Semantic Interoperability of Digital Twins in Smart Cities

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***Abstract**. Semantic Interoperability of digital twins in smart cities is crucial for improving the efficacy and compatibility of digital twins' communication, which will result in improved smart cities and lifestyles. Without constant interoperability improvement, it will be impossible to effectively communicate and share information between digital twins. This paper examines the possibility of interoperability enhancement focusing Microsoft Azure Digital Twin Definition Language (DTDL) and discusses future research ideas that could contribute to the enhancement of Azure DTDL.*

Keywords. digital twin, interoperability, smart city, azure dtdl

1 Introduction

Semantic interoperability refers to the ability of different devices to communicate and exchange information with each other in a meaningful way. In other words, these systems can understand and interpret the data they receive from each other, even if they use different languages or formats to represent those data. Achieving semantic interoperability is essential to ensure that different systems can work together seamlessly and efficiently, which is particularly important in fields such as healthcare, finance and government, where accurate and timely data exchange is critical (Nilsson & Sandin, 2018).

Digital Twins of Smart Cities (DTSC) are virtual replicas of physical cities that use data to simulate and analyse the behaviour of the city in real time. These digital models can be used to improve city operations, improve urban planning, and improve the overall quality of life of citizens. The digital twins of smart cities rely on semantic interoperability to gather and analyze data from various sources, such as sensors, cameras, and other IoT devices, to provide a comprehensive view of the city's activities (Deren et al., 2021).

Semantic interoperability is a crucial component in the development and implementation of DTSC, as it enables the seamless exchange and analysis of data from multiple sources, ultimately leading to more efficient and sustainable urban environments.

By achieving semantic interoperability, digital twins of smart cities can provide accurate and timely insights into the functioning of a city, allowing policymakers and urban planners to make informed decisions and implement effective strategies for sustainable development (Raghavan et al., 2020)(Yang et al., 2021).

In addition to improving decision-making, semantic interoperability also facilitates enhanced collaboration between different stakeholders involved in the development and management of smart cities. With a shared understanding of the data and its meaning, different departments and agencies can work together more effectively towards common goals, leading to greater efficiency and effectiveness in city operations. Furthermore, semantic interoperability also promotes transparency and accountability, as all stakeholders have access to the same data and can work together to ensure that the city is being managed in the best possible way (Raghavan et al., 2020).

Semantic interoperability can enable the automation of processes and workflows, reducing the time and effort required to perform tasks (Raghavan et al., 2020). By enabling different systems to work together, semantic interoperability can help foster innovation and the development of new solutions and services (Yang et al., 2021).

The existing problems regarding semantic interoperability in the context of smart cities and digital twins include technical issues related to data collection, retrieval, exchange, analysis, and processing, data sovereignty issues, and the lack of a unified approach to data exchange that takes into account the semantic relationships between different systems and their data. These challenges make it difficult to achieve seamless data exchange and integration between different systems and stakeholders in smart cities and digital twins.

According to Lehtola et al (Lehtola et al., 2022) in the context of smart cities and digital twins, there are some existing problems regarding semantic interoperability. These problems include the need for semantic recognition of data pieces that represent objects in the city, such as buildings. It also shows challenges of ensuring that different digital twins used in the city are interoperable and can communicate with each other effectively. Therefore the need for standardization of data formats and communication protocols to ensure interoperability between different digital twins and smart city systems.

This paper focuses on achieving semantic interoperability of digital twins in relation to DTDL implementation while relying on an ontology-based approach supported by MS Azure DTDL. The rest of the paper is organized as follows: Section 2 describes the current state of digital twins, smart cities, and the challenges of achieving semantic interoperability. Section 3 represents the reference model presented in the paper for building an interoperable system of systems supporting the implementation of smart cities and digital twins. Section 4 uses the reference model as a guide to demonstrate a framework for achieving semantic interoperability in digital twins of smart cities. Section 5 proposes future research ideas to improve the interoperability. To conclude, Section 6 summarizes the key points of the article.

2 Background

2.1 Digital twins and smart cities

A digital twin is a virtual copy of a physical system, which can be designed, tested, manufactured, and applied in a virtual environment. It is a set of virtual information constructs that are designed to fully describe a potential or existing physical manufactured product. In simpler terms, it is a digital representation of a physical object that contains all the attributes and behaviors of the real-life object through modeling and data.

A smart city is a city that uses advanced technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and data analytics, to improve the quality of life for its citizens, enhance sustainability, and optimize urban services. In the context of the paper, a smart city is conceptualized as a digital twin that includes the infrastructure, human dynamics, spatial and temporal information flow, and physical and virtual connectivity of a city.

According to Du et al (Du et al., 2020), using a digital twin model to collect cognitive data and analyze cognitive patterns under different information cues to create a personalized information system that reduces the risk of cognitive overload for people in a smart city. The personalized information system will tailor information based on the cognitive digital twin model of each person. This model will tell the system what information format to use, when to use it, and how to use it. This will make information delivery in a smart city more efficient and effective, making life better for the people who live there and making the most of urban services. So, the digital twin makes a smart city better by making it possible to create a personalized information system that reduces mental overload and improves the way information is delivered.

The definition of "semantic interoperability" is the use of the same language or framework between different systems and devices so that they can communicate with each other and share data. It is important to use the same frameworks, ontologies, and standards to make sure everything works together. But there are still problems that need to be fixed in order to make semantic IoT work better in smart cities (Nahhas, 2023).

2.2 Examples of existing architectures and standards for data exchange in smart cities and digital twins

The concept of "Common European data spaces", as in Figure 1, which refers to a rich pool of data that varies in accessibility and can flow freely across sectors and countries while fully respecting the General Data Protection Regulation (GDPR). It has several aspects related to the management of data that need to be considered in order to make smart cities and digital twins a reality. These aspects include technical issues related to collecting, retrieving, exchanging, analyzing, and processing data, data sovereignty issues, and data semantics, features, and metadata specifications. *For example, the European Union data strategy describes the creation of ”data spaces”, and explicitly conceives these as multiple interoperating data spaces for different domains* (Atkinson et al., 2022).

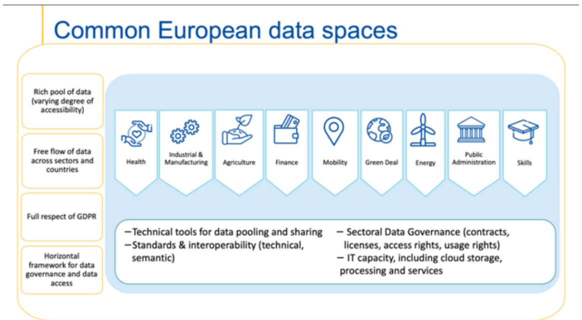

Figure 1. Common European data spaces (Dataspaces, 2023)

Common European data spaces refer to a concept of creating a shared platform for data exchange and collaboration among different sectors and countries in Europe. The Figure 1 shows a visual representation of the Common European data spaces, highlighting the different components involved in maintaining the flow of information among them.

DPA stands for Data Privacy-preserving Automation architecture. It is a backend computing architecture proposed in the research paper (Xiao et al., 2018) to facilitate online privacy-protection processing automation and secure data privacy. The DPA architecture can be seamlessly integrated with companies' principal application system in an interruption-free manner, allowing for adaption to flexible models and quality of service (QoS) guarantee for cross-entity data exchange.

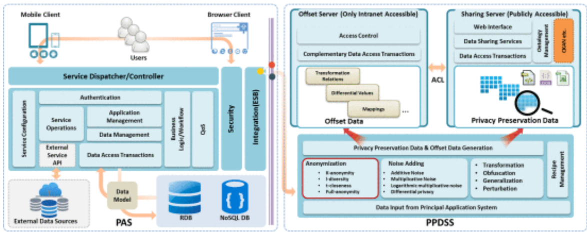

Figure 2. Examples of existing architectures and standards for data exchange in smart cities and digital twins (Xiao et al., 2018)

Data Privacy-Preserving Automation Architecture (DPA) is designed to automate the process of protecting data privacy while sharing information across different entities. The goal is to create a cooperative information sharing ecosystem that can bridge the gaps between different domains and enable advanced intelligence for smart cities (Xiao et al., 2018).

2.3 Challenges of achieving semantic interoperability

The main concern of the DT is the data and data management systems. Much research has been conducted focusing on the issue specifically based on IoT sensors and its data collection. *The main technological infrastructure is indeed dedicated to sensors and data management like FIWARE or Azure DT* (Sottet & Pruski, 2023).

However, ensuring data quality remains a challenge, as the data collected from different sources may vary in accuracy, completeness, and consistency. Another challenge is the interoperability of different data management infrastructures, which may use different data formats and standards (Nilsson & Sandin, 2018). Overcoming these challenges requires collaboration between different stakeholders, including government agencies, private companies, and academic institutions, to establish common standards and protocols for data collection, management, and sharing. With the right approach, semantic interoperability can unlock the full potential of digital twins.

Considerably crucial issues include data security. DTSC would remain to be attracted to hackers as it surrounds by potential information from all around the world. At the same time, DTSC is extremely hard to secure as each point of vulnerability can open a gate to overall DTSC (Raghavan et al., 2020).

Data analysis is essential as it enhances both interoperability and DT autonomy generally. The challenge arises from the data itself, which poses problems during collection, cleaning, and structuring before being fused for deeper meaning and used to process intelligent tasks (Raghavan et al., 2020)(Boje et al., 2020).

Without a doubt, implementing semantic interoperability can be costly, especially for smaller cities or organizations with limited resources (Yang et al., 2021). However, financial perspective of implementation is beyond the scope of this paper. Rather, this research focuses on ontology of semantic interoperability.

Semantic interoperability is important because it makes it possible for different systems, such as DT and non-DT systems like Computerized Maintenance Management System (CMMS) or Enterprise Resource Planning (ERP), to communicate and share information in a useful way. It makes it possible to combine data and models from different fields, which is necessary for making decisions in asset maintenance management that are based on DT. Without semantic interoperability, people may not agree on what data and models mean, which can lead to wrong interpretations and bad decisions. Because of this, semantic interoperability is a necessity for achieving efficient and proactive maintenance strategies that can improve the availability of assets and reduce downtime in a way that is both cost-effective and time-efficient (Ariansyah & Pardamean, 2022).

3 Reference Model

Atkinson et al (Atkinson et al., 2022) in their paper, proposed a reference model (Figure 3) for building an interoperable system of systems (SoS) that supports the implementation of smart cities and digital twins. The model consists of three components: Global Domain, Operational SoS, and Consumer System. The Global Domain refers to the overall environment in which the SoS operates, including the physical and digital infrastructure, policies, regulations, and stakeholders. The Operational SoS represents the interconnected systems that make up the smart city or digital twin, such as sensors, data platforms, and analytics tools. The Consumer System refers to the end-users who interact with the SoS, such as citizens, businesses, and government agencies. The proposed reference model aims to address the technical, semantic, and governance issues related to data management in smart cities and digital twins. This includes issues such as data collection, retrieval, exchange, analysis, and processing, as well as data sovereignty, semantics, features, and metadata specifications.
The authors Atkinson et al (Atkinson et al., 2022) also noted that, while current projects and frameworks have explored some of these issues and proposed solutions for subsets of them, there is no overall framework that connects all aspects in a unique model. The proposed reference model builds on current experiences and considers OGC standards and initiatives to provide open solutions for specific parts of the framework.

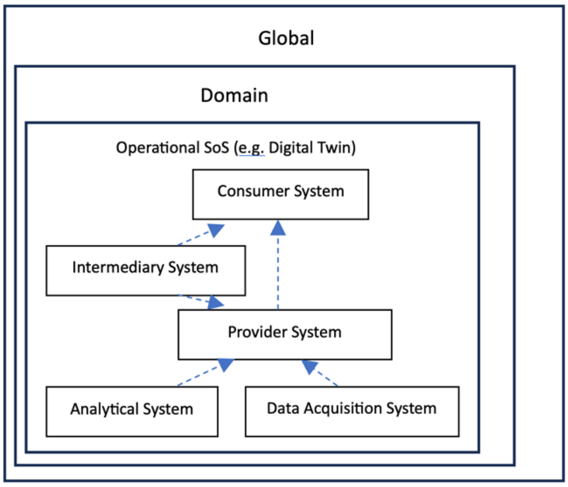

Figure 3. Scope Characterisation for SOS (Atkinson et al., 2022)

Boje et al (Boje et al., 2020) discusses the use of Building Information Modelling (BIM) and the concept of a Construction Digital Twin to improve the design, construction, and operation of buildings. While BIM provides a standardised way to represent building components and systems, it lacks semantic completeness in areas such as control systems and sensor networks. The authors propose a Construction Digital Twin as a more holistic and process-oriented approach that leverages the synchronicity of cyber-physical bi-directional data flows.

The paper by J. B. Correia, M. Abel, and K. Becker (Correia et al., 2023) suggests that semantic interoperability can be applied in smart cities by addressing the need for interoperability at all levels (semantic, data, and others) to provide fully integrated and optimized services for citizens. The interaction between DTs from different subdomains (smart buildings, urban planning) highlights the importance of data management between DTs.

To ensure consistency and accuracy in data interpretation, standardizing data models and ontologies that can be applied across various domains (Raghavan et al., 2020). This will also aid in the integration of different systems and facilitate communication between them.

Before expanding to larger areas, digital twin implementations are tested and improved in pilot projects (Chang & Jang, 2021).

4 Achieving Interoperability

There are numerous varieties of semantic interoperability, each of which enables distinct actions on the interoperability. This paper highlights on DTDL-based ontology.

The DTDL-based ontology for smart cities provides a modeling guideline for creating new entities, using English terms, camel case syntax for attribute names, and capital letters for entity type names. It also allows describing relationships between twins, which are digital representations of real-world environments brought to life with real-time data from sensors and other data sources.

The ontology is used to build Azure Digital Twins-based solutions and bring them to life in a live execution environment. The ontology is open source and aims to drive openness and interoperability (Bloch et al., n.d.).

4.1 Implementing DTDL Guideline

The guidelines for creating new entities in the DTDL-based ontology for smart cities recommend checking if the entity already exists in the repository before creating a new one. The ontology uses English terms, preferably American English, and camel case syntax for attribute names. Entity type names must start with a capital letter, for example, Streetlight. The ontology also allows describing relationships between twins, which are digital representations of real-world environments brought to life with real-time data from sensors and other data sources.

Telemetry refers to the data emitted by any digital twin, be it a regular stream of sensor readings, a computed stream of data, such as occupancy, or an occasional alert or information message. The following table details the properties that Telemetry may possess.

Property	Required	Data type	Limits	Description
`@type`	required	IRI		This must at least be "Telemetry"; it can also include a semantic type.
`@id`	optional	DTMI	max 2048 characters	An identifer for the Telemetry. If no @id is provided, one will be assigned automatically.
`comment`	optional	*string*	max 512 characters	A comment for model authors.
`description`	optional	localizable *string*	max 512 characters	A localizable description for display.
`displayName`	optional	localizable *string*	max 64 characters	A localizable name for display.
`name`	required	*string*	max 64 characters; contains only alphanumerics and underscore, starting with a letter, ending with alphanumeric; must be unique for all contents in Interface	The programming name of the element.
`schema`	required	Schema	must be *double*, *float*, *integer*, or *long* when a semantic type is present	The data type of the Telemetry, which is an instance of Schema.
`unit`	required when semantic type is present; disallowed otherwise	Unit		The unit type for data associated with the element.

Figure 4. Telemetry Table (Douceur, 2023)

The following example demonstrates a simple Telemetry definition for a currency using the double data type, declared based on the properties described above table.

```
{
  "@type": "Telemetry",
  "name": "eur",
  "schema": "double"
}
```

Figure 5. Telemetry Definition

This example illustrates the serialized Telemetry data for the aforementioned Telemetry model definition when JSON is utilized to serialize Telemetry data.

```
eur: 42.5
```

Figure 6. JSON Serialized

The following example demonstrates a Telemetry definition that includes a Currency semantic type and a unit property.

```
{
  "@type": ["Telemetry", "Currency"],
  "name": "eur",
  "schema": "double",
  "unit": "EUR"
}
```

Figure 7. Telemetry Definition

Figure 9 represents an example of telemetry definition in DTDL that includes a currency semantic type and a unit property. The example includes the following properties: "@type": specifies the semantic type of the telemetry, which in this case is "Currency". "name": specifies the name of the telemetry, which in this case is "eur". "schema": specifies the data type of the telemetry, which in this case is "double". "unit": specifies the unit of measurement for the telemetry, which in this case is "EUR".

4.2 Authoring DTDL ontology

Microsoft's Azure Digital Twins' instructional document (Learn, 2023a) describes ontology as a collection of models that comprehensively describe a particular domain, such as manufacturing, building structures, IoT systems, smart cities, energy grids, and web content, etc.

DTDL plays a significant role in the semantic interoperability of digital twins of smart cities. DTDL provides a common modeling language that enables developers to describe twins in terms of the telemetry they emit, the properties they report or synchronize, and the commands they respond to (Berhane Russom, 2021)(Azure, 2021). DTDL also allows describing the relationship between twins, which is essential for interoperability and enabling data sharing between multiple domains (Berhane Russom, 2021)(Azure, 2021). DTDL-based ontologies can be used to provide a common representation of places, infrastructure, and assets, which is paramount for interoperability and data sharing (Berhane Russom, 2021)(Azure, 2021). The Microsoft Digital Twins Definition Language (DTDL) has a “context model” which is similar to the NGSI-LD (Digital Twin Hub, 2023). Using DTDL to describe any digital twin's abilities enables the platform and solutions to leverage the semantics of each digital twin (Alina Cartus et al., 2022). DTDL version 3 is being developed, along with a new open-source parser that supports v2 and v3 (Minguez Pablos (RIDO), 2023). Therefore, DTDL is a crucial tool for achieving semantic interoperability of digital twins of smart cities.

As mentioned in the reference model section, according to Atkinson et al (Atkinson et al., 2022), there are key aspects which has to be addressed to achieve interoperability. Microsoft Azure DTDL reference model aims to address the technical, semantic, and governance issues related to data management in smart cities and digital twins. This includes issues such as data collection, retrieval, exchange, analysis, and processing, as well as data sovereignty, semantics, features, and metadata specifications. DTDL provides a common modeling language that enables developers to describe twins in terms of the telemetry they emit, the properties they report or synchronize, and the commands they respond to (Learn, 2023b)(Berhane Russom, 2021). DTDL also allows describing the relationship between twins, which is essential for interoperability and enabling data sharing between multiple domains (Learn, 2023b).

5 Future Research

As DTDL is a language for describing digital twin models of smart devices, assets, spaces, and more, contributing to DTDL will enhance the semantic interoperability of the digital twins. Future research could propose new ways of using DTDL or suggest improvements to the language. According to Cavalieri et al (Cavalieri & Gambadoro, 2023) purpose of proposing new ways of using DTDL is to enhance the interoperability of Digital Twins through integration into the OPC UA (Open Platform Communications Unified Architecture) domain. The authors (Cavalieri & Gambadoro, 2023) believe that interoperability between Digital Twins and the OPC UA communication standard should be enabled to meet the main requirements of Industry 4.0.

6 Conclusion

Semantic interoperability certainly plays a significant role in the implementation and integration of digital twins in smart cities. It facilitates data exchange between digital twins and enhances the analysis of data. The review paper explored the topic of semantic interoperability of digital twins in smart cities. It highlights the importance of improving interoperability for communication and data exchange between different twins. Achieving semantic interoperability is essential as it provides accurate and timely insights. And this leads to the existence of well-functioning smart cities. The paper introduces reference models that can be reliable in developing interoperability between digital twins in smart cities. It addressed technical, semantic, and governance issues related to interoperability. Further, it discussed challenges in achieving semantic interoperability. The paper focuses on Microsoft Azure Digital Twin Definition Language (DTDL) to enhance interoperability. It highlights the DTDL and demonstrates the practical application of DTDL in achieving semantic interoperability. It discussed future research ideas to further improve Azure DTDL.

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