having to worry about the details of how data is collected and processed from physical assets.

The digital abstraction layer enables a variety of use cases, such as real-time monitoring and control of industrial processes, predictive maintenance, quality control, and supply chain optimization. By providing a standardized and scalable interface, it also facilitates the development of new digital applications and services, which can leverage the data generated by physical assets to create new business opportunities and competitive advantages.

Overall, the digital abstraction layer is a critical component in modern industrial environments, providing a bridge between the physical and digital worlds and enabling digital applications and services to effectively manage and utilize the complexity of physical assets and devices.

In an industrial use case, there are various actors, services, and stakeholders involved, which can vary depending on the specific use case. However, some of the common ones are:

- **Physical assets and devices:** These are the machines, sensors, actuators, and other physical components that are used in industrial processes. They generate data that can be used to improve efficiency, quality, and productivity.
- **Industrial Internet of Things (IIoT) platform:** This is a software platform that enables the collection, processing, and analysis of data from physical assets and devices. It provides connectivity, security, and data management services to digital applications and services.
- **Digital applications and services:** These are software applications and services that use data from physical assets and devices to perform specific functions such as monitoring, control, optimization, and predictive maintenance. They can be developed by in-house teams or third-party providers.
- **Cloud service providers:** These are companies that offer cloud computing services such as data storage, processing, and analysis. They can be used to store and process data from physical assets and devices, as well as to host digital applications and services.
- **System integrators:** These are companies that specialize in integrating various components of industrial systems, such as sensors, machines, and software, into a unified system. They provide consulting, design, and implementation services to industrial customers.
- **End-users:** These are the customers or operators of industrial systems, who use digital applications and services to monitor and control physical assets and devices. They can be employees of the industrial company or external contractors.
- **Regulators:** These are government agencies or other organizations that oversee industrial operations and ensure compliance with safety, environmental, and other regulations. They may have a role in approving and monitoring the use of digital applications and services in industrial environments.

Overall, the stakeholders in an industrial use case are diverse, ranging from physical components and devices to digital applications and services, as well as cloud service providers, system integrators, end-users, and regulators. Successful deployment of industrial systems requires collaboration and coordination between all these actors and stakeholders.

In an industrial use case, different actors, services, and stakeholders can be interested in different levels of digitalization and abstraction of the same physical asset due to their application logic and business goals. For example, an operator responsible for the maintenance of a production line might be interested in monitoring the health status of individual machines, such as temperature, pressure, and vibration data. This data can be used to predict potential failures and schedule preventive maintenance activities to avoid unplanned downtime.

On the other hand, a production manager might be interested in monitoring the overall performance of the production line, such as throughput, efficiency, and quality metrics. This data can be used to optimize the production process, identify bottlenecks, and improve overall efficiency.

Furthermore, different digital services can be built on top of the same physical asset, each with their own requirements and goals. For example, a machine learning model might be trained on sensor data to predict the energy consumption of the production line. This can help reduce energy costs and improve sustainability. Another service might be built to optimize the production schedule based on demand forecasts and machine availability.

Stakeholders such as customers and regulatory bodies can also be interested in different aspects of the physical asset, such as product quality, safety, and compliance with regulations. A digital abstraction layer can enable these stakeholders to access the relevant data and information in a secure and transparent manner, facilitating collaboration and improving overall performance.

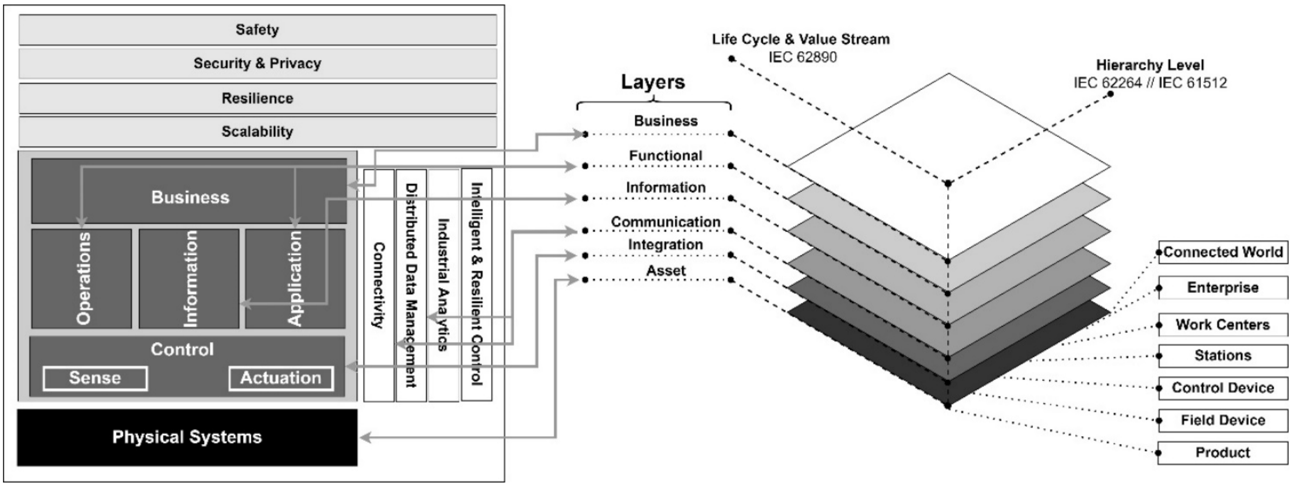

Figure 4: Industrial Internet of Things abstraction, functional domains, crosscutting functions and system characteristics

In the IIoT environment, the presence of multiple architectural layers introduces several challenges that need to be addressed for successful system development and operation. In this context, the Industrial Internet Consortium's (IIC), Industrial Internet Reference Architecture (IIRA) and their interoperability with other standards (as schematically illustrated in Figure 4) provided a high-level architectural framework and methodology for designing and creating interoperable IIoT systems. This approach perfectly depicting the existing multiple layers and the need of an effective coordination and interoperability through cyber-physical levels characterized by different responsibilities and challenges. These layers encompass various aspects of the IIoT ecosystem, from the physical devices and sensors at the edge to the cloud-based applications and services ([i.13] and [i.14]).

A layered architecture approach promotes modularity and standardization, allowing for seamless integration and interoperability with other industry standards and technologies. By clearly defining the interfaces and interactions between these layers, this approach facilitates the development of IIoT systems that can easily connect and collaborate with other existing and emerging standards, fostering a cohesive and interconnected IIoT landscape. This collaborative approach enables organizations to build robust and scalable IIoT solutions that can efficiently address the complexities and challenges of the industrial domain.

However, despite its strengths, open challenges persist in effectively bridging the gap between the physical and digital worlds, especially when implementing the proposed layered approach. Interoperability, security, scalability, and latency considerations become even more critical at the interface between the physical and digital layers. Ensuring seamless integration and communication between these layers is complex, particularly when dealing with diverse devices, protocols, and data formats. Furthermore, the real-time requirements of certain IIoT applications demand careful coordination and synchronization between the layers to meet low-latency and high-reliability expectations. Identifying fundamental requirements if the first step to try to overcome these challenges through a continued research, standardization efforts, and collaboration among stakeholders to foster a more cohesive and harmonized IIoT ecosystem, where the potential of a multi-layered approach can be fully realized to drive innovation and efficiency in cyber-physical industrial processes.

5.2 Requirements

An Industrial cyber-physical system is a complex integration of physical assets, digital technologies, and communication networks. To design an effective cyber-physical layer for an Industrial system, it is essential to understand the technological requirements of the system. These requirements are driven by the specific needs and challenges of the Industrial environment, such as low-latency requirements, interoperability issues, and security risks. Here are some detailed architectural and technological requirements associated with the design of an Industry 4.0 cyber-physical layer:

- **Interoperability:** The cyber-physical layer should enable seamless communication and integration of various devices, systems, and applications regardless of their brand, model, or protocol. Standardized communication protocols and interfaces such as OPC UA, MQTT, and REST APIs can facilitate interoperability.

- **Real-time performance:** The cyber-physical layer should be able to handle large volumes of data in real-time, with low latency and high reliability. Edge computing and fog computing technologies can enable data processing and analytics at the edge of the network, reducing latency and improving response time.

- **Scalability:** The cyber-physical layer should be designed to handle the scalability requirements of industrial environments, which can include large numbers of devices, systems, and applications. Cloud computing technologies can provide scalable computing and storage resources.

- **Security:** The cyber-physical layer should ensure the security and integrity of data and systems in industrial environments. Security measures such as encryption, access control, and secure communication protocols can help prevent unauthorized access and data breaches.

- **Flexibility:** The cyber-physical layer should be designed to accommodate changes and updates to the industrial environment over time. Modular and flexible architectures, such as microservices, can enable easier integration of new devices and systems.

- **Data management:** The cyber-physical layer should enable efficient and effective data management, including data collection, storage, processing, and analysis. Data management technologies such as data lakes and data warehouses can help aggregate and analyse large volumes of data.

- **Artificial intelligence and machine learning:** The cyber-physical layer should support the integration of artificial intelligence and machine learning technologies, enabling the development of predictive analytics and optimization algorithms to improve industrial performance.

- **Human-machine interaction:** The cyber-physical layer should enable seamless interaction between humans and machines in industrial environments. Technologies such as augmented reality and virtual reality can enhance human-machine interaction and enable remote monitoring and control of physical assets.

- **Augmenting physical capabilities:** The cyber-physical layer should enable the augmentation of physical entities capabilities through the integration of digital technologies and modules. For example, robotics and automation devices can be enhanced through the adoption of Machine Learning modules learning from generated data in order for example to detect anomalies, improve performance and predict future context variations.

- **Multiple and hierarchical abstraction points**: The cyber-physical layer should support multiple levels of abstraction, enabling different stakeholders to interact with the system at various levels of detail. Hierarchical abstraction points can enable stakeholders to access information and control the system at the appropriate level of granularity. For example, an operator may need to view high-level system performance metrics, while a maintenance technician may need to access detailed information about specific components or subsystems.

5.3 Challenges

- **Security and privacy risks:** As more and more devices and systems are connected in an Industrial environment, the risk of cyberattacks and data breaches increases. For example, an attacker could gain control of an industrial robot and cause physical harm to workers, or steal sensitive data related to a production process. Therefore, it is essential to design a cyber-physical layer that includes robust security and privacy measures to protect against these risks.
- **Interoperability issues:** Industrial environments often involve different types of devices, systems, and protocols that are not necessarily compatible with each other. For example, one production line might use a different communication protocol than another. This can make it difficult to integrate different systems and share data across them, which is a key requirement for Industry 4.0. Therefore, the cyber-physical layer has to be designed with interoperability in mind, and should include tools and technologies that facilitate data exchange and integration across different systems.
- **Low-latency requirements:** Many Industrial applications have strict low-latency requirements, such as real-time control of machinery or monitoring of critical processes. This means that data has to be processed and analysed quickly, often at the edge of the network. Therefore, the cyber-physical layer has to be designed with low-latency requirements in mind, and should include technologies that enable fast data processing and analysis, such as edge computing and real-time analytics.
- **Complexity management:** Industrial environments can be highly complex, with multiple devices, systems, and processes interacting with each other in real-time. This complexity can make it difficult to manage and maintain the cyber-physical layer and can lead to errors and downtime. Therefore, the cyber-physical layer has to be designed with complexity management in mind and should include tools and technologies that simplify the management and maintenance of the system, such as automation, AI-based analytics, and self-healing systems.
- **Hierarchical Abstraction:** In Industrial cyber-physical systems, the management of multiple and hierarchical abstraction layers can be particularly challenging due to the complexity of the physical assets involved. For example, a single production line may consist of multiple machines, each with their own sensors and control systems. These machines may be organized into zones or subsystems, each with their own set of sensors and control systems, which in turn may be part of a larger plant or factory. Managing the interactions between these different layers and ensuring that data and commands are properly passed between them, is essential for achieving the desired production outcomes. Furthermore, the management of different abstraction layers can have a significant impact on the security and safety of the system. Careful planning and management are therefore required to ensure that all layers are properly integrated and working together to achieve the desired goals while maintaining safety and security.
- **Scalability and flexibility:** Industrial environments are often subject to change, with new devices, systems, and processes being added or modified over time. Therefore, the cyber-physical layer has to be designed with scalability and flexibility in mind and should be able to adapt to changing requirements and environments. This means that the system should be modular, with components that can be easily added or removed, and should be based on open standards that allow for easy integration of new devices and systems.
- **Data management and analytics:** Industrial environments generate large amounts of data, which can be valuable for optimizing processes and improving efficiency. However, this data has to be managed and analysed in a way that is meaningful and actionable. Therefore, the cyber-physical layer has to include technologies that enable data management and analytics, such as data visualization, machine learning, and predictive analytics.

- **Human-machine interaction:** As Industrial environments become more digitized and automated, the role of human workers may change. This can create new challenges related to human-machine interaction, such as how to ensure that workers are trained and equipped to work effectively with machines, and how to design user interfaces that are intuitive and easy to use. Therefore, the cyber-physical layer has to be designed with human-machine interaction in mind and should include technologies that enable effective communication and collaboration between humans and machines.
- The technological challenges associated with augmenting physical capabilities include the need for seamless integration of digital technologies with physical systems, which can be complex and require significant expertise in both domains with the high-level target of minimizing the variations and changes on both already deployed physical assets and digital services. In addition, ensuring the safety and reliability of augmented physical systems is critical, as any failures or errors can have significant consequences. There may also be challenges in maintaining and updating the digital components of augmented physical systems, as hardware and software components may have different lifecycles and require different maintenance approaches.
- Multiple and hierarchical abstraction points can also pose significant technological challenges. Ensuring seamless communication and coordination between different levels of abstraction can be difficult, particularly when different stakeholders have different requirements and expectations for the system both in terms of collected and analysed data and of actionability on the physical layer. Additionally, the implementation of hierarchical abstraction points may require significant planning and design to ensure that the system is scalable and can accommodate changes in the industrial environment over time. Finally, ensuring that the appropriate security measures are in place to protect sensitive data at different levels of abstraction can also be a significant challenge.

5.4 Digital Twins in Industrial Environments

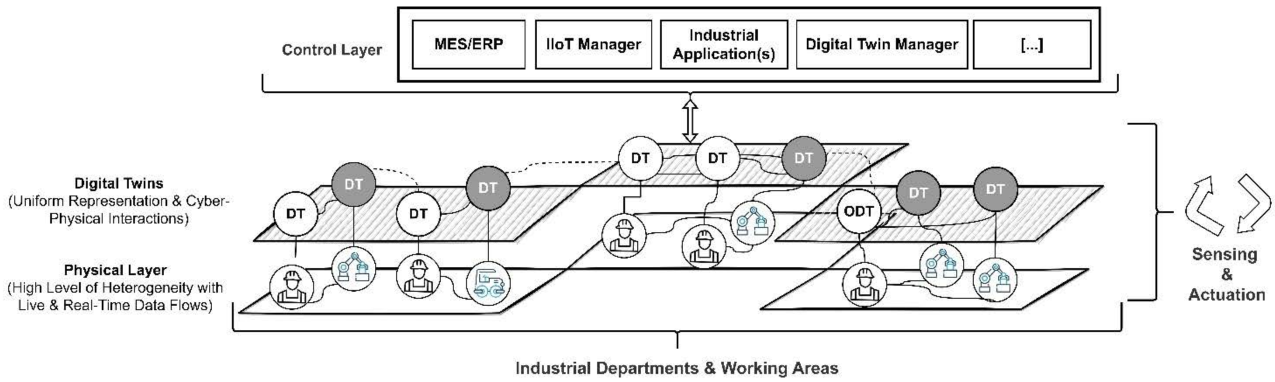

Figure 5: Schematic representation of an industrial environment where multiple DTs of machines and operators coexist and collaborate

The adoption of Digital Twins is increasingly being considered as a promising solution to overcome limitations and challenges in various domains, especially in the industrial sector. Traditional industrial systems often lack the ability to integrate and manage physical components and digital entities in a seamless manner. This leads to difficulties in monitoring and managing complex systems, hindering efficient decision-making and resulting in operational inefficiencies. In this context, Digital Twins have emerged as a powerful solution, enabling the creation of a digital representation of physical assets and their associated processes. Clause 5.4 will explore the benefits of using Digital Twins in the industrial sector and how they can address existing limitations and challenges.

Within an industrial ecosystem, DTs play a crucial role in improving the quality of cyber-physical management. By creating digital representations of machines and operators, DTs provide a unified platform for real-time monitoring, analysis, and decision-making. This, in turn, empowers operators to interact more intelligently with machines, optimally allocate resources, and respond dynamically to changing conditions.

In this challenging and dynamic context, the convergence of human-centricity and technological advancement has ushered in a new era of industrial production recently denoted as Industry 5.0 [i.15]. Traditional factory setups are being reimagined, where the well-being and collaboration of human operators are pivotal. This evolution, driven by the necessitates the incorporation of advanced technologies to create environments where humans and machines work collaboratively and effectively. At the heart of Industry 5.0 is the recognition that the workforce's well-being and capabilities are integral to a successful production ecosystem. The concept of Operator 4.0 has emerged, highlighting the need for skilled operators who can effectively collaborate with machines and cyber-physical systems. However, achieving this symbiotic relationship requires not only technological advancements but also the digitalization of operators themselves. Just as machines have digital twins representing their digital counterparts, operators can also benefit from having their DTs. These ODTs encapsulate operator attributes, capabilities, and interactions within the production environment.

Figure 5 provides a high-level representation of an industrial cyber-physical environment where multiple Digital Twins of machines and operators collaborate. This depiction showcases how digital replicas of machines and operators interact within the production landscape. Each entity's digital twin serves as an intelligent interface, facilitating effective communication, monitoring, and coordination. By merging these digital entities, the cyber-physical ecosystem becomes more adaptable, responsive, and capable of achieving the goals set forth by Industry 5.0.

Benefits of Digital Twins in Industrial Use Cases:

- **Security and privacy:** Digital Twins can simulate potential cyberattacks and data breaches to identify vulnerabilities and implement robust security and privacy measures. For example, in a power plant, Digital Twins can detect abnormal behaviour in sensors and proactively prevent unauthorized access to critical systems.

- **Interoperability:** Digital Twins can integrate different systems and devices by providing a common interface and data format. For example, in a smart factory, Digital Twins can enable seamless communication between machines that use different protocols by converting data into a standardized format.

- **Low-latency:** Digital Twins can process and analyse data at the edge of the network to meet real-time requirements. For example, in a transportation system, Digital Twins can use real-time data from sensors to optimize traffic flow and prevent accidents.

- **Complexity management:** Digital Twins can manage the complexity of industrial systems by providing a holistic view of the system and automating maintenance tasks. For example, in a chemical plant, Digital Twins can monitor equipment performance and predict maintenance needs to minimize downtime.

- **Hierarchical abstraction:** Digital Twins can model and manage interactions between different abstract layers by providing a clear view of the system hierarchy. For example, in an oil refinery, Digital Twins can simulate the behaviour of different components and subsystems to optimize production and reduce waste.

- **Scalability and flexibility:** Digital Twins can be easily scaled and modified to adapt to changing requirements and environments. For example, in a logistics system, Digital Twins can enable dynamic allocation of resources and real-time optimization of routes based on changing demand.

- **Data management and analytics:** Digital Twins can manage and analyse large amounts of data generated by industrial systems to optimize processes and improve efficiency. For example, in a manufacturing plant, Digital Twins can analyse data from sensors to identify trends and patterns that can be used to optimize production.

- **Human-machine interaction:** DTs can enable effective communication and collaboration between humans and machines by providing context-aware analysis and enabling remote monitoring and control. For example, DTs can enable remote monitoring of working operators and provide real-time feedback (e.g. detecting stress conditions) to plant manager to increase security workers wellbeing and optimize machines and human interactions over time within the production line also considering the relationships between physical and digital.

One major benefit of DTs is their ability to provide a virtual representation of physical systems, enabling a digital abstraction and augmentation point over the physical layer allowing the extension of provided capabilities and the optimization of system performance limiting the direct changes on the physical systems and extending security opportunities. For example, a DT of a robotic arm can be used to predict/simulate different operating conditions before deciding the best one to execute of can predict a future malfunctioning based on collected data. DTs can also facilitate seamless integration of digital technologies with physical systems, as they can provide a common platform for communication and coordination between different components and stakeholders. This can help overcome the challenges of maintaining and updating the digital components of augmented physical systems, as the complexity in the context of a specific physical asset to interact with both physical and digital worlds can be delegated to the DT that through a modular approach can expose a homogenous interface for digital services without the need to modify the physical counterpart.

Hierarchical abstraction points can also benefit DTs, as they can provide different levels of detail and functionality to different stakeholders, depending on their requirements. This can improve communication and collaboration between stakeholders at different levels of abstraction and enable more effective decision-making. For example, a maintenance technician can use a dedicated DT to access detailed information about a specific component, while a manager can use the same DT (or a different one targeting its operational context) to view high-level performance metrics of the entire system. Finally, DTs hierarchical modelling can also enhance the security of Industrial Cyber-Physical Systems by providing a secure and isolated virtual environment for testing and validation. This can help identify and address potential vulnerabilities before they are exploited in the physical system. Additionally, DTs can provide secure access to different levels of abstraction, ensuring that sensitive data is protected and only accessible to authorized personnel, services and digital applications over time.

5.5 Machine & Human Collaboration with DTs

In a modern industrial environment, the coexistence of both Machine DTs and Operator DTs holds a significant and interesting potential for enhancing operational efficiency and fostering a seamless human-machine collaboration. DTs associated to industrial machine are responsible for digitalizing and representing the physical attributes, behaviours, and operational data of machines and equipment on the factory floor ([i.16], [i.17] and [i.18]). They facilitate real-time monitoring, predictive maintenance, and process optimization, enabling informed decision-making. On the other hand, Operator DTs play a pivotal role in digitizing human operators' attributes, skills, and interactions within the production ecosystem. By continuously collecting and reflecting biometric signals, behavioural patterns, and situational context, they can provide insights into operators' well-being, cognitive state, and workloads. This dual presence of multiple categories of DT in the same industrial environment can create a harmonious synergy, where machines and operators collaborate effectively. On the one hand, digitalized machines offer insights into machine health and status, enabling operators to make informed decisions regarding maintenance and adjustments. On the other hand, DTs linked to industrial operators can empower technicians with real-time data about their own well-being and efficiency, allowing them to manage tasks more intelligently and simplify their discovery and interaction with physical appliances. Together, these digital twins cultivate a dynamic environment where humans and machines work cohesively, resulting in optimized processes, improved productivity, and a safer working environment.

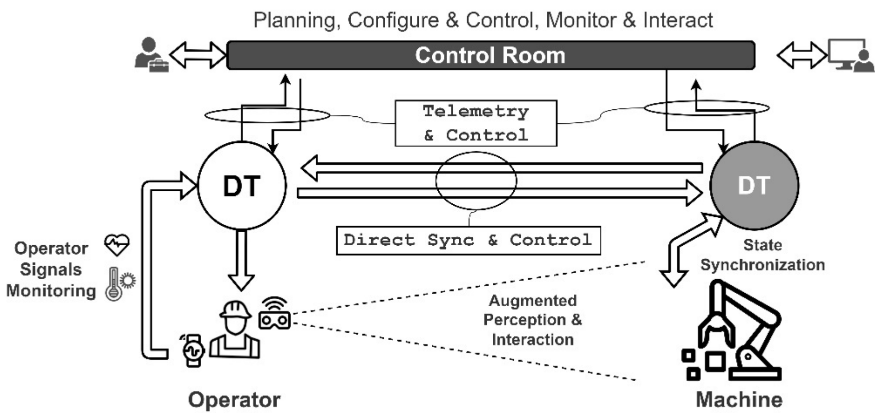

Figure 6: An illustrative example of Industrial collaboration between Operator and Machine for Training and Human-to-Machine interaction

In this context, also having the possibility to modelling and digitalizing existing physical and abstract relationships between Machine and Operator DTs carry paramount significance in enhancing the awareness of the industrial ecosystem and streamlining coordination among various entities. This approach can fundamentally improve the conventional way of managing interactions between operators and machines, introducing a new level of efficiency and flexibility, and offering a new level of intelligence to the industrial ecosystem. It fosters seamless coordination, empowers machines to collaborate with operators effectively, and paves the way for a more adaptable and efficient production environment.

Relying on this idea of building a collaborative environment between operators and machines, Figure 6 depicts a possible target application scenario and use case where for example a manufacturing company seeks to provide comprehensive training to operators for efficient and safe operation of complex industrial machinery located in various global plants. The company faces challenges in maintaining consistent training quality across different locations and ensuring that operators are well-prepared to handle diverse operational scenarios. By integrating and experimenting with DTs of machines and operators it will be possible to develop a new and innovative remote training solution.

In this envisioned scenario, each industrial machine is equipped with its corresponding DT, capturing real-time operational data, performance metrics, and maintenance history. Operators on-site are represented by their dedicated Operator twins in charge of encompassing their skills, experience levels, and biometric parameters through wearable devices. A central Control Room oversees the entire training process, orchestrating the interaction between active twins over time. During remote training sessions, expert trainers stationed in the Control Room initiate training programs by utilizing the machines telemetry data and insights through their digitalized replica. This data is used to simulate various operational scenarios, from routine processes to exceptional situations. On the other hand, DTs associated to operators participating in the training and are linked to the associated equipment in question and connected to their Machine DTs, creating a digital bridge between learners and machines.

In this new cyber-physical scenario, the adoption of Augmented Reality (AR) devices can improve and augment trainee operators allowing them to gain and build a real-time and immersive understanding of the machinery's functioning, receiving visual cues, operational guidelines, and alerts through their AR interfaces. Digitalized machines provide up-to-date information to connected and digitalized operators, enabling them to practice different scenarios as if they were physically interacting with the machines. The control room can effectively monitors trainees' progress, utilizing telemetry data coming from all the active twins evaluating trainees' decisions and reactions in various simulated scenarios and orchestrating target training sessions.

This new DT-driven machine-operator collaboration offers several advantages. Trainees can learn in a controlled yet realistic environment, without exposing themselves or the equipment to potential risks. Additionally, DTs of industrial machines abstract the complexity and interacting and collecting data from the physical world and enable the customization of training scenarios based on operators' skill levels and performance, creating personalized learning paths. Remote trainers can provide real-time feedback, enhancing operators' understanding and decision-making abilities. As operators progress through the training, their performance data is stored in their twin, contributing to a comprehensive competency profile.

This simple but innovative use case illustrates the potential of adopting DT technologies in the industrial ecosystem and apply them to the digitalization of both machines and operators at the same time to build a seamless and homogenous digital layer ensuring a potentially standardized and interoperable expertise across different plant locations and deployments.

6 Networking Use Case

6.0 Foreword

Clause 6 delves into the opportunity to integrate DTs technologies and approaches to the Networking field analysing open challenges and potential benefits. From enhancing network monitoring and awareness, human and machine learning training to improve development and deployment operations practices, network fuzzing, and inventory management, clause 6 analyses how DTs can be applied to the design, management, and monitoring of existing and new networks. Furthermore, clause 6 discusses the evolving research perspectives and security considerations that play a crucial role in realizing the full potential of this new cross-fertilization between DT and networking.

6.1 Introduction

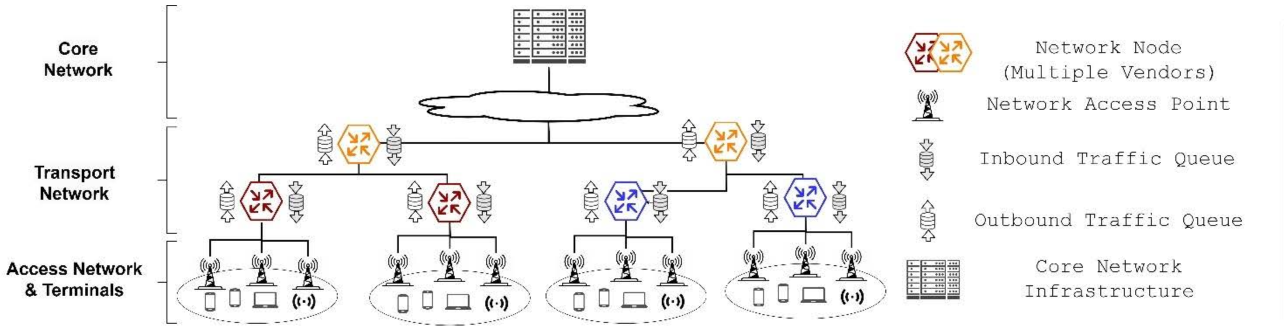

Figure 7: A high level representation of a distributed networking deployment characterized by multiple vendors with fragmented hardware, software and access technologies

The world of networking is continually evolving, driven by the increasing demands of modern digital society and upcoming new digital services and requirements. In today's landscape, networks are the lifeblood of businesses, enabling seamless communication, data exchange, and access to cloud-based services. However, this dynamic ecosystem is not without its open cyber-physical challenges.

One of the foremost challenges in networking is the management of ever-expanding distributed networks. As organizations grow and diversify, the complexity of their network infrastructures follows suit. For example, consider a large-scale network operator managing a telecommunications infrastructure that spans multiple regions and serves diverse industries, including finance, healthcare, and manufacturing. In this complex environment, the operator faces several challenges related to deployed physical assets, cyber-physical interactions together with hardware and software fragmentation, monitoring, and actuation (as schematically depicted in Figure 7). This complexity poses difficulties in terms of network optimization, troubleshooting, and ensuring high levels of service quality. Scalability and performance bottlenecks become significant concerns, particularly when accommodating the rising tide of IoT devices, edge computing, and bandwidth and energy hungry applications.

Moreover, the cyber-physical interaction between digital services and networking appliances and services introduces a layer of complexity. Ensuring seamless coordination between the digital and physical realms remains a challenge. This interaction requires precise orchestration to enable the network to become an intelligent tool, going beyond the role of a simple data pipe. The need for dynamic and reactive services further complicates this landscape, as networks have to respond swiftly to changing conditions, all while maintaining security and reliability.

To address these multifaceted challenges, the networking industry has been quick to embrace cutting-edge technologies. Software-Defined Networking (SDN) and Network Function Virtualization (NFV) have revolutionized network management by enabling dynamic, programmable, and agile infrastructures. These technologies allow for centralized network control, automated provisioning, and rapid response to changing traffic patterns.

However, the fragmentation of networking solutions remains a significant hurdle. The coexistence of various networking technologies, both physical and digital, creates a complex ecosystem. Achieving interoperability and seamless integration among these solutions is essential to unlock their full potential. Additionally, the transition to IPv6 and the adoption of 5G (and the upcoming 6G) networks are vital steps in addressing the fragmentation challenge.

Within this dynamic landscape, several opportunities abound. For example, as previously mentioned edge computing, for instance, allows for the processing of data closer to the source, reducing latency and enhancing the efficiency of real-time applications. The rise of 5G networks further empowers the expansion of edge computing capabilities, enabling the creation of dedicated network slices for specific applications.

The adoption of network slicing in 5G networks offers an opportunity to bridge the gap between physical and digital assets. This technology allows for the creation of virtualized, dedicated network segments tailored to specific applications or industries, facilitating the dynamic and reactive services where the network acts as an intelligent tool.

Summarizing, the networking ecosystem is undergoing a profound transformation. While challenges persist, state-of-the-art technologies and emerging opportunities offer the promise of more efficient, flexible, and responsive networks. As clause 6 delves further into this evolving landscape, exciting discovered possibilities have the potential to reshape the way to connect and interact in the increasingly digital world, all while addressing the complexities of cyber-physical interactions and network fragmentation.

6.2 Requirements

The design of the next generation of networking distributed infrastructure brings forth a set of critical requirements, particularly emphasizing cyber-physical considerations, complex network management, and its role as a foundational asset for the digital layer. This infrastructure has to seamlessly support a myriad of applications with diverse requirements, necessitating careful planning and execution. Below, clause 6.2 outlines the most important requirements that should guide the development of such a network:

- **Resilience and Reliability:** The network infrastructure has to prioritize robustness and resilience in the face of physical and cyber fragmentation, heterogeneity, and potential threats. Redundancy, failover mechanisms, and self-healing capabilities are imperative to minimize service disruptions even in application scenario characterized by multiple vendors, data formats and management APIs. For example, in a challenging scenario such as a network operator providing connectivity to an autonomous vehicle fleet, network resilience is crucial. If a section of the network supported by a specific vendor-layer with hardware and software peculiarities experiences a physical fault, such as a broken updated or a wrong re-configuration, the network has to detect the anomalies and automatically reroute traffic independently from the underlying hardware and software technologies.

- **Low Latency and High Throughput:** To support real-time applications like autonomous vehicles, telemedicine, and industrial automation, the network has to provide low-latency communication and high throughput. This requires efficient routing, edge computing, and dynamic Quality of Service (QoS) mechanisms. Distributed networks should be able to collect and process real-time data coming from the underlying layers decoupling the complexity of managing fragmented and heterogeneous data and metrics from the intelligent algorithms or procedure responsible to coordinate and optimize the network. Furthermore, a high level application requirements associated for example to a target QoS level should be propagated from the coordination point step-by-step to all the involved network components applying to each point the specific configuration languages, APIs or SDKs.

- **Geographical Distribution:** As the network spans diverse regions, including urban, rural, and remote areas, it has to accommodate varying geographical challenges through the support of multiple technologies and appliances according to the specific requirements or to already deployed infrastructures. A network operator covering both urban and rural areas has to consider the geographical challenges and in particular should take into account the structured and automatic monitoring of each deployed component without limitations or constraints associated to the different adopted technologies and/or used communication protocols and languages thanks to a high level digital abstraction digitalizing and mapping the entire network with its performance and evolution over time.

- **Interoperability:** Given the likelihood of multiple vendors and technologies in use, interoperability standards and open interfaces are essential. These facilitate seamless communication between different network components and services. A network infrastructure that supports multiple generations of cellular technologies (2G, 3G, 4G, 5G) through a plethora of different vendors, hardware and software version should aim to build an interoperable environment where the management, interaction and integration complexity will not affect management or business application, but it is managed through an intelligent digital abstraction layer ensuring that devices and services can communicate seamlessly across different network types and that application can have a uniform and usable representation of the network.

- **Orchestration and Automation:** The network infrastructure should support dynamic orchestration and automation of resources. This allows for on-the-fly adjustments to meet changing application demands and optimize resource utilization. In a smart city network, orchestration and automation allow for dynamic allocation of resources. For instance, during a major event, network resources can be automatically allocated to provide additional capacity for attendees' mobile devices.

- **Scalability:** As the digital layer continues to grow, the network has to scale horizontally to accommodate additional devices and services. Scalability ensures that new applications can be onboarded without major overhauls. A cloud gaming service may experience sudden surges in users during peak hours. The network has to scale horizontally by adding server resources to accommodate the increased demand without causing lag or downtime.

- **Resource Efficiency:** Efficient resource allocation, power management, and optimized routing contribute to resource efficiency. This is crucial for sustainability and cost-effectiveness. Through intelligent routing algorithms, the network can optimize the paths data takes to minimize energy consumption. This is particularly crucial in large-scale data centres and cloud networks.

- **End-to-End Monitoring:** Comprehensive monitoring tools and protocols are essential for real-time visibility into network performance, security, and resource utilization. Network administrators should have centralized dashboards for proactive management. Network administrators overseeing a global Content Delivery Network (CDN) require real-time monitoring to detect and address performance bottlenecks. Centralized dashboards provide insights into traffic patterns and content delivery times.

- **Service Diversity:** Recognizing that various applications have distinct requirements, the network infrastructure should be able to deliver services with varying characteristics, such as low latency for gaming or high reliability for critical infrastructure. An industrial IoT network has to cater to diverse applications, from sensor data transmission (low bandwidth, low latency) to remote equipment control (low latency, high reliability). The network should allocate resources accordingly.

- **Edge Computing Integration:** Edge computing capabilities should be seamlessly integrated into the network infrastructure. This allows for localized data processing, reducing latency and bandwidth demands on the core network. Edge servers placed at cellular base stations process data from IoT sensors locally, reducing the need to transmit large volumes of data to a centralized cloud. This minimizes latency for critical applications like autonomous vehicles.

- **Environmental Considerations:** Sustainability and energy efficiency should be at the forefront of design. Minimizing the network's carbon footprint and environmental impact is a societal responsibility. Data centres powering the network infrastructure can adopt renewable energy sources and employ advanced cooling techniques to reduce energy consumption and minimize the environmental impact.

- **User Experience:** Ultimately, the user experience is paramount. The network should deliver reliable, low-latency services that meet the expectations of end-users across various applications and industries. In online gaming, network quality directly impacts the user experience. A robust network infrastructure ensures low latency and minimal packet loss, enabling smooth and responsive gameplay.

In summary, the design of the next-generation networking distributed infrastructure necessitates a holistic approach that encompasses cyber-physical considerations, efficient management, and adaptability to diverse application requirements. By addressing these requirements, such an infrastructure can serve as a robust foundation for the digital layer, enabling a multitude of innovative and essential applications.

6.3 Challenges

As people venture into the era of the next generation of networking, marked by the convergence of cyber and physical worlds, they are faced with a plethora of challenges that necessitate innovative solutions. One of the foremost challenges in this context is the effective management of network fragmentation and heterogeneity. This challenge arises from the coexistence of diverse networking technologies, devices, and services across various domains, each with its own unique characteristics and requirements. Here, clause 6.3 delves into the open challenges associated with this fragmented landscape and explore the strategic importance of a uniform and homogeneous abstraction layer:

- **Diverse Networking Technologies:** The networking ecosystem encompasses an array of technologies, including cellular (2G, 3G, 4G, 5G), Wi-Fi®, wired Ethernet, satellite, and emerging technologies like Low-Power Wide-Area Network (LPWAN). Each technology has distinct capabilities and limitations. A unified abstraction layer can provide a common interface for applications and services to interact with various networking technologies seamlessly. This abstraction shields applications from the intricacies of underlying networks.

- **Heterogeneous Devices and Services:** In the cyber-physical realm, devices and services range from IoT sensors with minimal computing capabilities to high-performance cloud servers. Managing the heterogeneity of these devices and services in terms of communication protocols, energy efficiency, and computational power is a formidable task. The possibility to have an effective and intelligent abstraction layer can enable standardized communication protocols, allowing diverse devices and services to communicate effectively. It can also optimize resource allocation based on device capabilities.

- **Interconnected Domains:** Networks today span multiple domains, such as smart cities, healthcare, industrial IoT, and autonomous vehicles. These domains have specific requirements, and ensuring seamless communication and management across them is complex. The definition and adoption of a unified abstraction layer can provide domain-agnostic APIs and services, enabling cross-domain communication. It can offer flexibility to adapt to the unique needs of each domain while maintaining interoperability.

- **Dynamic and Reactive Services:** Emerging applications demand network services that are dynamic and reactive to real-time events. Traditional networking infrastructures may struggle to provide the agility required for services like augmented reality, autonomous navigation, and remote surgery. An abstraction layer can facilitate dynamic service orchestration and automation. It can monitor network conditions in real time and adjust services and resources accordingly, ensuring responsiveness to changing requirements.

- **Intelligent Network Management:** With the cyber-physical interaction, networks are expected to evolve into intelligent tools, capable of proactive optimization, predictive maintenance, and self-healing. Achieving this intelligence amidst fragmentation is a significant challenge. An abstraction layer can incorporate machine learning and AI-driven algorithms to analyse data from diverse sources and make intelligent decisions. It can enable autonomous network management functions.

- **Resource Management in Edge Computing:** Edge computing, a key component of the next-gen networking ecosystem, involves deploying compute and storage resources closer to the data source. Managing these distributed edge resources efficiently, especially in environments with varying connectivity and latency, presents a significant challenge. An abstraction layer can offer dynamic resource allocation and load balancing, ensuring that edge resources are optimally utilized. It can adapt resource allocation based on real-time network conditions.

- **Hybrid and Multi-Cloud Environments:** Organizations increasingly rely on hybrid and multi-cloud infrastructures for scalability and redundancy. These environments involve networking components from different cloud providers, each with its own networking policies and configurations. An abstraction layer can provide a unified interface for managing and orchestrating networking resources across diverse cloud environments. It can abstract the underlying cloud-specific configurations, streamlining multi-cloud networking.

- **Real-time Data Streaming and Analytics:** Many next-gen applications, such as autonomous vehicles and smart grids, require real-time data streaming and analytics. Network fragmentation can hinder the seamless flow of real-time data across diverse networks. An abstraction layer can optimize data streaming by selecting the most suitable network paths and protocols in real time. It can also provide integrated analytics tools for data processing at the network edge.

- **Interoperability with Legacy Systems:** Transitioning to the next generation of networking often requires interoperability with existing legacy systems. Legacy systems may lack the flexibility and capabilities of modern networks, making integration complex. An abstraction layer can act as a bridge between legacy systems and modern networking technologies. It can translate legacy protocols and data formats into modern equivalents, ensuring seamless communication.

- **Scalability and Performance:** As the number of connected devices and data volumes surge, scalability and network performance become critical. Managing these aspects across fragmented networks while maintaining low latency is a significant challenge. An abstraction layer can employ intelligent load balancing and route optimization to ensure scalable and high-performance networking. It can dynamically allocate resources based on traffic patterns and application demands.

In conclusion, the effective management of network fragmentation and heterogeneity is central to the success of the next generation of networking. An abstraction layer that provides a uniform and homogeneous interface, coupled with intelligent management capabilities, can address these challenges and pave the way for a cohesive and responsive cyber-physical networking ecosystem. Such an abstraction layer will be strategic in harnessing the full potential of emerging applications and services across diverse domains.

6.4 Networking & Digital Twins

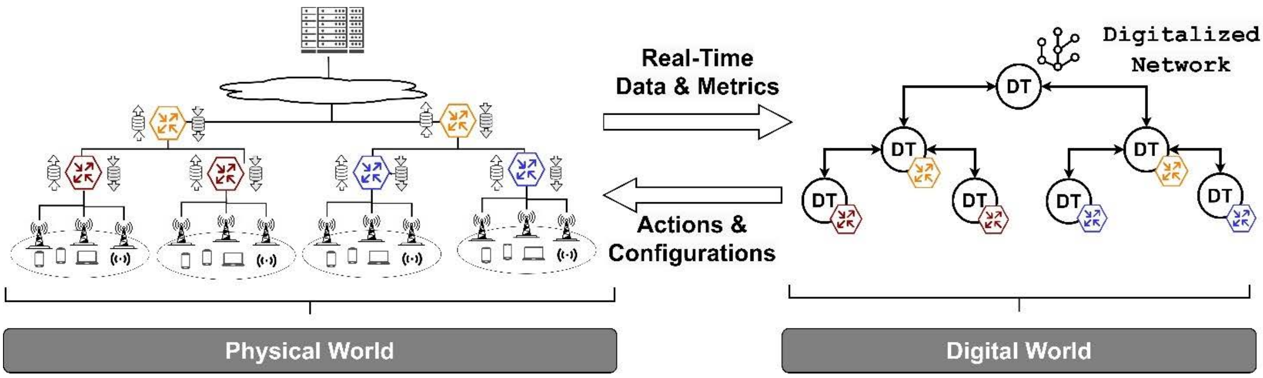

Figure 8: Schematic representation of Network Digital Twins associated to a distributed networking scenario with multiple and heterogeneous physical assets

The core principle of integrating DTs into networking involves the idea and vision of creating a virtual replica of the network itself with its nodes and functionalities through a hierarchical approach that can allow to build a complete digital representation of a deployment and augment its capabilities with intelligent functionalities based on collected data and actionable functions as envisioned and drafted also in [i.19]. This Network Digital Twin (NDT) replicates the network's topology, configuration, traffic patterns, and even the behaviour of individual network elements. It becomes a versatile resource for testing, predicting, and optimizing network performance.

One fundamental aspect of this integration in that specific context and operational domain is the real-time synchronization. To be effective, the DT has to maintain a constant and up-to-date reflection of the physical network. Any changes, events, or issues occurring in the actual network should be mirrored in its virtual counterpart. This real-time synchronization ensures seamless coordination between the physical and virtual layers.

The integration of DTs into networking offers several technological opportunities. Network planning and optimization become more efficient and accurate. Network operators can experiment with different configurations, routing strategies, and capacity planning scenarios within the DTs environment before applying effective changes on the deployment allowing them to identify the most efficient solutions and implement them in the physical network after a validation in the digital space.

Another significant advantage is predictive maintenance. Network DTs (NDTs) can analyse historical network data and simulate network behaviour to predict potential issues and outages. This proactive approach enables operators to identify and address problems before they impact end-users, improving overall network reliability.

However, several challenges have to be overcome to successfully integrate DTs and networking. Achieving real-time data exchange between the physical network and its DT demands robust mechanisms that address concerns like data volume, latency, and security. Additionally, managing accurate twin for large-scale networks, which may consist of numerous devices, protocols, and configurations, poses significant complexity and scalability challenges and highlight the importance of having an ecosystem of DTs organized through a hierarchical and discoverable structure.

The benefits of this integration are substantial. Network troubleshooting becomes safer and more efficient within the DT environment. Operators can simulate various scenarios, apply changes, and observe their effects without risking disruptions in the actual network. Furthermore, DTs enable operators to optimize resource utilization, ensuring efficient use of bandwidth, hardware, and software resources in highly distributed architecture involving several computational layers such as edge nodes with specific and demanding requirements.

Some examples of benefits provided by the design and adoption of NDT are:

- **Extended Network Awareness & Monitoring:** The adoption of DTs, especially through a hierarchical approach, can significantly enhance network awareness and monitoring capabilities. By creating a multi-layered representation of the network, organizations gain a more comprehensive understanding of distributed and heterogeneous networks (characterized by multiple vendors and hardware and software technologies), leading to improved decision-making and troubleshooting. Consider a large-scale telecommunications provider with a global network infrastructure. By implementing a hierarchical DTs modelling, they can create region-specific sub-twins that mirror the physical network in each geographical area. These sub-twins' aggregate data and events from various network elements, providing localized awareness. The global DT then consolidates information from all sub-twins, offering a holistic view of the entire network. This hierarchical approach enables the provider to detect regional issues quickly, assess their impact on the broader network, and implement proactive measures to ensure uninterrupted service.

- **Cyber-Physical Management:** The introduction of NDTs allows for the effective decoupling of business and orchestration logic from the inherent complexity of physical and infrastructure management. This decoupling is achieved through the creation of multiple NDTs that represent various layers and components of the network. These distributed NDTs form a hierarchy and ecosystem, encapsulating the intricacies of physical assets, configurations, and resource management. With this approach, organizations can focus on orchestrating services, optimizing network performance, and delivering innovative applications without being bogged down by the intricacies of physical network management. The NDTs abstract and simplify the underlying complexities, providing a unified and programmable interface for higher-level operations. For example, in a cloud-native 5G network, NDTs can represent different network slices, each tailored to specific services and applications. The NDTs manage the allocation of resources, ensure QoS, and adapt to changing demands, all while presenting a simplified interface to service orchestrators. This separation of concerns streamlines operations, accelerates service deployment, and enhances overall network agility.

- **Improved Network Reliability & Traffic Management:** The integration of DTs with networking appliances and deployments enables proactive monitoring and predictive maintenance, reducing network downtime and improving overall reliability. For example, a telecommunications company can use a DTs to monitor throughput behaviour on a target network portions with the objective to predict a degradation and anticipate it before moving traffic (e.g. of a specific class) through different routes it causes service disruptions.

- **Configuration Management:** The adoption of NDTs presents unparalleled configuration benefits to organizations managing complex network infrastructures. By virtualizing configuration management, offer a single source of truth for network settings, policies, and parameters based on the information provided by multiple twins responsible for different network portions and layers. This approach ensures consistency and minimizes the risk of misconfigurations, reducing the potential for service disruptions and security vulnerabilities. What sets NDTs apart is their ability to validate and test configuration changes within a safe, digitalized sandboxed environment before deploying them into the live network, guaranteeing that only validated configurations are implemented. This not only enhances the overall network stability but also accelerates the deployment of new services and updates. Furthermore, NDTs facilitate efficient troubleshooting by allowing real-time network state comparisons with the expected state, streamlining the resolution of issues. Overall, the configuration benefits of twin translate into improved network reliability, reduced operational risks, and enhanced agility in adapting to evolving networking requirements.

- **Data-Driven Decision-Making:** The use of DTs within networking deployments empowers organizations with data-driven decision-making capabilities that are instrumental in optimizing network performance and resource allocation. NDTs continuously collect and analyse vast volumes of real-time network data, offering valuable insights into network behaviour, traffic patterns, and resource utilization building, maintaining and providing an homogenous and exploitable overview of the entire managed network. This data-driven approach enables network operators and administrators to make informed decisions regarding capacity planning, traffic engineering, and network optimization without being affected by the fragmentation of the underlying physical network layers. For instance, predictive analytics powered by NDTs can forecast network congestion or potential failures, allowing proactive measures to be taken to prevent service disruptions. Additionally, by leveraging historical data and ML algorithms, NDTs can suggest intelligent recommendations for configuration changes, traffic routing, or security policies. As a result, organizations can achieve enhanced operational efficiency, reduced downtime, and the ability to adapt quickly to changing network demands, ultimately improving the overall quality of service delivered to end-users.

- **Support for DevOps Practices:** The combination of DTs within networking environments can introduce a new robust support for DevOps with the aim of automating development and operations as a means for improving and shortening the systems development life cycle. NDTs can serve as a critical bridge between network development and operations teams, fostering collaboration, automation, and agility. As previously anticipated, with NDTs, network configurations, policies, and changes can be tested and validated in a virtualized environment before deployment in the production network. This not only reduces the risk of misconfigurations but also accelerates the development and deployment pipeline. DevOps teams can leverage NDTs to automate the provisioning of network resources, ensuring that infrastructure is aligned with application requirements. Furthermore, NDTs facilitate continuous monitoring and feedback loops, enabling real-time visibility into network performance and the impact of changes. This integration of NDTs into DevOps practices streamlines development workflows, enhances collaboration, and promotes the rapid delivery of network services while maintaining reliability and security.

- **Knowledge Transfer and Training:** NDTs can also support platforms for knowledge transfer and training within the networking domain. By replicating real-world network environments in a virtualized setting, NDTs provide an immersive and risk-free space for network professionals to gain hands-on experience, experiment with various configurations, and troubleshoot issues also through distributed and complex network. This virtual training environment is particularly valuable for onboarding new network engineers, as they can explore complex network scenarios and best practices without impacting the live network. Additionally, NDTs can support the development of training modules and simulations for specific training scenario enabling them to practice on realistic use cases without a direct access to the physical layer but having a complete and realistic playground.

Potential applications of DTs in networking are diverse. They include network simulation and testing, where DTs prove invaluable for simulating and testing network changes before implementing them in the physical network. This reduces the risk of errors and downtime. Traffic engineering benefits from DTs as well, with operators using them for tasks like load balancing and route optimization, leveraging real-time data and simulations. Finally, security analysis benefits from twins by identifying security vulnerabilities through the simulation of attack scenarios and assessing network responses.

Summarizing, integrating DTs and networking represents a challenging opportunity and marks a paradigm shift in network design and management. Challenges such as DT design, implementation, and interoperability (to avoid siloed approaches across vendors) together with real-time data synchronization and network complexity exist, but the potential benefits, including enhanced troubleshooting and resource utilization, make this integration a promising avenue for future networking innovation. As technology advances, people can expect increasingly sophisticated applications of DTs in network operations fostered by the definition of new standards and advancements in development, deployment, and experimental evaluations.

6.5 Dynamic Traffic Management with Digital Twins

The possibility of dynamically managing network traffic results strategic in distributed deployment where multiple computational facilities and resources are integrated together trough edge and cloud locations. This category of distributed network infrastructure presents a multifaceted challenge driven by the constantly evolving digital service landscape and the increasingly diverse requirements of modern applications. This intricate problem revolves around the need to build an extended real-time time awareness of ongoing activities and performance and to adeptly orchestrate the flow of data, efficiently allocate network resources, and intelligently distribute computing workloads across a highly dynamic and heterogeneous network environment. This environment encompasses a spectrum of nodes ranging from edge devices and edge servers to traditional data centres and the core network.

At the heart of this challenge is the ever-changing nature of network traffic. Traffic volumes exhibit rapid and often unpredictable fluctuations. Events like flash crowds during online events, sudden surges in traffic due to the popularity of specific applications or content, and the pervasive influence of emerging technologies like the IoT all contribute to the unpredictability of network load. The art of dynamic traffic management lies in the network's ability to adapt to these variations without compromising the QoS expected by users and applications.

Another dimension of complexity emerges from the stringent low-latency requirements imposed by many contemporary applications. Systems such as autonomous vehicles, augmented reality experiences, and real-time industrial control demand ultra-low latency. Achieving this low latency necessitates meticulous traffic management, which ensures that data traverses the most optimal network paths to minimize delays. Edge computing, with its proximity to end-users and devices, is pivotal in meeting these latency demands, but the effectiveness of traffic management in exploiting this proximity is a critical factor.

Resource allocation represents another critical facet of dynamic traffic management. The judicious allocation of computing resources, storage capacity, and network bandwidth becomes paramount in an environment where edge nodes may possess limited resources compared to traditional data centres. Making informed decisions about where to process data, where to run applications, and how to efficiently utilize available resources becomes a complex yet essential aspect of dynamic traffic management.

In the era of shared infrastructure, where diverse applications and services coexist, service isolation is a significant challenge. Ensuring that critical services maintain their performance levels even during traffic surges or resource constraints is vital. Dynamic traffic management has to delineate the boundaries between services, prevent resource contention, and guarantee that each service receives the necessary resources to fulfil its requirements.

The concept of network slicing further intensifies the complexity of traffic management. As networks embrace greater flexibility and adaptability, they enable the creation of network slices, which are logical segments of the network tailored to specific use cases or services. Managing these slices dynamically to accommodate various traffic types, each with its unique demands, adds yet another layer of intricacy to the traffic management puzzle.

Addressing these multifaceted challenges requires a fusion of cutting-edge technologies and innovative approaches. Intelligent traffic routing algorithms, real-time monitoring and analytics, QoE measurements, and the ability to adapt network configurations dynamically are all crucial elements of the dynamic traffic management toolkit. Machine learning and AI-driven solutions hold significant promise in predicting traffic patterns, optimizing resource allocation in real-time, and enhancing the overall efficiency and responsiveness of the network. Ultimately, the overarching objective of dynamic traffic management in MEC and distributed network infrastructure is to ensure that the network operates with utmost efficiency, delivering low-latency, high-QoS services, all while seamlessly accommodating the ever-evolving demands of the digital ecosystem.

In this challenging context, NDTs can be considered and evaluated as a compelling solution to tackle the intricate challenges embedded in the dynamic traffic management landscape of MEC and more in general of distributed network infrastructure (an illustrative schema of cyber-physical interaction is depicted in Figure 9). They offer a multifaceted approach to address the highlighted open challenges comprehensively. Firstly, they provide real-time visibility and monitoring across the entire network fabric, encompassing edge devices, servers, and network resources. This granular perspective empowers network operators with continuous insights into traffic patterns, resource utilization, and individual element performance.

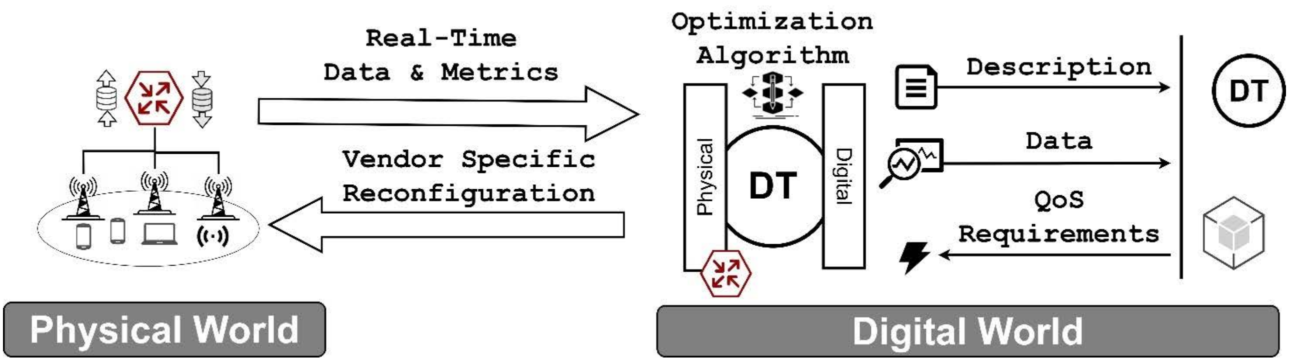

Figure 9: Illustrative example of dynamic and intelligent traffic management through network DTs

As first concrete benefits, NDTs offer the possibility to build and maintain a unified and holistic digital representation of the network and of its management bridging the divide between the physical and digital aspects of the network through different vendors, hardware and software configurations, data collection and capabilities. They provide an homogeneous and hierarchical digital approach for orchestrating traffic management strategies, fostering efficient collaboration among various stakeholders, including network operators, application developers, and service providers.

At the core of the provided potential benefits there is the real-time visibility offered by NDTs. They provide network operators with an overarching view of traffic patterns, resource utilization, and performance metrics across a distributed edge infrastructure characterized by fragmented physical assets and capabilities. This visibility empowers operators to monitor the network as events unfold, offering insights into how traffic flows and resources are being utilized.

Thanks to the built and maintained real-time visibility of the network NDTs can encapsulate the logic and the algorithms to handle the resource optimization as a fundamental aspect of traffic management in MEC. They continuously assess the availability of computing power, storage, and network bandwidth across edge devices and servers. Armed with this information, NDTs enable intelligent resource allocation, ensuring that applications receive the requisite resources even during traffic spikes. This approach guarantees consistent performance, even under varying workloads.

One of the most critical benefits of NDTs is their ability to facilitate low-latency routing. By maintaining a real-time inventory of edge node locations and their capacities, these digital twins empower networks to make routing decisions that minimize latency. Traffic can be directed to the nearest edge server or a node with abundant computing resources, ensuring that latency-sensitive applications perform optimally.

NDTs can support the creation of dynamic network slices or logical segments within the infrastructure. Each slice can be customized to accommodate specific services or applications, preventing resource contention and safeguarding QoS. This service isolation is crucial in MEC environments where diverse applications with varying requirements coexist. The combination of extended awareness and dynamic network slide management without the direct complexity of handling the physical layer empowers network algorithms to adjust rapidly to changing conditions. When traffic patterns shift or new applications are introduced, NDTs can recommend or implement configuration changes to maintain optimal performance and resource utilization. Nevertheless, the configurability at the NDT layer instead of at the physical one allows operators to create, modify, or decommission slices on the fly. This flexibility ensures that different traffic types receive the customized treatment they require, optimizing the utilization of network resources.

In essence, NDTs can represent a strategic pillar for the next generation of intelligent traffic management in MEC environments by enhancing visibility, enabling predictive analytics, optimizing resource allocation, ensuring low-latency routing, and providing robust security measures. They empower network operators to create custom network slices, make data-driven decisions, and achieve efficient, unified network management. Ultimately, NDTs empower networks to operate efficiently, deliver low-latency services, and respond effectively to the ever-changing demands of the digital landscape.

7 Digital Twin Standardization Opportunities

7.0 Foreword

Clause 7 focuses on the analysis and investigation of the standardization opportunities associated with DTs, following inputs, characteristics and requirements coming from the structured analysis of the presented reference use case aiming to shape and standardize as powerful and effective tools for the management and optimization of complex cyber-physical systems. DTs standardization plays a vital role in promoting interoperability, defining clear definitions, requirements, and responsibilities, and enabling collaboration among stakeholders through cross-domain application scenarios. Establishing a standardized approach to define and describe DTs is also crucial for their effective software implementation and their effective interoperability represents a significant challenge ensuring seamless communication and data exchange between DTs, physical assets, and digital services. Clause 7 explores standardization opportunities efforts highlighting the main aspects to be addressed as key enablers for DTs ecosystem promotion, collaboration, and innovation.

7.1 Digital Twin Definition & Description

The principle of cyber-physical is rooted in the integration of physical and digital components, allowing for seamless communication and interaction between them and the introduction of DTs can represent a paradigm shift to encapsulate the responsibility of bridging physical and digital world together. Having a shared definition of DT (starting from existing updated visions such as [i.4]) with its core principles and capabilities that is independent from the specific application domains and target implementations is of paramount importance opening to a common understanding, interoperability and integration across different stakeholders, regardless of their background or expertise. By establishing a standardized definition, the present document proposes to create a foundation for collaboration, knowledge sharing, and innovation in the field of DTs across various industries and sectors, facilitating the exchange of data, insights, and best practices. Moreover, a universal definition helps to establish a framework for research, development, and governance, enabling the advancement and adoption of DTs on a broader scale.

In this context, a Digital Twin Description (DTD) may be useful as a standardized and machine-readable representation of a physical asset or system. It encompasses the properties, capabilities, and interactions of the Digital Twin, providing a comprehensive definition of its functionalities. This description includes details about property, relationships, models, supported operations, communication protocols, generated events associated with a target DT. By having a uniform and interoperable DTD, stakeholders can easily discover, understand, and interact with different DTs, irrespective of their underlying technologies or manufacturers. This standardization promotes interoperability, simplifies integration, and facilitates the development of scalable and interoperable cyber-physical systems and DTs driven applications.

As introduced and presented in [i.2] and [i.3] some core aspects that should be taken into account in the standardization process of the concept of DT are:

- A DT should have a unique identifier too in order to make it addressable into a software space and it should be clearly associated to the associated PTs (e.g. using a unique identified of the physical entity).
- DT may have both a 1-to-1 or a 1-to-N cardinality/relation between the assets and the digital instance. In that second case different DTs replicas may exists with respect to the same PT and if more than a replica refers to the same PT, each of them should have a unique identifier and a pointer to the correct PT identifier.
- A DT should be supported by a **Model** responsible for the digitalization process and designed and implemented with a set of goals and purposes and refer to a target context in which the DT operate.
- A DT is the digital replica of one or more associated PTs and its digitalization is determined on how much it is able to represents the original PTs in terms of:
    - **Properties:** represent the observable attributes of the PT, as labelled data values (variables) that can change dynamically according to the evolution of the PT over time (e.g. a temperature sensor or a switch).
    - **Relationships:** represent relationships of the PT with other PTs, as links to other DTs. Like properties, even relationships can be observable, created dynamically and change over time. Differently from properties, they do not purely concern the local state of the PT, but they allow to refer other PTs, represented by the corresponding DTs. They can also represent different semantic meanings, such as *contains* ("floor contains room"), *cools* ("hvac cools room"), or *isBilledTo* ("compressor is billed to user").
    - **Events:** represent relevant observable events that occurred at the PT, at the domain level (e.g. a detected anomaly).
    - **Behaviours/Actions:** actions and capabilities exposed by the PT that can be performed by (or on) the device to change its status and/or interact with the environment (e.g. a toggle to turn on and off the light).
- The DT should at least represent those properties, behaviours and relationships that are necessary and sufficient to qualify it in the target operational context (e.g. optimize energy consumption in a building).
- The ***State*** of a DT is the combination of *Properties*, *Relationships*, *Events*, and *Behaviours* associated to a specific timestamp when the DT's State has been computed by the DT's ***Model***.
- Each DT's State should be associated to a reference timestamp identifying its computation time within DT's evolution timeline and with respect also to the evolution of the associated physical counterparts.
- Since PTs come with well-defined functionalities and services that are fixed for the entire life cycle of the object, DTs can leverage the software dematerialization to modify, update, and improve its functions over time. In other words, the PT's state of can be functionally augmented through the integration of new *Properties*, *Relationships*, *Events* and *Behaviours/Actions*. For example, a DT associated to a building can digitalize in its *State* the temperature associated to each single room in the building and provide aggregated representation averaging the temperature values for each monitored floor.

Relying on these principles and guidelines together with inputs from recent state of the art contributions [i.5], industrial [i.7] and IoT efforts [i.6] some of the fundamental characteristics that a DTD should include are:

- **Identity and Metadata:** each DT should be identifiable within is operational domain or event across multiple applications and use cases through a unique identifier. Furthermore, the association between the DT and the associated PTs should always be possible allowing a match between the current DT and the unique identifier of the associated physical entities or devices. As a general approach, information about the unique identity and metadata of the DTs, such as its unique identifies, associated PTs, type, description, and associated metadata or annotations should be adopted to provide context and support to DT deployment and discovery together with allowing the identification of DT's capabilities and its relationships with associated PTs.

- **State Description:** the DTD should define the *Properties*, *Relationships*, *Events* and *Behaviours/Actions* associated to the current context or conditions of the target twin. It provides access to read and update these characteristics, allowing for monitoring and control of the DT's behaviour and functionality.

- **DT's Physical & Digital Communication Capabilities:** the DTD should describe the available interactions patterns and communication layers both for the physical and the digital world that on the one hand implement the integration with the digitalized PTs and on the other hand that enable the communication and interaction with the DT allowing the access to its State, reading data, and invoking available actions. With respect to the digital interaction flows the DTD should specify supported protocols, data formats, and operations, allowing for seamless integration and interoperability across different platforms, implementations, and digital services.

- **DT's. Monitoring:** the introduction in the DTD of information about the monitoring metrics (e.g. phases of its life cycle and/or occurred errors) and that the DT can generate can increase the overall DT's accountability and support digital applications and service to proactively detect and handle specific occurrences, anomalies or changes in the DT's environment or internal state.

- **Security & Privacy:** the DTD should allow the specification of security and privacy measures associated with the DT and used to both communicate with the PT and external digital applications. These specifications can be associated to DT's communication layers including authentication, access control, encryption, and data protection mechanisms to ensure the secure and private interaction between the Digital Twin and authorized entities. Furthermore, specifications can be added also to describe internal DT's logics associated for example to built-in data storage solutions, adopted algorithms and software versions.

- **Semantics and Contextual Information:** the Digital Twin Description incorporates semantic annotations and contextual information to enhance the understanding and interpretation of the Digital Twin's capabilities and interactions. It enables semantic interoperability and facilitates meaningful integration and reasoning about the DT. In this context, the integration with [i.20] represents an appealing opportunity to introduce a structured and interoperable semantic representation for DTs in a structured ontology like SAREF oriented to support multiple application domains.

These fundamental characteristics of a DTD enable seamless discovery, integration, and interoperability within the DTs ecosystem by providing a standardized and machine-readable representation of existing twins and promoting the development of scalable and interoperable applications and services leveraging the and augmented and simplified cyber-physical overlay.

7.2 Digital Twin Capabilities & Responsibilities

According to the recent scientific literature ([i.2], [i.3] and [i.8]) the main aspects that should be taken into account referring to DT's capabilities and responsibilities are the following:

- **Representativeness & Contextualization:** it refers to how well a DT represents and accurately measures its physical counterpart within its specific context and design goals. This is achieved through the consideration of the fundamental aspects characterizing the computation of its State in term of *Properties, Events, Behaviours/Actions*, and *Relationships*.

- **Reflection:** the process of state alignment and synchronization between DT and its corresponding PT is a critical aspect of the twin's nature and functionality. This process ensures that the DT accurately reflects the current state of the PT, considering both the modelled behaviour and the unique characteristics of the physical target. For example, the DT may choose to mirror only a subset of the available functionalities or properties of the PA, based on its intended purpose or specific requirements. Additionally, the process has to account for the heterogeneity of PAs, which can vary in terms of protocols, standards, and technologies used. The DT has to be able to navigate diverse technologies and protocols to establish a seamless connection with the PA, ensuring effective data exchange and synchronization. This requires robust integration capabilities and the ability to adapt to different communication layers and protocols, whether they are standardized or legacy systems. Addressing this challenge is crucial for the successful implementation and operation of DTs. It involves developing innovative approaches and tools that can handle the complexity of mapping and integrating diverse PAs into the digital realm, enabling reliable and accurate state alignment between the DT and its physical counterpart. Within the literature and the current state of DTs, the reflection concept shares similarities with other terms like *digitalization* and *shadowing*. The present document adheres to the interpretation presented in [i.3], which centres on the concept of reflection as the process of *reflecting* what is present on the physical counterpart. However, it is worth noting that the principles and analyses discussed here can also be extended to encompass these alternative definitions.

- **Observation & Interaction:** the capability to enable external applications and services, including other DTs, to detect and monitor relevant changes in the *State* of both the PT and the DT together with the possibility to interact with exposed *Behaviours/Actions* is essential. This capability allows the observation of the DT, including all the field defining its *State* and all the metrics and logs that the DT might generate over time. By providing the possibility to observe and interact with a connected DT, an open system is created where connected, interoperable, and pervasive applications and DTs can operate and collaborate in distributed ecosystem. For example a DT can allow external entities to stay informed about the real-time state and behaviour of the twin and its corresponding PT and/or facilitate the integration of DTs into larger systems by providing opportunities for interaction and collaboration with other applications and services. In an open-system environment, the observation and interaction with DTs promotes interoperability and enables the seamless exchange of information and resources among different entities. Additionally, an open, secure and interoperable approach combined with an effective DTD can foster the development of distributed and scalable architectures, where DTs can be independently managed and orchestrated through various domains, enabling advanced analytics, optimization, and decision-making processes that can lead to improved operational efficiency and innovative solutions.

- **Augmentation:** PTs typically have a fixed set of functions throughout their entire lifecycle. While they may not have processing constraints, they often face limitations when it comes to updates due to factors such as dependencies, security considerations, and ownership. However, the concept of DTs introduces a crucial capability: the ability to modify, update, and improve the functionalities of PTs over time. This capability allows for the native support of defining and injecting new functionalities directly into the twin itself allowing to achieve a flexible and modular architecture, eliminating the need for additional external components to introduce new capabilities associated to deployed PTs. This approach empowers digital services, including applications and other DTs, to easily leverage on twin behaviours by interacting with a uniform abstraction layer, which conceals the underlying physical complexity. Furthermore, the ability to enhance and augment PTs through DTs potentially opens a realm of possibilities for new digital services by allowing the seamless integration of new functionalities such as dynamic adaptations, optimizations, and innovation throughout the lifecycle of the physical assets.

- **Replication:** the possibility to have multiple DTs instances associated to the same original PT is a transformative concept that bestows the remarkable ability to recreate and transpose physical objects into diverse environments, both virtually and within digital ecosystems. This dynamic capability essentially transforms physical entities into software-enabled counterparts, granting them the capacity to be cloned, altered, and disseminated across various spaces, with each instantiation retaining the core attributes of the original. At its essence, replication signifies the conversion of physical objects into software representations, thereby enabling the creation of multiple digital counterparts or "clones" within virtualized realms. This intricate process involves the translation of physical attributes into digital formats, serving as the foundation for subsequent replication endeavours. However, replication goes beyond mere duplication of physical entities; it extends to the digital realm. Each logical object, representing a DT, can implement its internal model to define a specific replication approach according to the target domain resulting in a complex network of interconnected digital counterparts. This hierarchical approach enhances versatility and adaptability, fostering a dynamic environment for DTs.

- **Composition:** represents the capability for abstracting the complexity of a larger system to simplify and focus on relevant properties and functionalities without the need for external digital applications understand or consider all the intricacies of the entire cyber-physical system or its hierarchical sub-components (e.g. interacting with the DT digitalizing a production line or a city neighbourhood). This allows for a more manageable representation and efficient utilization of resources augmenting and simplifying at the same time the awareness of the local cyber-physical complexity and enable the representation (through the DTD) of existing properties and relationships in the physical world. The implementation and adoption of the composition can facilitate dynamic and opportunistic digital collaborations in particular when DTs are applied to complex, distributed and hierarchical use cases (e.g. Industry, Smart City, HealthCare). Each Composed DT (CDT) will handle the composition internally reducing the overall architectural complexity and enabling external components to seamlessly interact with aggregated entities without the need to handle or have knowledge of the underlying complexities of the deployments. This flexibility supports different scopes, visibility, and granularity based on the specific application domain, modelled use cases, and the needs of data consumers. The ability to abstract and compose DTs at different levels empowers organizations to effectively manage and utilize complex systems, facilitating collaboration, information exchange, and interoperability in diverse application scenarios and opens up opportunities for agile and scalable deployments, driving innovation and enhancing the capabilities of digital services in a wide range of domains.

7.3 Design Requirements

7.3.0 Requirements Overview

Clause 7.3 outlines the key design requirements essential for creating effective and efficient DTs, derived from the thorough analysis of the presented use cases in the present document. From ease of implementation and interoperability to maintenance, scalability, and discoverability, these requirements stem from real-world scenarios, providing the foundational requirements and pillars for designing and developing resilient and adaptable DT-driven solutions. Each requirement is discussed through its key point and characteristics, offering insights into best practices and strategies to meet these essential criteria for successful and standardized DT design and implementation approaches.

Clause 7.3 delineates the imperative design requirements derived from the analysed use cases presented earlier in the present document. To comprehensively guide the development of robust Digital Twins, the focus is set on key aspects such as architectural principles, flexibility, compatibility, scalability, interoperability, and discoverability. Each of these facets plays a pivotal role in shaping Digital Twins that align with real-world needs and seamlessly integrate into diverse ecosystems. Through a detailed exploration of each requirement, the present document offers insights into the best practices and strategies that ensure Digital Twins are not only effective but also adaptable and with a long-term vision.

It is important to note that the identified requirements are not intended to impose constraints on the implementation of DTs; rather, they serve as reference guidelines and essential considerations based on the analysed use cases. These guidelines offer key points that should be taken into account, aligning with the overarching objective of constructing an ecosystem of distributed and interoperable DTs.

7.3.1 Architectural Principles

The architecture of Digital Twins (DTs) is a cornerstone in ensuring their efficacy, compatibility, and harmonious integration across multifaceted ecosystems. To establish a resilient foundation, several pivotal architectural principles have to be underscored.

DT architecture functions as a nexus for the harmonious interworking of diverse ecosystems and for this reason their design should be guided by the principles of *Interoperability* and *Mutual Interworking*. This is facilitated by the adoption of standardized and interoperable technologies both in terms of communication protocols with the physical and digital world and within the description and representation of the DT itself. This approach enables DTs to effortlessly engage with various systems, platforms, and fellow DTs. The result is seamless data exchange, cooperative insights generation, and a comprehensive comprehension of the physical entities they digitalize. This emphasis on interoperability since the architectural design ensures that DTs become effective contributors within the broader digital landscape.

The intrinsic strength of DTs lies in their *Adaptability* across different architectural layers, encompassing Edge, MEC, Fog, and Cloud. This adaptability tailors DT deployment to the specific prerequisites of each use case. Deploying multiple computational facilities (also at the same time in the same deployment) entails distinct roles and responsibilities, each aligned with the unique strengths and requirements of these environments. On the edge, DTs primarily focus on real-time interactions and immediate data processing. They are responsible for rapidly responding to local changes, offering real-time insights, and enabling quick decision-making. Edge DTs require lightweight and agile architectures, capable of handling limited resources while ensuring low latency and react to physical and computational load variations with the possibility for example to move and adapt DTs behaviours dynamically.

Edge DTs operate on a one-to-one basis, being closely associated with individual physical assets. Multiple edge DTs can coexist within an ecosystem, each addressing a specific asset. These edge DTs, while capable of hosting complex functionalities, operate within a confined operational range that aligns with their designated scope and context. This "limited" operational range is a deliberate design to ensure that edge DTs effectively process and respond to real-time data from their respective assets, maintaining a focused and agile approach. This constrained operational boundary enhances the accuracy and efficiency of edge DTs, allowing them to provide immediate insights and prompt actions within their defined context.

In the fog or on MEC computing realm, DTs assume an intermediary role between edge and cloud environments. They can build digitalized replicas of complex or composed physical counterparts (e.g. multiple production lines belonging to the same facility) collect, preprocess, and filter data from edge devices before transmitting relevant insights to the cloud. Fog/MEC based DTs ensure efficient data transmission, aggregate and augment data and capabilities reducing the load on the cloud while maintaining real-time and low-latency functionalities. These DTs are tasked with optimizing data flow, reducing bandwidth consumption, and enhancing the overall network performance. This category of DTs operates with a broader operational context (compared to those on the edge), capable of aggregating and digitalizing multiple lower entities, including both physical twins and/or other DTs on the edge. These Fog/MEC DTs encompass a more comprehensive view, orchestrating insights from various sources to provide a holistic perspective of a larger ecosystem (e.g. a neighbourhood of a Smart City or multiple departments in an Industry). With enhanced computational capabilities, these DTs can process larger volumes of data and execute a wider range of functionalities. By bridging the gap between the localized agility of DTs on the edge and the extensive resources of the cloud, Fog/MEC DTs strike a balance, enabling efficient data distribution, intermediate processing, and sophisticated analysis. This intermediary role allows them to optimize data flows, minimize latency, and provide a centralized yet responsive decision-making mechanism that benefits from both local and global insights.

Cloud-based DTs, on the other hand, focus on comprehensive data analysis, complex simulations, and long-term insights generation. Deployed in the expansive computing resources of the cloud, they can process massive volumes of data and perform resource-intensive tasks. Cloud DTs play a crucial role in in-depth historical analysis, predictive modelling, and resource-demanding simulations that contribute to strategic decision-making and future planning. In contrast to edge and Fog/MEC DTs, these categories of twins are well-suited for digitalizing extensive deployments that encompass multiple entities, including of course both physical counterparts directly connected to the Cloud or intermediate DTs deployed on lower layers. Leveraging the substantial computational and storage resources available in the cloud, these DTs are equipped to efficiently manage large-scale data processing and storage demands. Cloud DTs are particularly adept at handling big data, facilitating advanced data analysis, pattern recognition, and predictive modelling. Their robust infrastructure supports sophisticated Machine Learning training and capabilities, empowering them to harness data-driven insights for enhanced decision-making. In essence, Cloud DTs excel in handling complex and resource-intensive tasks, making them integral to comprehensive data analysis, strategic planning, and optimizing the overall digital twin ecosystem.

A robust DT architecture also hinges on the possibility to have standardized descriptions of involved entities and in the scenario of active DTs across the different architectural layers and through multiple implementations. These descriptions (as previously mentioned the DTD), rooted in shared, interoperable data models and descriptors, empower DTs to consistently communicate their attributes, behaviours, and interactions across a variety of platforms and applications. This standardization enriches the understanding of DTs among diverse stakeholders and enhances their integration into a myriad of applications and industries, fostering a unified grasp of the emulated physical entities.

The architecture of DTs (the single instance or an aggregation implementation supporting multiple twins at the same time) should be designed to adeptly manage diverse protocols and payload formats, traversing both physical and digital communication layers. This dynamic adaptability ensures seamless communication between DTs and a broad spectrum of devices, sensors, and systems, regardless of the specific communication requisites. By accommodating various protocols and payload formats, this architectural tenet augments interoperability and expands the practical scope of DTs across diverse use cases and application scenarios.

A robust DT architecture should also be engineered to accommodate diverse implementation patterns and design approaches. This spans from distributed and centralized models to event-driven and hybrid architectures involving for example Microservice based approaches or Serverless computational solutions. The architecture's flexibility empowers developers to select the most apt approach for their application, without being confined to a particular implementation. This adaptability resonates with the myriad use cases and scenarios that DTs engage with, fostering a dynamic application landscape.

The choice of DT implementation is closely intertwined also with the deployment location of the DTs. Each deployment environment - Edge, Fog/MEC, and Cloud - offers distinct advantages that can be effectively harnessed through various DT implementation options. Edge deployments often require lightweight and agile implementations due to limited resources, aiming to provide real-time insights and immediate responses where for example a Microservice oriented approach with a simple and effective virtualization layer can be more suitable. In the Fog/MEC, intermediary DT implementations can efficiently preprocess and filter data from multiple Edge DTs, optimizing data flow and minimizing latency and an advanced orchestration solution able to execute multiple twins at the same time can be strategic to support a wider ecosystem of interconnected. Cloud deployments, on the other hand, can accommodate more resource-intensive implementations, enabling comprehensive data analysis, Machine Learning training, and complex simulations. In this case, multiple implementations can be supported at the same time based on the requirements in terms of data volumes, time constraints and processing load taking to account managed solutions and multiple development patterns. This alignment between deployment location and DT implementation underscores the significance of tailoring implementation choices to the unique capabilities and requirements of each environment, ultimately optimizing the overall performance and effectiveness of the DT ecosystem.

Incorporating these architectural principles is pivotal in ensuring that Digital Twins seamlessly integrate into various environments, cater to evolving needs, and serve as reliable virtual analogues to their physical counterparts. This approach elevates the interoperability and efficiency of DTs, while simultaneously nurturing innovation and opening doors to diverse applications.

7.3.2 Flexibility

Flexibility represents a critical requirement in the design and implementation of DTs, as it enables the maximization of interactions between the physical and digital worlds. By adopting modular and standardized physical and digital communication layers (together with custom interfaces to support specific challenging physical deployments) DT can easily integrate on the one hand with diverse physical assets, sensors, actuators, and communication protocols and on the other hand with a plethora of different digital services and applications. This flexibility allows for seamless connectivity and interoperability, regardless of the specific technologies or systems involved. In the physical world, modular and standard interfaces enable DTs to interact with a wide range of physical assets, regardless of their brand, model, or type. This empowers organizations to leverage existing infrastructure and assets without the need for extensive modifications or customizations. By providing standardized interfaces, DTs can allow the access and control physical assets, gather real-time data, and execute actions to reflect changes in the digital realm back to the physical environment. In the digital world, flexibility in interface design allows DTs to integrate with various software systems, platforms, and data sources. By adhering to homogeneous and interoperable digital interfaces, DTs can seamlessly exchange data, interact with other digital systems, and tap into a vast ecosystem of software applications and services. This flexibility enables DT enabled cyber-physical systems to be effectively connected with the physical world and leverage advanced analytics, machine learning algorithms, and artificial intelligence tools to derive meaningful insights and drive autonomous decision-making processes. Overall, the flexibility of DT' design and interfaces also empowers organizations to create adaptable and scalable systems that can efficiently interface with both the physical and digital domains. It promotes interoperability, reusability, and future-proofing, allowing for the seamless integration of new technologies, assets, and services. This flexibility opens opportunities for innovation, optimization, and improved operational efficiency across a wide range of industries and use cases.

7.3.3 Compatibility

In the context of DT this requirement refers to the ability of different DTs and their associated systems to seamlessly work together and with external digital applications, regardless of their specific implementations or the application domains they belong to. It is crucial to establish compatibility to foster interoperability, collaboration, and data exchange between various DTs and their corresponding environments. A shared and standardized DTD plays a key role in achieving compatibility. By providing a standardized and uniform representation of DTs, it enables easy integration and communication between different systems, platforms, and stakeholders. The shared description serves as a common language that facilitates understanding and interaction, regardless of the underlying technologies or protocols used. Compatibility through a shared DTD allows for the efficient integration of diverse systems and components, enabling cross-domain collaborations and fostering innovation. It reduces the complexity associated with system integration, as it provides a consistent framework for describing and interacting with DTs. Moreover, it promotes scalability and future-proofing, as new DTs can be seamlessly integrated into existing environments by adhering to the established compatibility guidelines and leveraging the shared description. Overall, ensuring compatibility through a shared DTD enhances the effectiveness and versatility of DT deployments. It enables the creation of interconnected ecosystems where DTs can seamlessly interact, exchange information, and collaborate to address complex challenges and unlock new opportunities across various domains.

7.3.4 Scalability

The possibility to have an ecosystem of DTs that is scalable represents a crucial requirement in the design and implementation of DT architectures and frameworks, enabling them to support diverse application scenarios and meet the varying cyber-physical requirements of different environments. By leveraging a scalable architecture, DTs can be deployed simultaneously across Edge, Fog, and Cloud computation facilities, providing flexibility in resource allocation, and accommodating the specific needs of each application (e.g. real-time or batch processing). At the Edge, DTs can be deployed directly on devices or gateways in close proximity to the PTs they represent enabling real-time data processing, immediate response, and reduced latency, making them suitable for time-critical applications and environments where reliable connectivity to the Cloud may be limited. Edge-based DTs can handle local data collection, analytics, and control, providing localized insights and enabling autonomous decision-making at the edge. At the Fog layer, DTs can be deployed on distributed computing resources closer to the edge (e.g. on MEC facilities), offering a balance between local processing capabilities and Cloud connectivity. This allows for more complex data processing, advanced analytics, and collaborative decision-making while minimizing latency. Fog/MEC DTs can leverage a distributed architecture and networking to share data, insights, and resources across multiple physical locations and computational nodes, enhancing scalability and fault tolerance. Cloud-based DTs provide on the other hand, the highest level of scalability and computational power. They can handle massive data volumes, perform complex analytics, and support centralized control and management of a large number of DT for complex and hierarchical scenarios. Cloud deployments are suitable for applications that require extensive data aggregation, long-term analysis, and resource-intensive computing, providing a centralized platform for collaboration, scalability, and global accessibility. The scalability of DTs allows organizations to choose the deployment strategy that best suits their specific application requirements, considering factors such as data sensitivity, processing needs, network connectivity, and resource availability. By embracing a multi-tiered approach across Edge, Fog, and Cloud computing, DTs can effectively address a wide range of use cases, from localized and time-critical operations to global-scale analytics and decision-making. This scalability fosters innovation, adaptability, and the ability to meet evolving demands in the ever-changing landscape of cyber-physical systems.

7.3.5 Interoperability

Interoperability lies at the heart of building a seamlessly connected and collaborative digital twin ecosystem. Ensuring the integration of DTs across different physical devices and digital services is pivotal in achieving a cohesive and efficient digital representation of the physical world. Interoperability involves different open challenges posed by diverse deployment environments, cross-domain integration, and the harmonization of legacy and custom protocols.

A fundamental goal is to facilitate the effortless connection of DT-enabled devices with a multitude of digital services from different manufacturers and providers in order to make DTs an effective tool that can be exploited for target business goals. This connection should be based on standard description and interaction protocols to create a seamlessly "out of the box", communication requiring minimal configuration and eliminating the need for intricate custom integrations. By establishing a common ground for communication, DTs enable devices and services to collaborate cohesively, fostering a dynamic ecosystem of interconnected entities.

Interoperability presents unique challenges in diverse deployment environments such as Edge, Fog/MEC, and Cloud. The varying computational capacities, latency constraints, and data processing capabilities of these environments demand tailored approaches to interoperability. DTs at the Edge have to support multiple communication protocols and interaction patterns to handle the interaction with the physical world and with deployed digital services emphasizing real-time interactions, ensuring rapid insights and responses. Fog/MEC DTs require efficient data aggregation and distribution and as previously mentioned represent a bridge between edge and cloud building an homogenous digital layer composed of multiple twins and a broader operational context. On the other hand, DTs in the Cloud, with their extensive resources, and the focus on comprehensive data analysis and intelligent services are exposed to different interoperability challenges driven more by the digital layer (e.g. business tools and data analysis platform) and less by the physical fragmentation.

Interoperability extends beyond deployment environments, also encompassing the support for cross-domain integration. DTs have to transcend domain boundaries, enabling collaborative interactions between different sectors, industries, and applications. This cross-domain interoperability enriches data insights, facilitates innovative collaborations, and promotes the development of holistic solutions that overcome the limitation of closing DTs into individual domains. The complexity and the challenges associated to cross-domain interoperability may significantly vary according to the deployment level with a natural increased complexity moving from the edge to the upper layer until the cloud due to the broader operational scope that characterize DTs on higher architectural layers. For example a DT digitalizing the metering of a connected building in a Smart City has a limited number of interaction points compared to the DT of a neighbourhood or scaling up of the DT of an entire city that is natively characterized by a plethora of interconnected sub-systems and domains interacting over time.

Achieving interoperability also involves the capability to support both legacy and custom protocols. DTs have to possess the ability to communicate seamlessly across a spectrum of protocols, ensuring compatibility with existing infrastructure and future innovations with a long-term vision and aiming for technological longevity. This capability empowers DTs to create a uniform and homogeneous representation of the physical world, bridging the gap between disparate systems and technologies. By fostering a standardized communication framework, DTs enhance their interoperability across diverse environments and stakeholders.

In summary, DT interoperability is a cornerstone in constructing a harmonious digital twin ecosystem. By addressing challenges across deployment environments, embracing cross-domain integration, and promoting uniform protocol support, DTs can seamlessly collaborate, communicate, and contribute to a holistic and interoperable digital representation of the physical world.

7.3.6 Discoverability

Discoverability refers to the inherent capability of entities within a networked ecosystem to be easily located and accessed by other components, applications, or services. In the context of the IoT and DTs, discoverability holds paramount importance. It ensures that IoT devices, services, and DTs can be efficiently identified and interacted with, fostering seamless integration and effective utilization across diverse environments and applications. In this challenging context, discoverability can be classified into two distinct dimensions: Service Discoverability and Resource Discoverability.

Service Discoverability pertains to the ability of entities to make their available services and functionalities known to the network. This allows other entities to identify and access the specific operations or features that a service can provide. On the other hand, Resource Discoverability involves exposing the existence and attributes of individual resources, such as data points, interfaces, or Digital Twins, allowing other entities to directly interact with these resources.

In both cases, discoverability plays a crucial role in enabling effective communication, collaboration, and coordination between IoT devices, services, and DT to enable an effective cyber-physical ecosystem with a seamless collaboration reducing as much as possible the required information and configuration to interact and communicate. By effectively implementing discoverability mechanisms, the IoT and Digital Twin ecosystems can realize their full potential, facilitating efficient data exchange, informed decision-making, and innovative applications across a wide array of domains and scenarios. The present clause (Discoverability) explores the foundational principles that drive discoverability within the realm of Digital Twins, emphasizing its significance and detailing the strategies used to achieve it in both service-oriented and resource-centric contexts.

Discoverability within DTs can be addressed through a combination of different elements that have already been mentioned such as DTD and the support for ontologies and semantic descriptions and additional requirements associated to how effectively DTs architectures can implement and enable discoverability. On the one hand, a comprehensive DT description can provide metadata about devices and services and information about the attributes, behaviours, and functionalities of twin. Furthermore, the standardization of this description can enable and serve as an homogenous format to communicate the essence of a twin, enabling other twins, systems, and applications to understand and interact with it. The introduction of Semantic Interoperability just as already applied to Web technologies can enable the adoption of standardized vocabularies and ontologies enabling a shared understanding of DTs capabilities, data, and interactions also across different application domains enhancing the contextual comprehension of DTs functionalities and facilitating effective interactions across diverse implementations, applications, and systems.

On the other hand, DTs architectures should consider in their design architectural solution to support and enable a seamless discoverability between active DTs and digital applications interested to interact with them. In this context, both centralized or distributed discovery approaches can be adopted similar for example to directories and inventories. A central repository or distributed discovery services can store and expose DT descriptions and active twins can directly publish their descriptions or register them with intermediary services, ensuring their discoverability without relying solely on a central entity and through a distributed and synchronized deployment. Also with respect to discoverability, the aim is to decouple this complexity from the digital layer allowing a simplified interaction with the cyber-physical ecosystem and allowing to focus only on their specific application goal.

7.3.7 Accountability & Manageability

Accountability represents a fundamental principle that underscores the significance and functionality of a DT. In the context of DTs, it encapsulates the essential capability of the twin to offer transparency into its operations, interactions, and the utilization of resources by associated applications. This transparency ensures that stakeholders, ranging from operators to users, possess a clear understanding of the DT's performance, behaviour, and the entanglement between its digital and physical counterparts. By providing real-time insights and historical data, accountability enhances trust and facilitates data-driven decision-making across various domains.

In the context of accountability, the possibility to observe a DT with all its properties and variation over time during its life cycle is strategic. Beyond being merely self-aware, the DT has to make its state easily accessible through standardized interfaces like RESTful APIs and event-driven communication patterns. Furthermore, the DT should expose a comprehensive record of events, encompassing execution logs, in a manner that is readily understandable and analysable. This history not only aids in immediate operational comprehension but also fuels long-term analytics based on advanced algorithms, such as those used for anomaly detection and failure prediction. This amalgamation of observability and historical context propels accountability, nurturing a higher level of understanding, monitoring, and assessment of the DT's actions.

In conjunction with accountability, manageability emerges as a cornerstone in orchestrating an ecosystem of DTs effectively. Manageability pertains to the twin's capacity to be dynamically controlled, administered, and optimized throughout its lifecycle. This includes activities like scaling resources to meet varying demands, adjusting configurations, or even migrating instances between computational nodes. Effective manageability is essential to adapt to changing requirements, address performance bottlenecks, and ensure the DT's continuous alignment with operational objectives.

The interplay between accountability and manageability empowers DTs to seamlessly integrate into complex operational ecosystems. By embracing these principles, DTs foster a transparent, adaptable, and dynamic environment. Stakeholders are equipped to assess the trustworthiness of the DT's behaviour, validate its adherence to operational standards, and confidently utilize its data and insights. Furthermore, manageability empowers administrators to optimize the DT's execution, mitigating potential issues, and enhancing overall efficiency.

In conclusion, accountability and manageability form the bedrock of a resilient and effective DT ecosystem. These principles not only ensure transparent interactions and informed decision-making but also provide the agility required for DTs to thrive in dynamic operational landscapes. As the role of DTs continues to expand across industries, their accountability and manageability will remain pivotal in driving innovation and sustainability.

7.3.8 Cross-Domain Interactions

Enabling communication across different domains within DT ecosystems is a crucial capability that fosters interoperability and cooperation among DTs operating in diverse contexts or application scenarios. This capability opens up a wide array of possibilities, facilitating the exchange of information, insights, and actions among a variety of digital and physical entities.

In many applications, different domains often use distinct protocols, data formats, and communication patterns. Cross-domain communication allows DTs to bridge these disparities, ensuring that information can seamlessly traverse between them. This interoperability is vital for creating comprehensive solutions that encompass various aspects of both the physical and digital realms.

Furthermore, cross-domain communication plays a pivotal role in ensuring scalability. In extensive applications, the DT ecosystem may span multiple domains. For instance, in a Smart City project, DTs may cover transportation, energy, and public services, each with its own domain-specific DTs. Cross-domain communication facilitates the aggregation and coordination of these DTs, providing a unified perspective of the entire city.

Collaboration among different stakeholders and systems also benefits significantly from cross-domain communication. For instance, in an industrial context, manufacturing machines (DTs in one domain) might need to collaborate with inventory management systems (DTs in another domain) to optimize production and logistics. This collaboration becomes feasible through effective cross-domain communication.

The possibility for a DT to effectively interact with both the physical and the digital worlds through a modular and dynamic design and implementation is instrumental in enabling cross-domain communication. Physical interaction flows serve as the gateway for physical twin with diverse entities in cross-domain scenarios accommodating multiple protocols and communication patterns making the DT capable of communicating with different types of assets. On the other hand, the digital interaction flows models and support interactions and communication with external digital entities such as services, application and other DTs building a unified and abstracted view of the DT's capabilities and state, shielding external systems from domain-specific complexities. The possibility to design and build a modular and flexible digital shield for a DT plays a crucial role in translating digital requests and responses, ensuring that interactions with DTs from other domains are coherent and efficient.

In this context, techniques like Replication and Composition, as previously analysed, represent powerful tools for facilitating cross-domain communication. Replication, for example, becomes strategic when dealing with cross-domain scenarios. A DT from one domain can replicate itself to communicate with DTs in another domain. This replication allows for the creation of specialized intermediary DTs that understand the communication patterns and requirements of each domain involved, bridging the gap between them. Conversely, DT Composition can establish hierarchical structures where a parent DT oversees the coordination of child DTs from different domains. This hierarchical structure streamlines cross-domain communication, as the parent DT can act as a mediator and translator between the child DTs and external entities.

In summary, cross-domain communication within DT ecosystems is a fundamental enabler of interoperability, scalability, and collaboration across various application scenarios. It relies on the adaptability of both the Physical and Digital interaction flows, along with techniques like Replication and Composition, to ensure that DTs from different domains can effectively communicate, share insights, and cooperate in the broader digital landscape. This capability and principle paves the way for innovative solutions that span multiple domains and deliver comprehensive value to diverse stakeholders.

7.4 Interoperability & Communication Functionalities

7.4.0 Communication Functionalities Overview

Clause 7.4 delves into the analysis of interoperability and communication requirements and functionalities for a DT aiming to support and address the envisioned capabilities and requirements. As previously mentioned, the effective functioning of DTs in a diverse and interconnected landscape hinges on their ability to communicate seamlessly across various communication components and interaction flows. These layers, encompassing the *physical*, *digital* aspects around the core of a DT and lay the foundation for robust interactions and collaborations between DTs and the larger digital ecosystem as schematically illustrated in Figure 10. By emphasizing the significance of structured communication flows, clause 7.4 provides an initial analysis of the characteristics and requirements and how they serve as the essential conduits for achieving interoperability, ensuring that DTs can harmoniously coexist, share data, and contribute to the broader operational landscape.

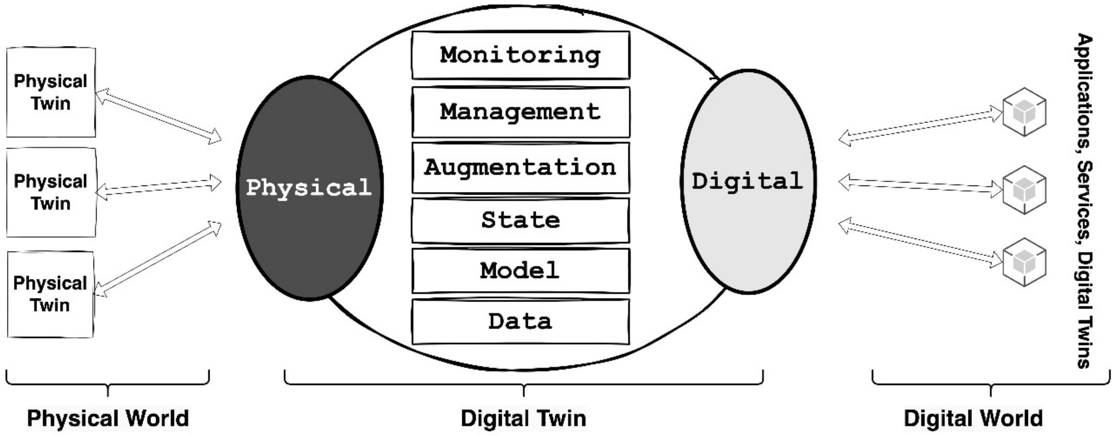

Figure 10: High level abstraction of a Digital Twin with its main physical and digital communications and interaction flows together with the main responsibilities of its core and internal modules

A DT is a complex system with several key responsibilities and modules that collectively enable its function. At its core lies the *Data* module, responsible for handling, distributing, collecting, processing, and storing information from the physical asset it represents together with the current DT's State and potentially also the history of previous states. This module serves as the foundation upon which the entire DT operates, capturing real-world data such as sensor readings, equipment status, and environmental conditions.

The *Model* module represents the fundamental core of a DT embedding the logic of reflecting and digitalizing targets PTs into a digital replica. It is intricately linked to the Data module, as it uses this data to create a digital representation of the physical asset. This digital model is also in charge of computing the new DT's State according to the received information from the physical world and the design of the DT. It encompasses the physical asset's structure, behaviour, and attributes, allowing the DT to replicate, analyse, and understand its real-world counterpart.

The *State* module plays a crucial role in maintaining a synchronized representation of the DT and its physical counterpart. It represents the status and condition of the twin as representation of the connected physical world. Through the State module, the DT tracks changes, and updates, ensuring that it mirrors the real world as accurately as possible. The State oversees structuring and maintaining the list of properties, events, relationships and actions that are available on the twin over time. The possibility of having this structured representation of the DT is also strategic taking into account interoperability opportunities where multiple DTs can share a common structure allowing external services and applications (or event other DTs) to discover available capabilities and interact with them.

In the realm of DT, having an architectural module focusing on Augmentation introduces the possibility of a layer enabling versatility and adaptability. It empowers the DT to enhance, modify, or extend its capabilities over time. By adding new properties, relationships, behaviours, and even entire components, the DT can evolve to meet changing needs and requirements.

The *Management* components should be in charge of managing the DT's lifecycle allowing external authorized entities to orchestrate its creation, deployment, operation, and eventual retirement. It ensures the proper configuration and integration of the DT into its operational context, managing its interactions with other systems and services.

Lastly, the *Monitoring* module encapsulates the responsibility for observing and assessing the DT's performance, health, and behaviour with a specific focus of the entanglement quality within the cyber-physical relationship between the DT and the associated PTs. This monitoring function helps identify issues, anomalies, or opportunities for optimization, providing insights into the DT's operation and its impact on the physical asset.

Together, these modules should represent the intricate and interdependent components that make up a DT, allowing it to bridge the physical and digital worlds, support decision-making processes, and deliver valuable insights for a wide range of applications and industries. Envisioned modules will be involved in both physical and digital communications to enable DT's cyber-physical capabilities. The next clause (Physical Communications) analyses the main responsibilities associated with both physical and digital communications of a DT and how they can involve presented core components.

7.4.1 Physical Communications

The possibility to communicate with the physical world and the target PTs stands as a cornerstone that bridges the gap between the digital and physical realms. It plays an indispensable role in shaping the DT's interoperability, communication capabilities, and adaptability, enabling effective communication among diverse physical twins (e.g. objects, devices and/or any target asset) and their digital counterparts. DT's Physical Communications serves as a conduit for the interactions between the physical world and the digital representation with the possibility to support multiple interaction forms (e.g. Pub/Sub, RESTful, etc.) and protocols (e.g. HTTP, MQTT, etc.) at the same time to facilitate the support and integration of various physical entities into the DT ecosystem. Interaction flows with the physical realm should be supported by a flexibility and adaptable structure allowing the DT to interact with diverse physical assets, detecting and translating their characteristics such as exposed properties, events, actions, and relationships into a homogeneous physical description useful for the DT to understand the nature and the capabilities of the associated physical twins. Nevertheless, this process has the responsibility to harmonize distinct protocols and data formats, promoting interoperability and addressing the native physical fragmentation and heterogeneity.

The possibility to have an effective communication is a linchpin in design and implementation of the functionality of DTs. Envisioning a modular physical communication, equipped with its versatile management (e.g. add the support for a new protocol or reconfigure an existing setup), empowers DTs to engage in meaningful exchanges with their physical counterparts. It enables the detection of physical events, the transmission of relevant information, and the synchronization of states. This fluid communication supports real-time insights and responses, making the DT a dynamic reflection of its physical counterpart.

Moreover, the utilization of multiple interaction and communication components within the same physical communication layer of the DT offers the advantage of disentangling the management from the actual communication and engagement with the physical world. This approach also paves the way for the reusability of various modules across a range of DT implementations and deployments. This approach can be useful across different application scenarios involving for example a manufacturing machine with multiple protocols, a sensor-rich device using different data formats, or a complex infrastructure characterized by both several protocols and interaction patterns. It harnesses a diverse array of adaptable components, tailor-made to suit the distinctive traits and communication requirements of various physical objects. This adaptability is not confined to singular instances but extends its reach to simultaneously manage interactions with multiple physical entities, significantly broadening the DT's reach and versatility.

Summarizing, having a structured and easy to manage Physical Communication layer on a DT plays a crucial role in converting real-world events into digital information, which perfectly aligns with the primary goal of DTs – providing practical insights for informed decision-making. It enhances the DT's ability to mimic, simulate, and coexist with the physical environment by facilitating communication, synchronization, and adaptability. In simpler terms, this fundamental capability serves as the essential link between the tangible and digital worlds. Its multifunctional nature ensures that DTs can smoothly communicate, integrate, and adjust to the ever-changing landscape of physical objects. It embodies the vision of a seamless blend between the physical and digital realms, enriching the DT ecosystem with real-time interactions and valuable insights.

7.4.2 Digital Communications

On the other hand of the Physical Communication there is a second fundamental component of the architecture of a DT associated to the Digital Communication responsibility. It is the second pivotal communication and interaction DT component responsible to facilitate the interactions between the internal dynamics of the DT and external digital entities. This layer holds profound implications for the DT's communication prowess, interoperability, and its ability to seamlessly engage with a spectrum of applications and services.

As for the physical interaction flow, plays a strategic role to interact with the physical world, the digital counterpart serves as a gateway through which the DT communicates its internal variations, events, and state to the external digital landscape and receive actions request that should be processed by its internal model and if required forwarded to the associated physical counterpart. In order to make it scalable and adaptable to different scenarios and use cases, this digital communication layer within the DT should be able to adeptly be handling digital interactions and events, ensuring that the DT's essence and functionality are effectively communicated to external applications enabling the DT to extend its influence beyond its immediate boundaries, fostering a dynamic and continuous dialogue between the DT and the broader digital ecosystem.

As a bidirectional mediator between the DT and external digital entities, this digital communication layer contributes significantly to interoperability embedding the following main responsibilities:

- expose the DT description (potentially also through multiple formats) to external digital applications in order to describe twin's nature and characteristics,
- translate internal DT variations in terms of properties, events and relationships into protocols and formats that external applications can understand and exploit for their business logic,
- map DT's actions into executable endpoints and digital interaction points through dedicated protocols and communication patterns allowing external services to trigger specific actions on the DT and if necessary, also on the associated PT.

This structural digital communication layer together with a modular design of and reusable components fortifies the DT's adaptability by extending beyond the interactions with single applications to embrace multifaceted digital landscapes. For instance, as the DT undergoes dynamic transformations, its digital communication capabilities can manage these variations, ensuring that external digital entities comprehend and respond to these changes seamlessly. This adaptability empowers the DT to remain pertinent and responsive in the face of evolving application requirements and decouple the complexity of adapting to external digital requirements from the core of the DT that remains independent and unaffected by the complexity of both physical and digital worlds.

The digital communication layer goes beyond simple data transfer. It fosters DT description and representation together with a collaborative innovation by enabling various applications to interact with the DT's insights and functions according to their need and application logic. This native digital interoperability opens a range of application scenarios, from data analysis and predictive modelling to real-time decision-making and process optimization. This layer serves as a pivotal component that enhances the DT's value proposition by positioning it as a central figure in a broader digital ecosystem acting as a bridge through which the inner workings of the DT connect with external digital entities. Its significance extends to communication dynamics, improved interoperability, enhanced adaptability, and collaborative innovation. Furthermore, the possibility to design it with a modular structure ensures that the DT's insights and capabilities remain accessible, responsive, and compatible across a wide array of digital applications and services.

7.4.3 DT's Management

At the core of DT orchestration there is the possibility to empowers authorized entities to dynamically control, configure, and manage the behaviour of DTs through their deployments. This capability should be supported and enabled by the internal core of the DT through a dedicated management component and natively integrated with DT's communications layers to support a pivotal role in enabling dynamic adaptability, efficient resource allocation, and seamless coordination and synchronization between the digital and physical realms.

The possibility to dynamically manage a DT serves as a digital control centre from which it will be possible to navigate the operational landscape of DTs. It can offer various configurable options, allowing the customization the DT's behaviour in terms of both physical and digital interaction flows together with their configuration, DT's behaviour, performance thresholds, and resource allocation to align with evolving operational needs. This dynamic governance fosters proactive decision-making, facilitating swift adjustments to DT configurations and behaviours to accommodate changing contextual requirements supporting a vision where DTs will be deployed in a structured ecosystem where it has to be managed and monitored during its life cycle following both application goals and context variations over time.

One of the primary functions of this envisioned management capability is to oversee, facilitate, and streamline the synchronization process between the DT and its physical counterpart within the cyber-physical realm. For a DT to effectively operate, it needs to continuously receive and process real-time data from the physical environment. This data is then used to construct a digital replica of the physical entity and its twin, which is subsequently exposed to the external digital world. The possibility to manage the DT shoulders the responsibility of managing both cyber-physical configurations and their execution, utilizing the necessary physical and digital modules based on the specific use case and the characteristics of the "connected" physical and digital entities.

In an ever-changing operational landscape, this envisioned capability also provides a critical mechanism for real-time adaptability. Whether responding to shifts in environmental conditions, variations in performance, or unexpected challenges, it enables prompt modifications to the DT's behaviour. This adaptability is vital for maintaining operational efficiency, predictive accuracy, and ensuring that the DT remains a dependable representation of its physical counterpart. This includes the execution of physical and digital communication components, which can be added or removed on both physical and digital communication layers as needed to respond to significant variations in the operational context and/or cyber-physical requirements. In essence, the DT's management acts as a flexible and responsive orchestrator, ensuring that the DT remains aligned with its ever-changing environment and objectives. It serves as the central point of control, coordination, and adaptability within the digital representation of the physical world. It empowers authorized actors to guide DTs instance behaviour, optimize resource allocation, synchronize operations, and ensure real-time responsiveness to changing contexts. As the orchestrator of the DT's dynamic evolution, this management architectural feature enhances the DTs ability to navigate a dynamic operational landscape while maintaining fidelity to the physical entities they represent.

7.4.4 DT's Monitoring

Another strategic and structure capability of DTs in particular in a vision where multiple instances are active at the same time is the possibility to monitor how twins operate overtime during their cyber-physical life cycle. This layer is all about capturing, conveying, and analysing the wealth of data and metrics that shed light on the DT's performance, health, and interactions associated to the entanglement with its physical counterpart.

DT's monitoring interacts with both physical and communication layers and with all the internal DT's components with the aim to act as a vigilant observer, constantly collecting real-time data on the DT's performance, how it is using resources, and its interactions. This information gives a complete picture of how the DT is doing, helping administrators assess how well it mirrors the physical asset. This empowers proactive decision-making by revealing potential areas for improvement or identifying issues.

Beyond just raw data, DT's monitoring pulls out metrics that provide insights into the DT's operational context. This context-awareness boosts the accuracy of the DT's digital representation, ensuring it stays in sync with the ever-changing physical world. By looking at metrics that show how closely the DT mimics the physical asset, the monitoring makes sure the DT accurately reflects real-world behaviour.

The DT's monitoring is not limited to providing a static snapshot of DT performance. It is also a dynamic hub for operational analytics, allowing us to spot patterns, trends, and anomalies over time. For example, by using machine learning and data analysis, twin's monitoring can be enhanced to find potential inefficiencies, predict upcoming issues, and support data-driven decisions to optimize DT behaviour.

The collected data is not just about what happened in the past; it helps us look into the future too. It contributes to predictive maintenance strategies by spotting potential issues before they become major problems. Armed with insights into the DT's operational health and performance history, administrators can make informed decisions about resources, configurations, and other adaptations to keep performance at its best.

The data gathered and presented by the monitoring components and its relationship with both physical and digital interaction flows and internal DT's modules adds to the accountability and trustworthiness of the DT. By offering a clear view into the DT's behaviour, actions, and interactions, it promotes accountability in decision-making. This transparency is crucial for building trust among stakeholders and ensuring the DT functions reliably within its operational context.

In a nutshell, this architectural requirement serves as a dynamic observatory that captures the essence of a DT's existence and interactions. Through real-time performance assessment, contextual insights, operational analytics, and proactive maintenance support, the monitoring module empowers DTs management applications to make informed decisions, fine-tune DT behaviour, and maintain trustworthiness. It acts as a bridge between the digital and physical realms, facilitating an ongoing conversation between the two and enhancing the DT's effectiveness within the broader operational landscape.

Annex A (informative): Change history

Date	Version	Information about changes
March 2023	V0.0.1	Early draft
May 2023	V0.0.2	Milestone A - Interim Draft D1
September 2023	V0.0.3	Milestone B - Final Draft D1
September 2023	V0.0.4	Milestone B - Final Draft D1 R1
October 2023	V0.0.5	Milestone B - Final Draft D1 R2
8 November 2023	V1.1.1	Final Draft approved by SmartM2M reviewed by Technical Officer
November 2023	V1.1.1	First published version

History

Document history		
V1.1.1	November 2023	Publication