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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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Introduction

In an increasingly interconnected and technology-driven world, the concept of Digital Twins (DTs) has emerged as a powerful tool in various domains. Among these domains, the urban landscape stands out as a fascinating and complex environment where DTs have immense potential. A Digital Twin (DT) refers to a virtual representation of a physical entity, such as a building, infrastructure, or even an entire city, that is synchronized and connected in real-time with its physical counterpart. In the urban domain, DTs offer a transformative approach to urban planning, development, and management. By leveraging advanced technologies like the Internet of Things (IoT), Artificial Intelligence (AI), big data analytics, and cloud computing, DTs enable a comprehensive understanding of urban systems and facilitate data-driven decision-making.

DTs for the urban domain go beyond traditional 2D maps and static models by incorporating real-time data streams from sensors, cameras, and other devices embedded throughout the city. These data streams provide a continuous flow of information on various aspects of urban life, including traffic patterns, energy consumption, air quality, infrastructure health, and social dynamics. By capturing and analysing this wealth of data, DTs create dynamic, virtual replicas that mirror the behaviour and characteristics of the physical urban environment. One of the key benefits of DTs in the urban domain is their ability to simulate and predict outcomes. Urban planners, architects, and policymakers can use DTs to model different scenarios and assess the potential impact of changes in the urban landscape before implementing them. This predictive capability helps optimize resource allocation, enhance sustainability, improve infrastructure design, and ultimately create more liveable and efficient cities.

Furthermore, DTs enable enhanced situational awareness and real-time monitoring. City officials and emergency responders can use DTs to monitor critical infrastructure, detect anomalies, and respond swiftly to incidents or emergencies. By integrating data from various sources, such as surveillance cameras, weather sensors, and social media feeds, DTs provide a holistic view of the urban environment, fostering proactive and informed decision-making. However, the adoption of DTs in the urban domain comes with challenges. Ensuring data privacy and security, managing the complexity of integrating diverse data sources, addressing interoperability issues, and gaining public trust are some of the hurdles that need to be overcome. Additionally, the scalability and sustainability of DT ecosystems require careful consideration to ensure their long-term viability. Despite these challenges, DTs have the potential to revolutionize urban planning and management. By harnessing the power of technology, these virtual replicas provide invaluable insights, empower decision-makers, and enable the creation of more sustainable, resilient, and inclusive cities. As urban populations continue to grow and cities face unprecedented challenges, DTs offer a promising pathway towards a smarter and better-connected urban future.

The present document provides an analysis of the utilization of DTs in the urban field, with a specific emphasis on interoperability. The adoption of existing standards and the utilization of semantic-based solutions have been surveyed to determine their implementation. Furthermore, a comprehensive examination of the SAREF suite in relation to various use cases is discussed together with the identification of the priority gaps that need to be addressed in the near future.

1 Scope

The present document provides an overview of the DT landscape for the urban domain. It is also discussed how the DT domain has been addressed from the standard perspectives by presenting the existing ones by also including a deeper overview about how ontologies have been employed to manage interoperability aspects. The present document also lists a set of use cases is presented in order to depict concrete implementation of DTs to use as starting point for an interoperability analysis. Finally, the present document provides preliminary insights about how the SAREF Core ontology, and its extensions can be exploited to support interoperability aspects within the DTs domain.

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 non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

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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): set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level

ontology: formal specification of a conceptualization, used to explicit capture the semantics of a certain reality

real time: timespan sufficient for the entity to accomplish the task for which the entity has been built

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
BIM	Building Information Modelling
DT	Digital Twin
IoT	Internet of Things
JSON	JavaScript Object Notation
OWL	Web Ontology Language
RDF	Resource Description Framework
SAREF	Smart Applications REFerence ontology
TR	Technical Report
TS	Technical Specification
XML	Extensible Markup Language

4 Digital Twins Landscape for the Urban domain

In Europe, more than 74 % of the population resides in cities [i.1]. As urban populations grow, challenges arise, but so do potential solutions [i.2]. With effective management, a city rich in human capital has the potential to become a hub for exporting innovative solutions, often referred to as an 'innovation machine' [i.3]. Such a scenario is desirable as innovations bring economic benefits and enhance citizens' quality of life [i.4]. However, it is not straightforward for city management to assemble such a machine. Instead, what they truly seek is an ecosystem. By organizing all stakeholders, including private companies and public entities, in a well-coordinated manner, there is a promise of improved economic efficiency [i.5]. Due to the complexity involved, centrally managing the system stifles its dynamics. Hence, the solution lies in an ecosystem that incentivizes participants to align themselves appropriately. This ecosystem leverages the core strengths of each player to foster innovation, operates dynamically, and can be guided through a process called orchestration [i.6]. Orchestration entails harmoniously organizing activities through effective planning, enabling informed decision-making, and avoiding costly impromptu problem-solving. Digitalization aids in activity planning by ensuring essential information is readily available and facilitates stakeholder involvement, ensuring everyone is informed with the latest updates. This is why DTs hold value for cities.

DTs were first established in manufacturing [i.7] and [i.8]. Then, they have been used in several other domains like construction [i.9] and [i.10], facilities management [i.11] and [i.12], industrial maintenance [i.13], and smart city applications [i.14], [i.15] and [i.16]. Depending on the domain in which a DT is used, different types of interaction with the physical world is implemented. Figure 4-1 shows a summary of the main types of interaction between DTs and the physical world.

A holistic city DT differs from previous ones by accommodating various levels of detail specific to different local areas. Given the presence of buildings from different time periods within a city, it becomes necessary to scan and integrate them into the DT. These scanning efforts, along with updates, typically occur incidentally during other activities, resulting in internal variations in the level of detail across different areas and themes. When a construction or maintenance project takes place in a city district, that specific area is meticulously scanned, leading to a locally detailed update. The remaining parts of the city DT remain unaffected and retain their previous level of detail. However, a city DT should adhere to the original concept of digital planning for a collectively shared model, similar to its application in manufacturing. To effectively serve ecosystem orchestration, a city DT has to also consider human factors. It entails not only the characteristics of a computer model but also the organization of everyday services within the city to facilitate collaborative planning in a shared digital model. Striking a balance between technocracy and democracy is crucial to genuinely involve stakeholders. Consequently, if any changes are made to an existing city, digital planning should address the resulting consequences on the dynamics of the city. Moreover, this digital planning should be accessible to third parties for testing new services and alterations to city plans.

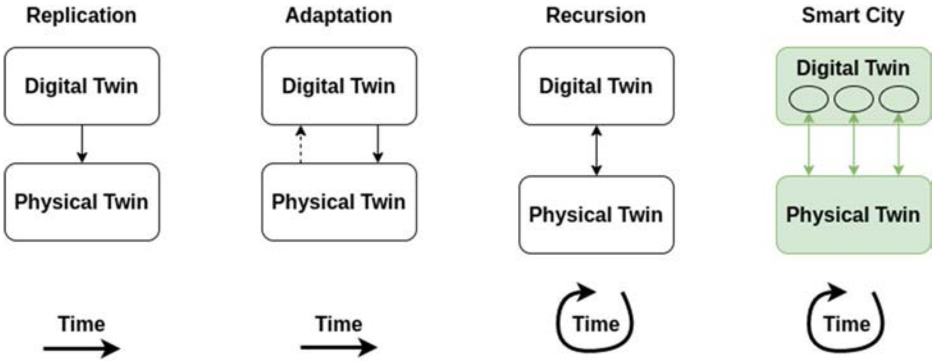

Figure 4-1: Summary of the main types of interactions between DTs and the physical world

Certain DT techniques provide advantages to city management, as observed in Helsinki [i.17], Zurich [i.18], and Vienna [i.19]. Although these DTs fall under the same DT umbrella [i.20], they possess distinct characteristics and cater to different purposes. One can argue that they represent evolving DTs that lie between maintenance-focused DTs and comprehensive city DTs, effectively addressing a wide range of urban requirements.

Therefore, it is conceivable to inquire about the usefulness of DTs in addressing the needs of cities. What should be included in a DT of a city and how should it be regularly updated (as shown in Figure 4-1) to serve a dynamic ecosystem and improve its efficiency? It can be argued that a DT of a city would represent the ultimate achievement in digitizing city assets and services, consisting of the following four components:

1) The foundation of the DT should be designed to meet the city's specific requirements.
2) The DT should support a wide range of content with varying levels of detail, including well-developed Building Information Modelling (BIM) information, as well as less detailed content that accounts for local variations.
3) Keeping the DT up to date is crucial due to the continuous changes that occur in a city. This involves automated updates from sensor systems, such as Internet of Things (IoT) sensor networks, drones, and robotic cars, as well as data collected through professional surveying.
4) To ensure the benefits of interacting with DTs, it is essential to have secure and user-friendly systems that enable agents to visualize and share information effectively, enhancing decision-making processes. Considering human factors is crucial in identifying the potential advantages and future applications of DT systems in supporting city decision making.

5 Digital Twins and Ontologies

5.1 Introduction

Previous studies on DT models, as described by Grieves [i.21], consisted of three main components:

i) a physical environment encompassing real-world physical entities;
ii) a virtual environment consisting of digital objects and computational tools; and
iii) a connection for data and information exchange between the physical and virtual environments.

Grieves and Vickers [i.22] further classified DTs into three sub-types:

i) a DT prototype that includes requirements and models related to the concept of a physical entity;
ii) a DT instance that represents a specific physical entity throughout its entire lifecycle; and
iii) the DT environment, which is an integrated, multi-domain physics application space where DTs operate and abide by the laws of physics and relevant rules.

Another more advanced model suggests five dimensions for DTs [i.23]:

i) a physical environment;
ii) a virtual environment that encompasses all models representing physical entities;
iii) services executed by the DTs, such as model execution, visualization, machine learning prediction, task allocation, and maintenance;
iv) data accessible to the DT from both the physical and virtual environments; and
v) connections linking all the dimensions together.

In contrast to the three-dimensional model, the 5D model distinguishes between data and communications, and additionally incorporates services within the DT domain, typically provided externally to the virtual environment where the DT's settings and properties are defined, such as on a cloud platform.

The creation of a DT involves a computational process that consists of various computational services representing models for each stage of the process and their interactions. As a result, DT platforms need to effectively coordinate these independent services to offer both flexibility and computational efficiency. To achieve this, a DT platform should encompass different levels of abstraction, as follows [i.24]:

- DT User Level: At this level, users can access the available DTs through applications designed for this purpose.
- DT Developer Level: This level of the platform provides resources and tools for developers to create and customize DTs.
- Computational Service Developer Level: The platform also offers an API (Application Programming Interface) for developers to build computational services that can be integrated into the DT ecosystem.
- Infrastructure Provider Level: Here, the platform facilitates the allocation of computing resources by mapping instances of the computational services to the appropriate computing infrastructure.

The initial step in establishing a DT's ontology involves delving into the concept of a model. Since a DT's virtual environment consists of representations of the physical environment, it is important to define what a model entails. Referring to a model as an artifact that abstracts a system or process from a specific perspective [i.25], it is possible to identify several distinct aspects:

i) the idea of modelling itself, which is considered a universal concept of modelling;

ii) a model as a representation that includes information, rules, methods, and premises, such as a 3D model or a class model;

iii) a model of a particular type, serving as a prototype, like a 3D model of a car; and

iv) an individual model, such as a 3D model of John's car.

It is worth noting that a model universal refers to a type whose instances are models since each model embodies a specific modelling concept (e.g. 3D Model, 2D Model). General model universals can be specialized subtypes of model universals, representing prototypes that individual models have to adhere to in terms of properties, dispositions, and modes. The same entity can be represented by models instantiating different prototypes, which are specific subtypes of model universals.

Therefore, it is essential to have a comprehensive theory with multiple levels [i.26] to define how a model fits into a DT ontology. This theory should cover various aspects such as power-types and categorization schemes, which are integral parts of the subject matter [i.27]. According to Guizzardi et al. [i.27], a prototype can be seen as a power-type that has variable embodiments, which classify instances of individual models. A variable embodiment is an individual entity that, in each scenario, adopts a specific fixed embodiment - a group of individuals related to each other - based on a given principle. Consequently, a prototype can possess overarching properties that describe that particular variable embodiment, including properties derived from instances of models associated with an individual classified by the prototype. It can also have regularity properties that capture patterns observed across instances of a specific type, as well as direct properties of the type itself, but not of any individual instance [i.27].

DTs are commonly associated with objects like cars, spacecraft, or oil platforms, as well as agents like people, companies, or societies. While it is possible to model events and moments, the focus of DTs is typically on these objects and agents. In the real world, an event occurs and involves the object or agent of interest. This event needs to be mapped to a corresponding event in the digital world that reflects the real situation and involves the model. Similarly, a moment that exists within an object or agent can be abstracted into a moment that exists within the model of that object or agent. In our context, the term "real-world" refers to the part of reality that pertains to the object or agent of interest and other relevant individuals. The real world may be considered as a complex situation comprising situations in which these individuals participate.

5.2 Standards for Digital Twins

ISO, IEC, ITU, and IEEE are prominent standard development organizations that are actively involved in standardization efforts pertaining to DT technologies, among others. These organizations have been diligently working on the development of standards for DTs and related technologies.

The purpose of this clause is to align the DT-related standards with the DT model consisting of five dimensions, as introduced in [i.103]. Figure 5.2-1 illustrates these dimensions, each of which encompasses specific standards related to DTs or DT technologies. It is important to note that there are numerous other standards related to DTs that are not explicitly mentioned here, such as those concerning physical entity definition, data format, and interface standard, as they were not specifically created for DTs.

Apart from the five key points, the definition of a DT serves as a fundamental aspect for the application of DTs. However, there is currently no consensus among standard organizations regarding the definition of a DT. For instance, ISO 23247-1 [i.28] defines a DT in the manufacturing field as a "fit for purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization". Conversely, in the field of smart cities, ITU- Y.scdt-reqts defines a DT as "a digital representation of an object of interest" [i.29].

Given the variation in DT standards across different application scenarios and objects, it is necessary to establish a comprehensive definition that clarifies and defines the core concept of a DT. Efforts are currently underway to develop this potential standard in the committee draft ISO/IEC AWI 30173 [i.30].

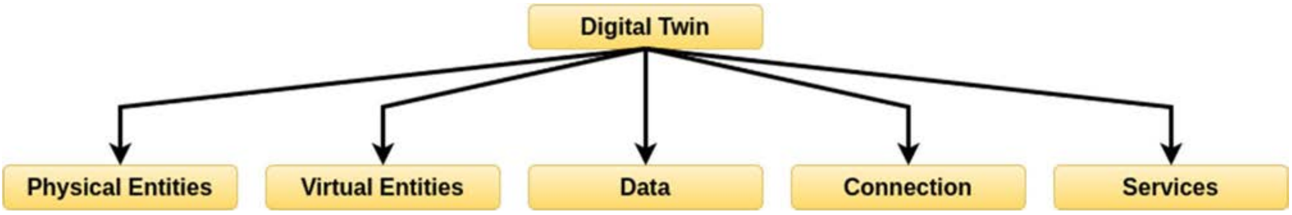

Figure 5.2-1: Summary of the different dimensions related to DTs which existing standards refer to

Physical entities: A DT system incorporates physical entities that fulfil two primary roles: data collection and device control. These physical entities serve as sources of data and units that activate actions for virtual entities. The definition of physical entities within DT standards can slightly vary across different fields, as they are tailored to specific application scenarios. While there is no universally published standard for physical entities in DTs, it is possible to leverage and refer to existing standards, such as fieldbus profiles, companion specifications, and other specifications that define properties of devices and components. These standards should be converted into standardized dictionaries, and standardized dictionaries should also encompass the characteristics of conceptual assets like planning documents.

Table 5.2-1: List of existing standards concerning the Physical Entities dimension

Physical Entities standard	Description
IEC 62832-1 [i.32]	It expands the definition of logic objects to include intangible things such as software, concepts, patents, ideas, methods, and anything that could define as an asset of the industry.
IEEE 1451 [i.33]	It provides a common interface by creating a self-descriptive electric datasheet and a network-independent smart transducer object model, which allows sensor manufacturers to support multiple networks and protocols, thus facilitating the plug and play of sensors to networks.
IEEE 2888.1 [i.35]	They define the vocabulary, requirements, metrics, data formats, and APIs for acquiring information from sensors and commanding actuators, providing the definition of interfaces between the cyber world and physical world, but the standard series are still in progress.
IEEE 2888.2 [i.36]	
ISO 23247-2 [i.31]	It identifies the "physical" object as an "observable manufacturing element", which includes personnel, equipment, materials, facilities, environment, products, and logical objects such as supporting documents and processes.
Recommendation ITU-T Y.4473 [i.34]	It specifies the Application Programming Interface (API) which provides a framework to interconnect Internet of Things (IoT) devices, data, and applications over the Web, thus managing and retrieving observations and metadata from heterogeneous IoT sensor systems.

Virtual entities: A DT system utilizes virtual entities to represent physical entities in a digital form. These virtual entities consist of models that describe physical entities across different time periods and spatial scales. When working on standardizing DTs, it is advisable to employ established modelling standards. However, it is important to note that certain elements like gateways and cameras, which are essential in both manufacturing and smart cities, require collaboration among multiple communities to fully capture their significance and complexity.

Table 5.2-2: List of existing standards concerning the Virtual Entities dimension

Virtual Entities standard	Description
IEC 63278-1 [i.37]	It defines a semantic model that describes characteristics of assets, which is the serialization and exchange format between models, submodules, and Asset Administration Shell (AAS).
ISO 23247 [i.38]	It promotes the usage using existing modelling standards for implementing the standard
ISO 23247-3 [i.39]	Those standards are not intentionally developed for the DT, but those standards can satisfy most of the use cases with implementation of XML, JSON, RDF, AML, OPC-UA, and any other common data description language or format.
ISO 10303 [i.40]	
IEC 62264 [i.41]	
IEC 62714 [i.42]	
IEC 13399 [i.43]	
IEEE P2806 [i.44]	It proposes digital representation for DT, it defines high-speed protocol conversion, unified data modelling, and data access interfaces for heterogeneous data situations in the DT.

Data: The DT relies heavily on data as its main driving force. Within the DT system, the various models and representations of information do not operate independently. Instead, they collaborate with other DT systems through data and model exchange. As a result, it becomes crucial to establish standardized data structures and properties, including default values, data types, and data formats. Many existing data processing standards can be employed to achieve most of the data-related technologies in the DT. However, special attention is required when it comes to processing and managing data associated with virtual entities. For instance, the models in the DT system change dynamically in response to alterations in the physical entities. Consequently, standardized properties such as timestamps and validity statements become necessary. Another aspect to consider is that data generated by virtual entities should be easily distinguishable from that produced by physical entities, necessitating identification standards that account for these unique features. These specific requirements may prompt updates to existing standards or the creation of new ones.

Table 5.2-3: List of existing standards concerning the Data dimension

Data standards	Description
ISO/IEC guide-77 [i.45]	Those standards set up a fundamental rule for data exchange, and standardized the data element type, data structures, data library and data type element for the industrial system.
ISO 13584 [i.46]	
IEC 61360-1 [i.47]	
ISO 29002 [i.48]	
IEC 61987 [i.49]	

Connection: The concept of connection pertains to the interaction and compatibility that collectively facilitate the interlinking between entities. The presence of a DT network and connectivity is crucial for deploying a DT. This connection goes beyond simply exchanging data between different DT systems; it also encompasses the transmission link itself. In contrast to traditional IoT communication systems, the DT necessitates enhanced transmission capabilities, such as greater determinism, higher broadband, improved synchronization, and other augmented features. These enhancements are vital for improving DT services and catering to various application needs. Although there are numerous existing standards that can be reused, there are still several essential steps to be taken regarding DT and DT networks. Firstly, it is crucial to specify the types of equipment and parameters that should be taken into account for network interoperable management. Considering the numerous networks and connectivity standards already published by 3GPP, IEC, and IEEE, it is necessary to determine the extent of standardization required for DT implementation. Secondly, the term "real-time" is a fundamental characteristic of the DT; however, there is currently no standardized definition or quantification of this term for different industries. Therefore, it is necessary to consolidate parameters and methodologies for evaluating real-time communication and establish a uniform definition within a standard. Thirdly, while the standard for the network DT has been proposed, it primarily focuses on the core network or cell network, neglecting proximity networks such as TSN, OPC UA, field bus, and Ethernet, as well as their integration. Hence, a unified standard is needed for the DT proximity network to effectively monitor and manage all coexisting networks, enabling a seamless transition.

Table 5.2-4: List of existing standards concerning the Connection dimension

Connection standards	Description
IEEE 2888.3 [i.50]	This standard provides a framework overlooking interactions between general objects in cyber and physical world cyber and physical world, including capabilities to interact between physical things and digital things (cyber things), capabilities to easily integrate with backend infrastructure / integrate with other external systems, capabilities to access to things by authorized parties, capabilities to describe physical devices, virtual devices, or anything that can be modelled.
OPC UA [i.51]	It supports data transmission, but it also contains the information-centric data model, thus transfers heterogeneous data into unified information, which enables the secure data exchange industrial systems.
IEEE 802.3 [i.52]	Those standards offer solutions for wired communication to fulfil the high requirement of the DT.
IEC 61158 [i.53]	
IEC 61784-2 [i.54]	
IEC 62591 [i.55]	Those standards provide flexibility and mobility for wireless connectivity.
IEC 62601 [i.56]	
IEC 62734 [i.57]	
IEC 62948 [i.58]	
IEC 62657-1 [i.59]	It provides the requirements for a wireless spectrum that specifies the predictable performance of wireless devices in multiple wireless network coexistence environments, and it provides coexistence management concepts and processes.
5G ACIA [i.60]	It explores the integration of 5G with Time-Sensitive Networking for Industrial Automation and Integration of OPC UA with 5G network for coexisting network management.
Y.DTN-ReqArch [i.61]	It specifies network resource management to provide analysing, diagnosing, simulating, and controlling the physical network based on the network DT.
ITU X.sg-dtn [i.62]	It describes security considerations and security requirements for DTN, it also provides countermeasures to strengthen the security, which could be helpful for the DTN security improvement.

Services: DTs serve the purpose of delivering services. A comprehensive collection of user cases from different fields is documented in a standard reference. However, there are several crucial steps that have to be taken to enhance DT services. Firstly, it is necessary to address certain characteristics specific to DT services, such as establishing connectivity between the DT service and the virtual entity. This entails updating certain DT service standards, including the framework for testing DT services, ensuring Quality of Service (QoS) for DT services, and managing DT services, among others. Secondly, there is a lack of non-functional QoS standards for DT services, such as scalability and reusability, as well as a deficiency in a test benchmark for evaluating DT services. Thirdly, there is currently no standardization of the DT service level. Despite the introduction of a recommendation proposal for the DT maturity model in ITU-T SG20 [i.104] in May 2021, it was ultimately rejected. This issue requires collaborative efforts from the DT community and will significantly impact the roadmap for implementing DTs in various vertical domains. Although there are already existing service standards, even though they were not specifically designed for DT services, they can still be leveraged to address DT-related challenges.

Table 5.2-5: List of existing standards concerning the Service dimension

Service standards	Description
ISO 23247-4 [i.63]	It describes model DTs of product, process, and resources for dynamic scheduling of manufacturing tasks between multiple robots.
IEEE 2888.4 [i.64]	It proposes an architecture for virtual reality disaster response training system with six degrees of freedom.
ITU-T Y.DTN-ReqArch119 [i.65]	This draft presents several use cases about DT networks.
ISO 13372 [i.66]	Those standards refer to DT service description.
ISO 17359 [i.67]	
IEEE 1671 [i.68]	
IEEE 1232.3 [i.69]	Those standards relate to standard service testing within various domains, such as industrial automation system, Information Technology (IT) integration, information technology application, IT terminal and other peripheral equipment, interface, and interconnection equipment, and so on.
IEEE 1904.1 [i.70]	
ISO 20242-3 [i.71]	
ISO 20242-4 [i.72]	
ISO/IEC 14393 [i.73]	
Recommendation ITU-T E.800 [i.74]	It provides a set of commonly used terms in the study and management of Quality of Service (QoS) where the technical and non-technical terms related to the QoS are listed.
Recommendation ITU-T G.1010 [i.75]	It defines service QoS as the comprehensive effect of service performance that determines the satisfaction of service users by defining the support capability, operation capability, business capability, and security of all parts of service performance.
Recommendation ITU-T G.1000 [i.76]	It divides quality of service QoS into different functional parts, and links them with corresponding network performance. It expounds the QoS criterion from four aspects: customer QoS requirements, QoS provided by the service provider (or planned/targeted QoS), QoS obtained or delivered, and customer perception QoS.
Recommendation ITU-T E.802 [i.77]	It defines the framework and methodologies for the determination and application of QoS parameters.

5.3 Usage of Ontologies for Digital Twins

A classical definition of ontology defines it as a formal and explicit specification of a shared conceptualization [i.78]. In this sense, ontologies represent a conceptual model of a part of the (real or virtual) world and include interlinked concepts concerning a given application domain [i.79]. Focusing on the urban domain perspective, several works have addressed the use of ontologies [i.80], [i.81] and [i.82].

Ontologies are essential instruments in DTs as they allow the modelling of the physical or virtual entities of the world in terms of concepts and relationships, facilitating understanding and representing complex systems related to DTs. These knowledge representation models describe the structure, behaviour, and function of physical or virtual systems, allowing diverse stakeholders (e.g. engineers, designers, etc.) to develop accurate and realistic models of them on the digital side. Additionally, ontologies are an essential component of DTs to enable interoperability and exchange of information between different DT systems, which is crucial in developing large-scale and complex systems.

The use of semantics is also crucial in DTs since it enables the interpretation of data and information in a meaningful way. Semantics provides a common language and meaning for data and information, allowing for more efficient communication and collaboration between different stakeholders involved in developing and operating DT systems. Moreover, semantics facilitate the development of intelligent systems that can reason and make decisions based on the knowledge represented in ontologies.

Furthermore, ontologies are critical to dealing with heterogeneous data sources associated with DTs. Their utilization allows integrating multiple and heterogeneous sources of data, managing a large amount of data in distributed environments, validating the correct operation of the DT, standardizing the communication between all pieces that interact with the DT, or managing different actors [i.83] and [i.84].

Considering the five dimensions of DTs [i.23], the presence of ontologies in each one is essential since it plays a crucial role in ensuring the effective operation of the DT systems. Here is a breakdown of the importance and usage of ontologies in each dimension:

1) Physical Entities. DTs dynamically simulate attributes, operating states and evolution laws of physical entities in the real environment and digitize expert knowledge that could never be maintained before [i.85]. In this line, ontologies enable the accurate representation of physical entities for DTs. They allow the creation of precise digital models of physical components, including their geometry, material properties, and behaviour, among other aspects.

2) Virtual Entities. These entities are defined as computer-generated representations of the physical artefact, for instance, a component, vehicle, model, system, product, etc. [i.8]. Generally, a DT is defined based on virtual entities that exhibit similar behaviour to their physical counterpart and are coupled to this physical entity [i.86]. In this context, ontologies represent virtual entities in the DT. They allow designers and engineers to create digital models of virtual components, including their behaviour and function.

3) Data. DT systems handle large volumes of data from various of their components that are collected and managed. These data are spread out in diverse repositories and are rarely shared [i.87], remaining as data silos. Ontologies allow the structuring of multiple and heterogeneous kinds of data available in the DT, connecting to their respective semantics to promote retrieval, interpretation, and exploitation of data associated with physical and virtual entities.

4) Connection. One of the main challenges of the DT connection is the heterogeneity of the equipment that composes the networks. In this sense, ontologies can create a semantic representation of the network and characterize its behaviour [i.88]. Additionally, ontologies in semantic DTs permit the connection between physical and virtual entities. They allow homogeneity of the data exchanged between the physical and virtual model, enabling consistent communication without losing information.

5) Services. Ontologies are used for providing diverse services with distinct purposes in DT systems. Herein, services related to rule-based reasoning, supervised and unsupervised Machine Learning, simulations, etc. appear in [i.89], [i.90] and [i.91].

In summary, ontologies and semantics are crucial for effectively developing and operating DTs across all five dimensions. They enable accurate representation of physical and virtual entities, effective data management and analysis, modelling and simulation of the system, representation of the connection between physical and virtual entities through a common language, effective management and provision of services, meaning for data and information, and facilitate communication, collaboration, and interoperability between different DT systems or elements. Finally, this leads to more efficient and practical complex system design, operation, and maintenance [i.83] and [i.84].

6 Urban Digital Twins Use Cases

6.1 UC1: Rome, Rinascimento III Area

DESCRIPTION: This use case involves integrating ICT-based digital techniques with energy management systems to enhance effectiveness, automate repetitive tasks, and optimize decision-making processes. The objective is to develop a robust approach that combines ICT, IoT, big data, and AI potential. These technologies interact with BIM models, enabling the creation of three-dimensional information and predictive systems for energy management. The project, led by the CITERA Interdepartmental Centre at Sapienza University of Rome, explores the potential of merging digital-twin models with AI systems. The aim is to find a specific application where this methodology can be implemented effectively. The case study focuses on developing an efficient DT model for a residential district in Rome. The goal is to improve energy efficiency and identify a cost-effective solution that reduces both consumption and expenses.

DATA MANAGEMENT: The infrastructure begins with a subsystem that can handle different communication protocols and time frames. Its primary output is the synchronized power consumption or production data from smart metered devices. The second component allows control over specific devices by commanding the aforementioned subsystem to turn them on or off. This second element needs to be physically located near sensor networks to ensure smooth connectivity and enable local environment monitoring, even without a connection to the central control system. These elements are collectively referred to as "Elettra".

In the second architectural element, each subsystem is represented by a separate "proxy." These proxies receive the outputs of the first subsystem as input and address network reliability and bandwidth issues by transmitting data to the central unit and receiving it back from the same device. The central control system serves as a centralized unit responsible for data storage, processing, controlling digital simulation models, and issuing commands to the proxies. It is essential for the proxies to be physically close to the first subsystem.

To implement this infrastructure, multiple inexpensive small computers or System on Chips (SoCs) were required. Each computer houses both the "Elettra" subsystem and the proxy subsystem. These computers are interconnected with a powerful server located in a data center. This server runs the software for the central control system.

INTEROPERABILITY ANALYSIS: In the context of information management in construction processes using BIM methodologies, interoperability has been tackled through the utilization of three distinct standardization models. These models are the Industry Foundation Classes (IFC), the CityGML, and the Information Technology Vocabulary (ISO/IEC 2382 [i.105]). While current research predominantly concentrates on information exchange, IFC and CityGML have been chosen due to their status as the primary semantic models for configuring object-oriented information management systems. By combining IFC and CityGML, an enhanced 3D city information model is being pursued.

STANDARDIZATION ACTIONS: The use case refers to the adoption of the IFC standardization model. The SAREF4BLDG extension has been built starting from such a model. Hence, it is a good candidate to start the construction of the DT model described in this use case. The SAREF4BLDG extension covers partially the IFC model, but it may be flanked by several new concepts supporting the complete description of the DT.

6.2 UC2: West Cambridge Campus

DESCRIPTION: The paper attempts to describe a system architecture for DTs specifically designed for the building and city levels and targeted to the Architecture-Engineering-Construction & Facilities Maintenance (AEC/FM) sector. A small research pilot was developed at the West Cambridge site of the University of Cambridge of a single academic building as a case study, and an even smaller commercial pilot built some 3-D diagrams of several buildings along with an IoT sensor data analysis of one pump.

DATA MANAGEMENT: Based on these implementation experiences, the authors proposed a multi-tier architecture that would enable the integration of heterogeneous data sources, support effective data querying and analysing, and support decision-making processes in Operations & Maintenance management. They stated their significant data management challenges as: data integration, heterogeneity in source systems, data synchronization and data quality. University firewall policies forced the consolidation of data from local IoT sources (e.g. MySQL databases) into a NoSQL cloud database.

INTEROPERABILITY ANALYSIS: The proposed hierarchical architecture would be implemented in different scales from individual assets (e.g. pump), buildings, up to cities organized into five layers: data acquisition layer, transmission layer, digital modelling layer, data/model integration layer and service layer. There is no mention of any event processing. It was recognized that exchanging information across data source boundaries makes interoperability a primary issue. The authors propose solving this issue with Industry Foundation Classes (IFC) files, an Open Data schema and set of formats used to store Building Information Modelling (OpenBIM) data. The authors did not mention that the quality of vendor support for IFC data varies significantly between software.

STANDARDIZATION ACTIONS: Their recipe for successful development of building and city DTs requires:

1) a clear objective for DT construction;
2) a clear definition of DT value;
3) a well-designed and practical process of collecting, updating, transferring and integrating IoT data and its model throughout the life cycle through federated services;
4) a well-executed and standardized interoperability procedure and data compatibility plan for curation and further possible evolution;
5) a valid performance strategy that promotes security, openness, and quality.

Analysing the value and usefulness of integrating city-level information was not discussed.

6.3 UC3: City of Sofia

DESCRIPTION: This use case presents the preliminary results from creating a CityGML 2.0-compliant 3D model of the city of Sofia [i.92]. It explains the 3D transformation of proprietary geospatial data into the CityGML schema. A 3D model of the terrain and buildings at a district scale is created, covering the territory of district Lozenets of Sofia city. A crucial issue is the integration of buildings and the terrain. Problems arise due to the float of the buildings over or sinking into the terrain. Thus, an interpolation of the building's footprints is performed. Additionally, the buildings' features are enriched with address information.

DATA MANAGEMENT: The buildings' data is stored in a PostGIS database and exported in shapefile format. In addition, a Digital Surface Model (DSM) and Digital Elevation Model (DEM) were provided in .tiff format. The data source coordinate reference system is BGS2005 / CCS2005 (Bulgaria Geodetic System 2005, EPSG: 7801), which Sofia city generally uses. The buildings have 11 attributes, such as cadastre region, function, floor count above the ground, apartments count, footprint area, etc. The addresses are described with 12 attributes, including district, neighbourhood, street name and number, postal code, etc.

INTEROPERABILITY ANALYSIS: This use case handles interoperability by applying a widely adopted standard as CityGML. This standard enables the reusability and interoperability of 3D models over different applications. Until now, it is mainly used to model buildings due to their dominant role within the urban environment and lack of data for other thematic objects such as road infrastructure, underground networks and utilities, water bodies, etc. Additionally, this approach tries to achieve interoperability of the 3D city model with other relevant data sources and systems, such as real-time sensor data, weather forecasts, and other data sources, to enable decision-makers to make informed decisions promptly.

STANDARDIZATION ACTIONS: The use case promotes interoperability of the 3D city model, adhering to their approach to international standards such as CityGML and Open Geospatial Consortium (OGC) standards. It ensures the 3D city model can be easily integrated with other systems and data sources, allowing seamless data exchange and interoperability.

6.4 UC4: Digital Twin Victoria

DESCRIPTION: Digital Twin Victoria (https://www.land.vic.gov.au/maps-and-spatial/digital-twin-victoria) is a program to create a virtual replica of the State of Victoria, Australia. The program supports developing the digital foundations for a future-ready Victoria, employing data to reply to new questions and make better data-led decisions. Their vision is to create Victoria online so that government, industry and the community can collaborate through shared open data, technology and algorithms to enhance real-world results and set the State as a place of relevant data and innovation. This program will unlock value for Victorians through economic recovery through digital workflows that reduce red tape, smarter and faster government services through digital data and platforms, and stronger and more resilient communities through spatial technology.

DATA MANAGEMENT: The Digital Twin Victoria platform provides a collaborative digital workbench that connects local, state and national data owners with users. The extensive shared data catalogue provides access to more than 4 000 datasets, including 2D, 3D and live data visualizations. It includes 3D building data of Melbourne and regional locations, detailed 3D photo meshes of Melbourne and regional towns and locations such as the Great Ocean Road, live state-wide data feed for energy production and Phillip Island penguin habitat comparison between 1997 and 2019. Also, this platform features a suite of tools to visualize, compare and analyse spatial data, including the ability to measure objects in the virtual world, explore at street level using the pedestrian mode, use the timeline to see the shadow moving through the day, save 3D data using our clipping tool, share views created with other users and use a slider to compare datasets.

INTEROPERABILITY ANALYSIS: Interoperability is crucial for ensuring the success of Digital Twin Victoria. So, this use case asserts that their DT system has to be interoperable with other systems and data sources, including real-time sensor data, traffic management systems, and other smart city technologies. This will enable decision-makers to make informed decisions in a timely manner based on accurate and up-to-date data.

STANDARDIZATION ACTIONS: The use case covers a broad set of different types of data: maps, 2D and 3D spatial data, images, sensor data, etc. applied to different domains such as Building Information Models, traffic, utility, urban planning, etc. These data are usually represented using standards and in some cases they can be represented using the SAREF ontology and its extensions.

6.5 UC5: Smart Construction Digital Twin

DESCRIPTION: The use case presents a real-time digital representation (twin) of a construction project, utilizing methods to ensure interoperability among diverse components and technologies constituting their DT ecosystem. It considers the construction phase embedded and a part of the construction project design and lifecycle thread rather than in isolation. In that way, upstream information like the as-designed model is employed as input. This use case has been developed in the COGITO H2020 project (https://cogito-project.eu/).

DATA MANAGEMENT: An ontology model allows:

a) construction stakeholders to have live access to information about the state of the construction site provided by real-time monitoring of worker, equipment, tool and material monitoring (aligned with the lean construction principles);

b) evolution of the BIM model as the process evolves to mirror the as-build status through input from a multitude of reality capture tools;

c) automated and real-time geometric tolerance compliance checking (using data acquired by robotic systems, like drones) with communication to stakeholders (including Building Control authorities);

d) on-the-field guidance to construction workers - through wearable device applications - and real-time asset monitoring for real-time safety management;

e) more efficient planning and scheduling of construction steps with optimal resource (human, material, equipment, etc.) allocation including real-time readjustment to counter contingencies or actual discrepancies between plans and construction; and

f) documenting and evolving the digital infrastructure of the construction project and create functional tests to ensure proper installation and programming.

INTEROPERABILITY ANALYSIS: Interoperability has been addressed in the specific case of information management in construction processes based on BIM methodologies by adopting the Industry Foundation Classes (IFC) standardization model. Also, there are other types of information, such as the schedule to create with the IFC the 4D BIM and information about resources (human and equipment). All of this information is linked to enriching the 4D BIM model.

STANDARDIZATION ACTIONS: The DT requires a deep understanding of the BIM standards and how the various BIM layers are interlinked into an information exchange framework. Some of them have worked in the past in semantic enrichment of earlier BIM models toward establishing the nDBIM, which encapsulates schedule, time, and cost information on top of the structural construction attributes. The BIM standards need to be structurally and semantically analysed to design an appropriate methodology for incorporating dynamic information in the existing standards, considering the potential requirements of innovative digital tools for construction stakeholders. Relevant ISO 19650-1 [i.93] definitions related to BIM and well-known definitions of the DT concept [i.94] are being analysed to propose new definitions linking BIM to DTs.

6.6 UC6: Interoperable Urban Digital Twins

DESCRIPTION: Cities are complex systems where different DTs may be developed for different verticals (e.g. mobility, environment, health). This use case motivates the need for semantic interoperability and coordination mechanisms between DTs for a transversal application. In the event of a heat wave, the objective is for a city to distribute groceries to vulnerable peoples and check if they are in good health. This use case relies on four different specialized DTs: a Digital Twin for eHealth/Ageing-well (DT4EHAW), a Building Digital Twin (DT4BLDG), an Environment Digital Twin (DT4ENVI), and a Logistics Digital Twin (DT4LGST). Two main issues are tackled:

1) identify the vulnerable people;

2) optimize visits. Inhabitants may be considered vulnerable if they are known to be isolated elderly people, living in poorly insulated dwellings, in heat island areas.

The cost of visiting rounds directly depends on the number of persons to visit, that is why vulnerable people need to be identified precisely.

DATA MANAGEMENT: DT4EHAW contains information about inhabitants such as their age, address, isolation and autonomy levels. It also harvests data from their wearables, forecasts health issue evolutions, and can generate a ranking of the most vulnerable persons and their addresses. This knowledge is combined with the insulation quality of the buildings at these addresses. This is done by DT4BLDG that runs a machine learning model trained on territorial open data about buildings whose construction year and insulation level is known. DT4ENVI is used to decide which address is the most affected by heat waves, and when. This DT modulates national notifications about heat waves with urban planning data, weather forecasts, and real-time temperature data measured at different places in the city. To detect potential heat islands (See for example, https://territoire.emse.fr/solutions/?type=geobuilding). The three DTs are combined to rank every morning vulnerable people that live in poorly insulated dwellings located in heat islands. Based on this ranking the city can then organize distribution using a fleet of vehicles, which uses a distributed DT4LGST that uses real-time vehicle positions and traffic conditions (See for example https://territoire.emse.fr/solutions/?type=geodelivery). Distribution routes may be re-optimized during the day according to real-time traffic events or if DT4EHAW reports that a person's wearables detect heat exhaustion.

INTEROPERABILITY ANALYSIS: Different DTs specialized in different verticals need to interoperate for a transversal application. Machine-to-machine platforms such as oneM2M may need to coordinate with regional decision support platforms such as the Plateforme Territoire (https://territoire.emse.fr) Decision as a Service (DaaS) to support this use case.

STANDARDIZATION ACTIONS: SAREF is a clear solution to the cross-domain semantic interoperability required in this use case, as these four DTs may model data using different SAREF extensions such as SAREF4EHAW, SAREF4BLDG, SAREF4ENVI, SAREF4AUTO, which are using common core ontology patterns.

7 Analysis of SAREF with respect to the Urban Digital Twin context

7.1 Introduction

This clause links the use cases discussed above with the ontologies that are part of the SAREF suite. In particular, it has been reported how the concepts modelled within SAREF Core and a subset of 7 SAREF extensions may be useful in the context of DTs and how they may represent a basis to define a novel, and missing, standard to describe DTs.

The selection of the eligible SAREF extensions has been performed by analysing the information that were relevant within each use case. At the end the clause, it has been reported a table summarizing how each module included in SAREF Core or in one of its extensions relates to the use cases described in clause 6.

7.2 Analysis of SAREF Core

This clause provides insights on how the SAREF (core) [i.95] ontology may be used in the context of urban DTs. SAREF focuses on the representation of IoT devices and their capabilities as well as of the measurements provided by those devices. The following parts of SAREF can be applied in the context of urban DTs:

- Devices and their capabilities. SAREF enables the representation of IoT-related devices and their capabilities (e.g. tasks, functions, etc.). Device information is highly relevant in urban DTs because it provides contextual information that allows a better processing and understanding of urban data.

- Features of interest and their properties. Features of interest and properties can be represented with SAREF; furthermore, the ontology does not impose strong restrictions on these components, so they can be easily specialized for the urban domain. Features of interest (i.e. the relevant physical and their virtual models) appear in every urban DT scenario.

- Measurements. IoT measurements are a central component of the SAREF ontology. They also appear in every urban DT due to the need for synchronization between the physical and digital worlds, either as one-time events or for dynamically updating the virtual representation in the DT.

- Services. The services exposed by a device can be represented using SAREF. In urban DTs, the semantic representation of services enhances the interaction and communication both internally inside the DT and externally among the DT and other systems.

- Profiles. SAREF supports the representation of profiles associated to devices about certain properties (usually related to some utility). Profile information is relevant for any urban DT that includes utility information (e.g. electricity, water, gas).

7.3 Analysis of SAREF Extensions

SAREF4BLDG [i.96] is an extension of SAREF for the Building domain that extracts devices and other physical objects from the Industry Foundation Classes (IFC) standard version 4 for building information. It can contribute to the modelling of DTs in the urban domain with the following concepts.

- Spatial things. Classes s4bldg:Building, s4bldg:BuildingSpace and s4bldg:PhysicalObject are subclasses of the class geo:SpatialThing in order to reuse the conceptualization for locations already proposed by the geo ontology. Properties enable to model simple topologies of buildings.
- Taxonomy of devices. SAREF4BLDG contains a taxonomy of 62 classes that reflects the subset of the IFC hierarchy related to devices, as defined in the buildingSMART documentation. Core classes include:
    - s4bldg:DistributionControlDevice;
    - s4bldg:DistributionFlowDevice;
    - s4bldg:ShadingDevice;
    - s4bldg:TransportElement;
    - s4bldg:VibrationIsolator.

SAREF4LIFT [i.97]. The Smart Lifts domain benefits from an extension of SAREF, which offers a conceptual model for the installation and data representation of smart lifts. This extension enables the monitoring and analysis of smart lifts' operations. It serves as a valuable conceptual model that can be integrated with the SAREF4BLDG extension to facilitate an interoperable representation of buildings within an urban DT. The SAREF4LIFT extension comprises four modules, each described below along with a summary of their significance for modeling a DT in the urban domain:

- *Systems and connections.* This module establishes the various systems present in a smart elevator setting. These systems have the capability to be interconnected. Interconnected systems engage in interactions with one another. The modelling of these systems and their connections plays a significant role in defining the digital representation of an entire building, known as a DT. Consequently, this information can be utilized to simulate an entire virtual urban environment.
- *Devices and commands.* This module establishes the components present in a smart lift. A device is described as a physical item created to fulfil a specific function. These devices make up the individual parts of a smart lift system and can also contribute to creating a more comprehensive representation of an urban DT. By utilizing commands, simulations can be conducted on the DT that has been constructed.
- *States and measurements.* This module establishes the categories in which significant aspects of a smart lift installation can be identified, as well as the various measurements that can be taken regarding those aspects. By incorporating these concepts along with the device and command categories, it becomes possible to analyse simulation outcomes and gain a more comprehensive comprehension of a particular scenario.
- *Signals.* This module provides an overview of the signal types that a smart elevator can handle. An application example of incorporating these signal representations into a DT involves creating virtual scenarios for engineers to evaluate various behaviours and their effects on overall building management.

SAREF4AUTO [i.98] is an extension of SAREF for the automotive domain. SAREF4AUTO is designed to connect to existing ontologies such as ETSI TC ITS for V2V communications, the SENSORIS data model for exchanging data between vehicles and cloud services, and the DATEX II standard for information exchange between traffic management centres, traffic information centres and service providers. The primary use case of the SAREF4AUTO extension represents the complete flow of vehicular traffic (including disruptions) within an urban domain. The SAREF classes Device, Measurement, Property, FeatureOfInterest and State are fundamental to the operation of a DT. SAREF4AUTO classes derived from FeatureOfInterest represent the primary objects in the automotive domain: RoadEntity, RoadObject, and Vehicle. AutomotiveObject represents vehicles, personal devices, traffic management centres, and roadside communication hubs. The Confidence class represents the accuracy of vehicular speed, acceleration, and position Measurements.

The VehicleEnvironment class describes the local environment a vehicle senses while it moves on the road. The VulnerableRoadUser class represents objects in that environment which can possibly move in front of the vehicle's path: pedestrians, bicyclists, motorcyclists, and animals. Specialized classes derived from Property represent the various configurations of vehicles, their position, speed, and acceleration. SAREF4AUTO extends the SAREF core ontology with the State class and the hasState property to define the various states in which vehicles, platoons and parking resources assume over time (by electric and automated vehicles, in particular). Traffic and parking regulation classes include ParkingSpot, RoadSideActuator (e.g. TrafficLight), RoadSideSensor, and ElectronicControlUnit. A parking map topology for the automotive domain identifies which electric vehicle recharging stations are unavailable, reserved, occupied, or available. SAREF4AUTO assumes the GeoSPARQL ontology describes all traffic routes. The Vehicle class is central to SAREF4AUTO as it is sub-classed from AutomotiveObject, FeatureOfInterest, and System.

SAREF4AUTO can easily accommodate other common urban domain situations such as where and when there has been a vehicle accident, and railroad crossing environments.

SAREF4ENVI [i.99] is an extension of SAREF for the environment domain, focusing on light pollution. It has two main aims: on the one hand, to be the basis for enabling the use of SAREF in the environment domain and, on the other hand, to exemplify how to enable interoperability between environmental devices in cooperation. It adds to SAREF Core the following classes and properties, that may be for interest for DTs in the urban domain:

- *Actuators affect properties.* s4envi:Actuator has been added in order to represent devices that can act (s4envi:affectsProperty) over properties. Although there exists saref:Actuator, the property s4envi:affectsProperty may prove useful.

- *Systems composition and communication.* system can be composed of other systems and this is represented by the property s4envi:hasComponent and its inverse s4envi:isComponentOf. A system can also be connected to other systems, represented by the s4envi:isConnectedTo property. The communication protocol and interface that a system might use are represented by the classes s4envi:CommunicationProtocol and s4envi:CommunicationInterface, respectively.

- *Digital representations of objects.* Services that allow the access to digital representations of a given physical object (e.g. devices, sensors, etc.). The main entity in this model is s4envi:PhysicalObject that represents a general class for devices and systems and any other entity with a physical representation in order to make the model extensible to other domains. Such object can have digital representations (s4envi:DigitalRepresention) that can be accessed through services (saref:Service). In addition, the digital representation can be linked back to the physical object that it encapsulates by means of the property s4envi:encapsulates, defined as inverse of s4envi:hasDigitalRepresentation. It is worth noting that s4envi:hasDigitalRepresentation is defined as inverse functional since a digital representation can encapsulate only one object. Finally, the relation between a physical object and its location is represented by the reused property geo:location. In addition, s4envi:PhysicalObject is declared to be subclass of geo:SpatialThing.

SAREF4CITY [i.100]. This extension has been created by investigating resources from potential stakeholders of the ontology, such as standardization bodies (e.g. Open Geospatial Consortium), associations (e.g. Spanish Federation of Municipalities and Provinces), IoT platforms (e.g. FIWARE) and European projects and initiatives (e.g. ISA2 programme) as reported in ETSI TR 103 506 [i.106]. It adds to SAREF Core the following classes and properties, that may be for interest for DTs in the urban domain:

- *Topology:* In the SAREF4CITY ontology existing models have been reused when needed in order to increase interoperability and reduce effort in modelling general domains. As an example, for modelling the requirements related to the topology domain, standard ontologies already developed have been reused and connected to the SARE4CITY elements. For representing spatial objects the geosp:SpatialObject class from GeoSPARQL has been reused along with its subclasses geosp:Feature, geosp:Geometry and the properties geosp:sfContains, geosp:sfWithin and geosp:hasGeometry. In addition, the class geo:Point and the property geo:location have been reused from the W3C de-facto standard for geographical information "WGS84 Geo Positioning vocabulary" in order to be able to indicate that something is located at certain coordinates.

- *Administrative Area:* The model describes administrative. In this sense, the ability to connect administrative areas (e.g. a city) with their inner areas, (e.g. its neighbourhoods) is given by inheritance of the geosp:SpatialObject class and through the geosp:Feature class. That is, as s4city:AdministrativeArea is subclass of geosp:SpatialObject, the geosp:sfContains and geosp:sfWithin properties could also be applied to all the administrative areas defined, namely s4city:City, s4city:Country, s4city:District and s4city:Neighbourhood.

- *City Object*: The model represents city objects. The ability to connect city objects with the city or with the parts in which they are located is enabled by means of the properties geosp:sfContains and geosp:sfWithin inherited from the geosp:SpatialObject class.

- *Event*: The main concept of this pattern is the class s4city:Event. Such event is linked to the agent organizing it by means of the s4city:organizedBy property. A public administration is a subclass of agent; therefore, this model includes the possibility of events being organized by public administrations as well as by other types of agents. The events can take place at a particular facility (s4city:Facility) which is indicated by the s4city:takesPlaceAtFacility property and at a given time, which is represented by the s4city:takesPlaceAtTime property that links the event to temporal entities (time:TemporalEntity) defined by the W3C Time ontology. Finally, as events can be part of bigger events, this relation has been modelled by means of the property s4city:isSubEventOf.

- *Measurement*: The modelling of measurements in the SAREF4CITY ontology totally relies on the measurement model proposed in SAREF. This modelling includes the saref:FeatureOfInterest class that provides the means to refer to the real world phenomena that is being observed in the given measurement. To reduce duplication with SAREF documentation, the reader is referred to the SAREF specification for details about SAREF modelling including here details only for the new concepts.

SAREF4ENER [i.101] should be used to annotate (or generate) a neutral (protocol-independent) set of messages to be directly adopted by the various manufacturers or mapped to their domain specific protocols of choice. SAREF4ENER is an OWL-DL ontology that extends SAREF with 63 classes, 17 object properties and 40 data type properties. SAREF4ENER focuses on demand response scenarios, in which customers can offer flexibility to the Smart Grid to manage their smart home devices by means of a Customer Energy Manager (CEM). The CEM is a logical function for optimizing energy consumption and/or production that can reside either in the home gateway or in the cloud. Moreover, the Smart Grid can influence the quantity or patterns of use of the energy consumed by customers when energy-supply systems are constrained, e.g. during peak hours:

- PowerProfile: This clause presents the classes of interest for smart energy management. These classes are used to schedule devices in certain modes and preferred times using power profiles to optimize energy efficiency and accommodate the customer's preferences. These classes are s4ener:PowerProfile, s4ener:Alternative, s4ener:PowerSequence and s4ener:Slot.

- PowerSequence: The s4ener:AlternativesGroup consists of one or more power sequences (s4ener:PowerSequence class) and, inversely, a s4ener:PowerSequence belongs to only and exactly one s4ener:AlternativesGroup.

- Slot: The s4ener:PowerSequence consists of one or more slots (s4ener:Slot class) and, inversely, a s4ener:Slot belongs to only and exactly one s4ener:PowerSequence.

- LoadControl: This module defines how to model events used in, for example, a direct load management and power curtailing scenarios. The classes of interest are s4ener:LoadControlEventData, s4ener:LoadControlEventAction, s4ener:LoadControlStateData and s4ener:LoadControlState.

SAREF4WATR [i.102] focuses on extending SAREF to create a common core of general concepts for water data oriented to the IoT field. The main idea is to identify the core components, as mentioned, that could be extended for water subdomains, for example, for water supply:

- Measurement: The modelling of measurements in the SAREF4WATR ontology mostly relies on the measurement model proposed in SAREF. In order to reduce duplication with SAREF documentation, the reader is referred to the SAREF specification for details about measurement modelling including here details only for the new concepts. SAREF allows to define the temporal extent of a measurement by defining the timestamp for it (using the saref:hasTimestamp property). However, the SAREF4WATR extension also required to be able to define the temporal interval to which a measurement applies, apart from the temporal instant defined by the timestamp. Therefore, the s4watr:hasPhenomenonTime property has been defined in this extension to define the time for which the measurement applies to a feature of interest. The range of this property time has been defined as a time:TemporalEntity, which allows defining temporal intervals or instants.

- Water meter: the representation of water meters and their properties has been extracted from the European M-Bus standard (EN 13757-2 [i.107]). A water meter may be defined by the properties inherited from SAREF (e.g. saref:hasManufacturer or saref:hasModel) and also by a set of properties defined in SAREF4WATR to indicate:
    - its fabrication number (s4watr:hasFabricationNumber);
    - its firmware version (s4watr:hasFirmwareVersion);
    - its hardware version (s4watr:hasHardwareVersion);
    - its version (s4watr:hasVersion);
    - the radio frequency in which it operates (s4watr:operatesAtRadioFrequency); and
    - its required power (s4watr:requiresPower).
- Water flow: Water meters are mainly intended to measure water flows. SAREF4WATR defines the main properties related to the water flow that are defined in the European M-Bus standard (EN 13757-2 [i.107]):
    - pressure (s4watr:FlowPressure);
    - rate (s4watr:FlowRate);
    - temperature (s4watr:FlowTemperature); and
    - volume (s4watr:FlowVolume).
- Tariff: SAREF4WATR allows describing the tariff that is applied to a water meter by means of the s4watr:Tariff class. The representation of tariffs has been extracted from the TR 17167 [i.108]. A tariff may be described using different properties to describe its:
    - start timestamp (s4watr:hasStartTimestamp);
    - duration (s4watr:hasDuration);
    - period (s4watr:hasPeriod);
    - billing date (s4watr:hasBillingDate); and billing period (s4watr:hasBillingPeriod).

  Besides, a tariff can be related to a water meter by means of the s4watr:appliesTo property.
- Water types: SAREF4WATR defines four types of water as instances of the s4watr:Water class:
    - raw water (s4watr:RawWater);
    - drinking water (s4watr:DrinkingWater);
    - storm water (s4watr:StormWater); and
    - waste water (s4watr:WasteWater).

  All these types of water are defined as features of interest (saref:FeatureOfInterest), so measurements and key performance indicators can be defined over them.
- Water properties: SAREF4WATR includes a classification of the different water properties based on the classification proposed by the World Health Organization [i.4]. Water properties (s4watr:WaterProperty) are classified into acceptability (s4watr:AcceptabilityProperty), chemical (s4watr:ChemicalProperty), and microbial (s4watr:MicrobialProperty) ones, being bacterial (s4watr:BacterialProperty) properties a subclass of microbial ones.
- Water infrastructure: In SAREF4WATR water infrastructures can be defined using the s4watr:WaterInfrastructure class. Such infrastructures may be designed for one of the water types through the s4watr:isDesignedFor property, may have an intended use (through the s4watr:isIntendedFor property), and may be classified into five different types, although others may be defined if needed:
    - distribution systems (s4watr:DistributionSystem);

- storage infrastructures (s4watr:StorageInfrastructure);
- treatment plants (s4watr:TreatmentPlant);
- hydroelectric power plants (s4watr:HydroelectricPowerPlant); and
- monitoring infrastructures (s4watr:MonitoringInfrastructure).

Table 7.3-1 shows the suitability of the SAREF extensions described above with respect to each use case described in clause 6.

Table 7.3-1: Results of the suitability analysis of SAREF Core and Extensions to contribute to the modeling of the use cases described in clause 6

SAREF Module	Use Case 1	Use Case 2	Use Case 3	Use Case 4	Use Case 5	Use Case 6
SAREF Core	X	X	X	X	X	X
SAREF4BLDG	X	X	X	X	X	X
SAREF4LIFT		X	X		X	X
SAREF4AUTO	X	X	X		X	X
SAREF4ENVI	X	X	X		X	X
SAREF4CITY	X	X	X	X	X	X
SAREF4ENER	X	X	X		X	X
SAREF4WATR	X	X	X	X	X	X

The analysis of the six use cases reported in Clause 6 combined with the SAREF Core and Extensions highlighted several aspects that should be considered towards the possible expansion of the SAREF suite and, at the same time, to fulfil the gaps in building interoperable DTs. They have been identified two priority gaps:

1) to enhance the interoperable communication between entities composing a DT; and

2) to enable the modelling of time series to represent how a DT evolves through time.

Overall, existing standards lack the capability of both generalizing the representation of DTs and, above all, to model the interactions between the entities involved in a complex DT. The urban domain is a significant scenario in which such gaps come to light since there is the need of creating the digital version of different types of entities that should be able to communicate among them, i.e. to allow the composition of different DTs. The communication aspect is fundamental to create the DT of an urban domain since it works as enabler to simulate the interaction between the different types of entities through, for example, the exposure of specific services allowing each entity to gather information from the others. Moreover, the analysis of the standards performed in clause 5.2 put the light on the fact that a lot of effort has been put related to defining the standard of low level, or physical, networking or transport. On the contrary, it is the opposite about the information that gets exchanged between the component of a DT and regardless the details of how such information is transported. This issue is replicated also within the SAREF suite since the capability of modelling such services is missing, i.e. the requirement of composability is not satisfied. The straightforward recommendation is to propose the definition of conceptual model, possibly through a new SAREF extension, supporting the composability of services exposed by different devices. This may be considered a potential solution to enhance the overall capabilities of the SAREF Suite and, at the same time, to contribute to the definition of a new standard within the DT scenario.

The creation and the management of a DT includes the requirement of representing how such a DTR evolves through time. By starting from this requirement, the definition of a methodology to model time series is needed since no standards are currently available, neither a semantic representation in SAREF. Time series serves as the ultimate reference for truth since they play a crucial role in validating the authenticity of your DT. Another advantage of having a standard for time series lies in its ability to act as a data source for AI-based systems, enabling aggregation and presentation of data in a manner that enhances the AI-based solutions' value proposition through intelligent insights.

Furthermore, it can be envisioned as a data management service, possibly even referred to as AI-based, with the capability to efficiently collect time series databases to satisfy the requirements of detecting time-based situations, better defining contexts, and representing events of interest.

Both priority gaps should be addressed through extending SAREF with the needed semantic capabilities to enable the creation of effective and interoperable DTs.

8 Conclusion

In the future, the DT is expected to play a significant role across various industries, revolutionizing the design, development, and operation processes. It offers advanced capabilities that go beyond the current level of life cycle management. Key DT technologies, such as models, data, connections, and communication, are driving the digital transformation of different sectors. However, as the concept and technologies surrounding DT become more mature, the need for a well-established standard system becomes crucial. Such a system would expedite the engineering implementation of DT, enhancing clarity, ensuring quality, and promoting service delivery.

The present document serves as a comprehensive literature review, providing essential background information and establishing the current state of the art for DTs. The analysis of technical standards for DT is organized into five dimensions: the physical entity, the virtual entity, data management, connections, and services. The standards are examined, and the corresponding challenges are identified, along with proposed suggestions for addressing them. It is important to note that due to the complexity of DT technologies, this work primarily focuses on the key technologies and overall architecture of DT. Many other detailed techniques, such as modelling tools, platforms, development processes, and other engineering techniques, have not been extensively explored. These standards should be customized by individual companies or industries to align with their specific requirements.

The present document aims to assist practitioners in gaining a comprehensive understanding of the latest trends in DT technical standards. Additionally, it provides valuable insights for companies seeking to implement DT applications by explaining the standards from five different perspectives. Furthermore, the findings presented here serve as guidance for the development of standardized ideas for DTs.

Finally, the reported analysis shows the SAREF suite can be employed to model complex urban DTs given the absence of standard. It has been discovered that to fill the gaps between the current version of the SAREF suite and the definition of complex urban DTs further concepts aiming to model device services and time series are required. Such identified gaps identified will be discussed in ETSI TS 103 828 [i.109] through the definition of the guidelines about how to use SAREF in the context of Urban Digital Twins and with Digital Twins and how it may be extended, if needed.

History

Document history		
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