

Digital Twin and Metaverse in the Context of Industry 4.0

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Abstract. The lack of an ontology integrating Digital Twins (DTs) into the Metaverse presents a fundamental challenge for synchronising physical and digital worlds. This study proposes the development of a specific ontology to address this very gap. To achieve this, two methodological approaches are employed: MDCP modelling and the OApIS process, allowing a comparison between a more rigid structure and a dynamic, adaptive approach. The expected outcomes include the creation of a flexible, scalable, and interoperable ontology capable of efficiently representing DTs. The study concludes that robust ontological frameworks are essential for enhancing DT-Metaverse interactions, contributing to more immersive, secure, and predictive experiences.

Keywords: Metaverse · Digital Twins · Ontologies · Digital Twin-Metaverse Unified Ontology

1 Introduction

The digital transformation is being driven by significant technological advancements, with two emerging concepts taking centre stage: Digital Twin (DT) and the Metaverse. These concepts are crucial to the evolution of digital systems, enabling new ways to represent and interact between the physical and digital worlds. Accordingly, ontology development has become an essential tool for modelling and integrating these domains, providing a structured knowledge framework that enhances communication and interoperability across systems.

This article explores methodologies for ontology development, analysing existing approaches for DTs and the Metaverse while highlighting the absence of a unified ontology that integrates both. It begins by examining the stages and best practices in ontology creation, followed by an analysis of how different methodologies structure and model information in various contexts. Building on these insights, the study then demonstrates the development of a unified ontology that bridges DTs and the Metaverse.

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However, achieving seamless data exchange and identity continuity across heterogeneous virtual environments poses major challenges. Efforts towards standardising the Metaverse landscape, especially in terms of semantic alignment and cross-platform identity, are ongoing and rapidly evolving, yet remain fragmented. This work aims to address these gaps by proposing an ontology capable of integrating Digital Twins into the Metaverse under a unified framework.

Unlike approaches that address DTs and the Metaverse in isolation, our proposed solution unifies both into a single ontological framework. This integration tackles real-time synchronisation, scalability, and interoperability challenges, effectively bridging physical and virtual realms. By weaving DT and Metaverse concepts together, we aim to fill critical gaps in existing literature and provide a more holistic mechanism for Industry 4.0 applications. As such, our framework goes beyond a conventional ontology study, positioning itself as a novel solution that consolidates two rapidly evolving domains into a cohesive model.

Finally, an integrative ontological model is proposed to establish a common framework for data representation and communication between these two domains. This ontology aims to capture real-time interactions between physical and virtual objects within the DT, extending its capabilities to the broader, immersive ecosystem of the Metaverse.

As part of this integration process, two ontology development methodologies will be examined, discussing their practical applications, challenges, and proposed solutions for strengthening the connection between DTs and the Metaverse.

2 Background

Ontology, as defined by Gruber [1], is a formal and explicit specification of shared understanding, enabling machine-interpretable knowledge representation. By integrating data sources, ontologies enhance interoperability and support semantic-based information processing. Ontologies have gained significant importance in various fields, including industrial environments, due to their ability to represent complex relationships and ensure standardised knowledge exchange.

The development of ontologies follows structured steps to formalise knowledge and improve data management. Typically, according to Abu-Salih [2], the main stages of ontology creation involve:

1. **Identifying key terms**: Defining concepts (nouns), attributes (properties of entities), relationships (verbs linking elements), and instances (real-world entities).
2. **Building the conceptual model**: Structuring classes and subclasses hierarchically.
3. **Defining relationships**: Object properties link entities, while data type properties describe attributes, specifying their type (e.g., string, integer, boolean) and cardinality.
4. **Creating instances**: Assigning values to classes to instantiate the ontology, with tools like Protégé facilitating evaluation and reasoning.

At the Metaverse scale, ontologies must handle cross-platform semantic alignment, decentralised identity, and near-instant data exchange, all of which surpass

typical ontology requirements. The following discussion highlights relevant standardisation approaches aimed at bridging these gaps.

2.1 Interoperability, Standardisation, and Predictive Capabilities

The rise of the Metaverse has accelerated efforts to develop interoperability frameworks that ensure seamless semantic and identity continuity across heterogeneous virtual environments. Recent initiatives address both syntactic alignment of data formats and deeper semantic integration through ontology-driven approaches. Notable efforts include Abu-Salih's MetaOntology [2], which outlines a domain-specific framework for core Metaverse constructs, and the MPAI Metaverse Model (MPAI-MMM) [3], which proposes a standards-based architecture for interoperability. Additionally, Li et al. [4] enhance ontological reasoning with AI to manage spatiotemporal complexity, emphasising context-awareness and semantic consistency.

Moreover, proposals for identity interoperability, such as Self-Sovereign Identity (SSI) systems, leverage blockchain for privacy-preserving cross-platform continuity [5–8]. These initiatives emphasise decentralised identity solutions and include policy-aware governance [5] and verification schemes [9,10]. However, the literature highlights persistent fragmentation and the lack of robust ontological standards capable of integrating semantic reasoning with identity tools [11,12].

Our proposed ontology unifies data and identity interoperability under a cohesive, standards-driven framework. By incorporating real-time semantic integration with decentralised identity models, it aims to reduce fragmentation and align with emerging cross-metaverse protocols, supporting a scalable, semantically enriched environment.

Furthermore, the predictive capabilities of our ontology arise from integrating predictive modelling techniques, enabling the analysis and forecasting of behaviours in industrial systems. Roopa et al. [13] have shown how ontology-based models contribute to predictive maintenance by forecasting component lifespan and improving real-time decisions. Additionally, the combination of ontologies with machine learning techniques, as demonstrated by Zhang et al. [14], proves effective in anomaly detection and failure prediction, thus enhancing decision-making and operational efficiency in industrial systems. These capabilities provide a solid foundation for the predictive power embedded in our ontology, which can be applied to optimise both DT and Metaverse environments.

2.2 MDCP Methodology

Building on these general principles of ontology construction, the MDCP methodology proposed by Singh et al. [15] stands out. It provides a structured and practical approach for creating and managing ontologies, particularly for integrating Digital Twins (DTs) within industrial systems. The MDCP methodology consists of five key stages, each essential for improving data management and constructing databases for DTs. These stages include:

1. **Map**: Identify the classes and relationships within the ontology model and link them to industrial processes that analyse asset behaviour.
2. **Define**: Specify data elements for each class, such as attributes and data types (e.g., temperature, pressure), which describe the properties of each class.
3. **Create**: Construct the ontology model by converting relationships between classes into object properties and defining data properties with logical constraints to formalise interactions.
4. **Convert**: Transform the ontology model into a relational database format by applying keys and cardinality to efficiently organise the data.
5. **Populate**: Insert real-world data into the relational database model, validating it with actual data to ensure it reflects the asset behaviour accurately.

Following the MDCP methodology, other approaches can be adopted to suit different needs. One such approach is the **OApIS methodology**, proposed by Duarte et al. [16]. In contrast to the previous methodologies, OApIS emphasises flexibility and dynamic data integration. It is organised into three distinct phases: 'Data Characterisation', 'Information Specification', and 'Ontological Mapping'. These phases enable the creation of an ontology model that supports real-time data processing and continuous adaptation to evolving industrial requirements.

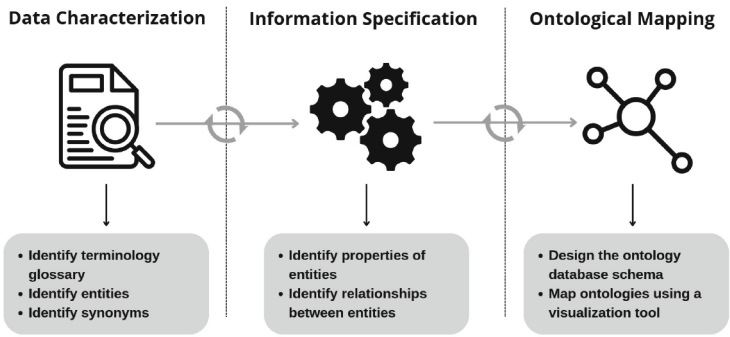

Fig. 1. OApIS Ontology Development Process [16].

In the first phase, 'Data Characterisation', terms are defined and associated tasks are described in detail. This helps to understand the domain and activities involved, creating a foundation for further analysis. The next phase, 'Information Specification', focuses on mapping these terms using a UML class diagram. This process involves following design rules for class diagrams, such as representing classes, associations, generalisations, compositions, and aggregations. The final phase, 'Ontological Mapping', maps the ontology schema to a graph-based database, where tools like Neo4j are employed to ensure the efficient management and retrieval of data (Fig. 1).

3 Ontological Approach for Metaverse and Digital Twins

3.1 MDCP Methodology

In this section, the development of the ontology will be based solely on the MDCP and OApIS methodologies. Initially, according to Singh et al. [15], the MDCP methodology will be followed. As mentioned in the previous section, the development of an ontology includes the stages 'Map', 'Define', 'Create', 'Convert', and 'Populate'. This methodology will form the foundation for the approach adopted throughout this section.

In addition to considering the stages for ontology development outlined by Singh et al. [15], this work also draws upon the Digital Twin (DT) ontology developed by these authors. Accordingly, a customized ontology for DT was developed. In adapting their framework, elements from their model were integrated, with adjustments made to ensure alignment with the specific objectives of this study and the broader research context.

The 'Define' stage clarifies key data elements and their types for each class, developing an ontology model for DT. To build this ontology, key terms were defined, which were essential for DT characterization.

- **Asset**: Refers to physical objects or systems digitally represented in the DT, ranging from industrial machinery to complex infrastructure.
- **Events**: Record real-time interactions and changes, enabling system behaviour analysis and fault detection.
- **Sensor and Sensor Data**: Play a crucial role in real-time data collection, ensuring continuous updates in the digital model.
- **Digital Model**: Provides a virtual representation of physical systems, allowing for accurate analysis, simulation, and control.
- **Behaviour**: Represents not only the physical appearance but also the system's functionality and interactions.
- **Actionable Insights**: Transform collected data into valuable information for optimizing processes and decision-making.

Relationships between classes were established, as shown in Fig. 2:

- **Asset** connects to **Events, Sensor,** and **Actionable Insights**. Events affect assets by detecting faults and changes, linking them to system behaviour.
- **Sensor** collects data from assets, linking to **Sensor Data**, which feeds into the **Digital Model** for accurate representation.
- **Actionable Insights** analyse **Behaviour** to identify patterns and improvements, optimizing processes and impacting assets.
- **Behaviour** is essential for representing physical elements in the **Digital Model**.

Subsequently, an ontology model was created for Metaverse, as shown in Fig. 3. The terms were carefully selected and were considered essential for Metaverse: 'Physical Environment', 'Technologies', 'Digital Environment', 'Digital Twin', 'Interoperability', and 'Virtual Entity'. The term 'Virtual Entity' is made up of the sub-terms Scene, Avatar and Non-Player Character (NPC), while the term 'Technologies' is made up of the sub-terms Computer Vision, Virtual

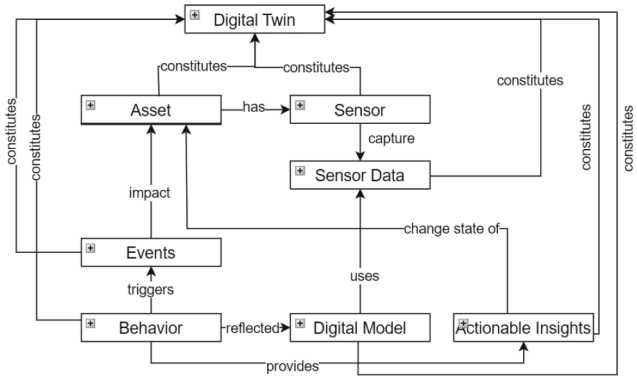

Fig. 2. Ontology model corresponds to Digital Twin.

Reality, Mixed Reality, Extended Reality, Internet of things (IoT), Blockchain, Edge Computing, Artificial Intelligence and Network Tech.

In this context, the Physical Environment in the Metaverse digitally replicates the real world, enabling immersive experiences. Technologies are fundamental, supporting the Metaverse's creation and operation.

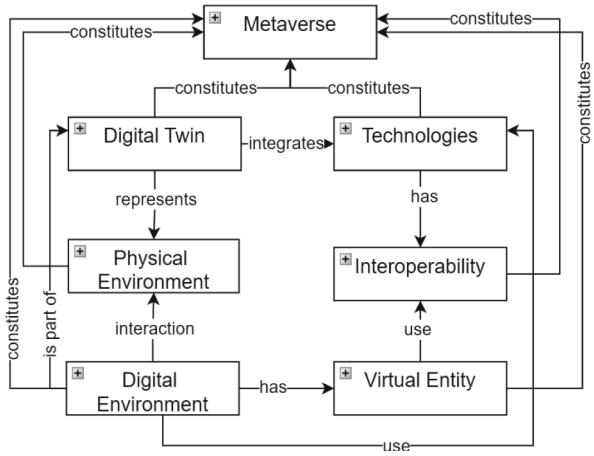

Fig. 3. Ontology model corresponds to Metaverse.

To understand how DT integrates with the Metaverse, ontology models were compared, Fig. 4. This analysis reveals that the Digital Environment serves as the foundation of the Metaverse, enabling interactions between users and digital objects. DT technology ensures accurate and interactive virtual replicas of real-world entities, while interoperability facilitates seamless transitions between platforms for users and Virtual Entities (avatars, NPCs).

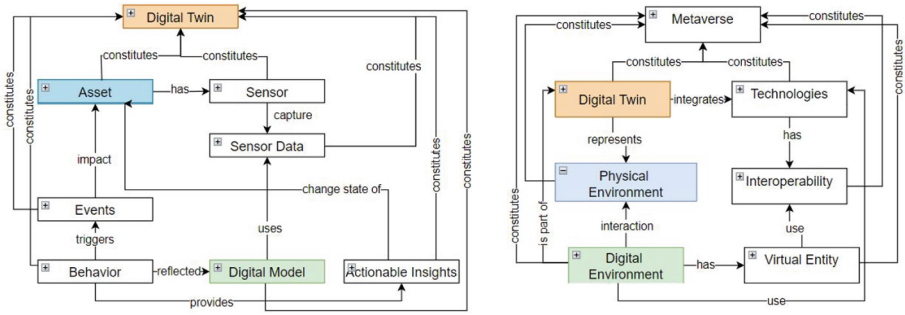

Fig. 4. Comparing ontology models.

The Digital Environment connects with the Physical Environment, DT, Technologies, and Virtual Entities, reflecting their interdependence. DT relies on Technologies for data processing and replication, while Technologies support Interoperability for smooth system integration. So, the terms were merged, with 'Asset' and 'Physical Environment' being grouped together under the name 'Asset', and 'Digital Model' and 'Digital Environment' being consolidated into a single term called 'Digital Environment'.

With regard to the 'Sensor', there was a relevant discussion about how it could be represented. In the model developed for DT it was considered as a class, while in the model developed for Metaverse it was treated as an attribute of the term 'Digital Twin', but given that the DT ontology model is considered mandatory in relation to Metaverse, it was decided to categorise it as a class in the final model.

The final ontology results from the integration of the ontology developed for DT and elements from the Metaverse domain, Fig. 5, ensuring a comprehensive representation of both concepts. In this context, the term 'Metaverse Platform' was added to clarify the process of publishing a DT in the Metaverse. It defines the technical requirements for interacting with a DT in the virtual environment.

The 'Metaverse Platform' is linked to 'Asset' and 'Digital Model'. The connection with 'Asset' shows how the platform supports the reception and interaction of digital or physical assets represented by DTs. The link to 'Digital Model' highlights the platform's role in managing and providing access to the digital models needed for DT operation in the Metaverse.

In general, these connections illustrate how the Metaverse Platform supports the integration and operation of DTs, enabling immersive interaction and control of assets in the virtual environment.

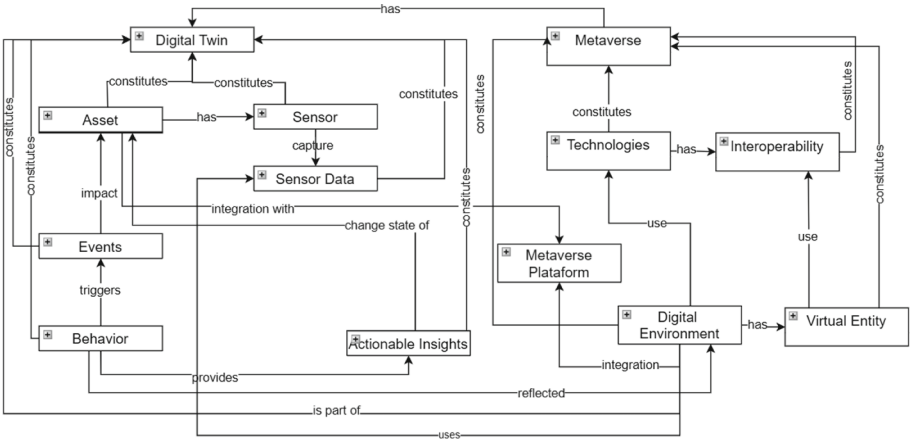

Fig. 5. Digital Twin-Metaverse Unified Ontology.

Implementation in the Protégé Tool

The next phase, 'Create', involves converting the ontology model into classes with data properties. This phase is carried out using the Protégé tool, which was used to implement the ontology model proposed above. Thus, the terms selected in the ontology model were organized in the 'Entities - Classes' section of the tool, Fig. 6.

During the development of the model, each attribute corresponding to each of the terms was meticulously organized in the "Entities - Data properties" section within the tool itself. Subsequently, time was devoted to assigning each attribute an appropriate data type.

The semantic relationship between the classes was structured and organized in the "Entities - Object properties" section, Fig. 6. Each relationship between the classes was defined and specified to accurately reflect the interconnections and dependencies between the different elements of the model. This careful and detailed organization of object properties is fundamental to ensuring an accurate and coherent semantic representation of the model, allowing a clear understanding of the relationships between the classes involved.

Object properties in the 'has' and 'use' cases have sub-properties due to their application in various instances of the diagram. For example, in the final diagram, 'has1' links 'Asset' to 'Sensor', 'has2' links 'Technologies' to 'Interoperability', and 'has3' links 'Digital Environment' to'Virtual Entity'. Similarly, 'use' links 'Digital Environment' to 'Sensor Data', 'Metaverse Platform' to 'Technologies', and 'Virtual Entity' to 'Interoperability'.

Finally, after establishing the connections between the classes, the restriction properties were applied to each established relationship.

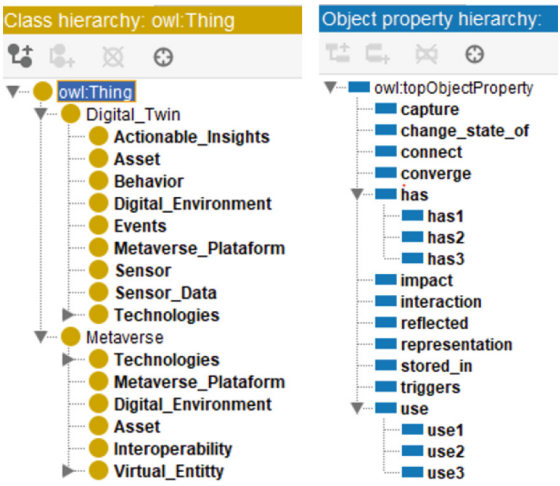

Fig. 6. Hierarchy of Classes and Object Properties in the Protégé Tool.

In the Protégé tool, in the OntoGraf tab, you can see a graphical visualization of the ontology (Fig. 7). In this same graph, it is possible to comprehensively explore the concepts related to Metaverse and DT technology, as well as understand their interrelationships.

3.2 OApIS Methodology

In this section, the ontology is developed following the OApIS process, which provides a structured and systematic approach to ontology construction. OApIS was chosen as it ensures a rigorous methodology for selecting relevant concepts, defining relationships, and validating the ontology, making it well-suited for integrating DT and Metaverse concepts. The first step is divided into four subphases. The first involves collecting sources via IEEE Xplore, searching for 'Digital Twin' and 'Metaverse', yielding around 840 references filtered by relevance.

Next, sources are selected based on relevance and applicability. The Snowball method is used, iteratively analysing citations from initial documents to identify new relevant sources.

The third subphase consists of three steps: first, extracting terms from selected sources. Table 1 presents these terms, including 'Digital Technologies', 'AI Technology', 'Synchronization', 'Internet of Things' (IoT), 'Services', 'Simulation', and 'Virtual/Physical Spaces', along with the sources identified in the second subphase.

After selecting the terms, related synonyms were grouped together. At this stage, terms like 'Artificial Intelligence Technology', 'IOT Technology', and 'Digital Technologies' were combined under the single term 'Digital Technologies'. Similarly, 'Virtual Space' and 'Virtual Twin Space' were unified into 'Virtual

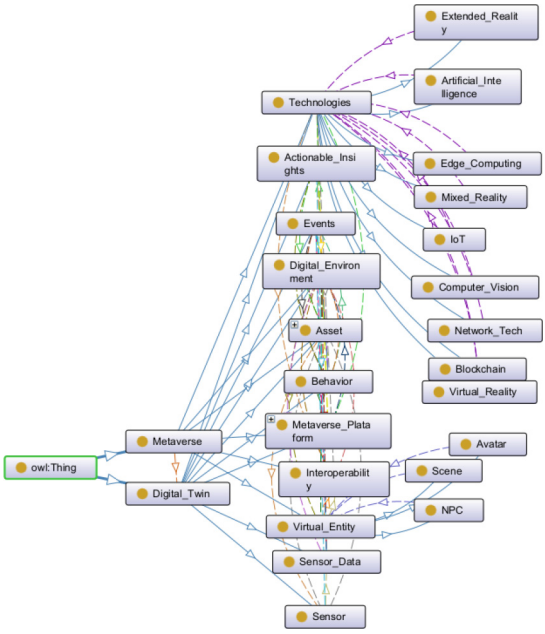

Fig. 7. OntoGraf in the Protégé tool.

Table 1. Terms of the First Iteration of the OApIS Method.

Data source	Term
[17]	Digital Technologies
[18]	Multitechnologies
[19]	Artificial Intelligence Technology
[19]	Synchronization
[20]	IOT Technology
[21]	Services
[22]	Simulation
[23]	Sensor Technology
[24]	Virtual space
[25]	Virtual Twin Space
[25]	Physical Space

Twin'. The term 'Physical Space' was renamed 'Physical Twin' to maintain consistency with Virtual Twin.

In the third sub-phase, only terms considered essential for the ontology were kept. This meant removing 'Multitechnologies', 'Digital Technologies', and all technologies that had been grouped together in the previous step, as well as the term 'Simulation'. These terms were excluded because they were not deemed

relevant to this specific ontology, which centres on Digital Twin technology, while Simulation is already included under Services.

Table 2. Terms of the Second Iteration of the OApIS Method.

Data source	Term
[23]	Data Communications
[26]	Avatar
[26]	NPC
[26]	Scene
[27]	Data
[27]	Real-time Systems
[27]	Cyber-Physical Systems

The fourth and final sub-phase involved repeating the final steps from the first iteration. As shown in Table 2, this second iteration included a renewed source search using the Newest filter. As a result, additional terms that had been missing from the initial ontology and from recent literature were identified. These newly added terms include 'Data Communications', 'Avatar', 'Non-Player Character' (NPC), 'Scene', 'Data', 'Real-time Systems', and 'Cyber-Physical Systems'.

In the second iteration, we excluded all terms except'Data Communications', as we deemed the remaining terms irrelevant for the ontology in question. 'Data Communications' was then simplified to 'Communication', considering that, in the field of Information Systems, it involves not only data exchange but also the exchange of information, knowledge, and wisdom. These relationships are depicted in a DIKW pyramid. Accordingly, these concepts were also integrated into the ontology.

Table 3. Terms of the Third Iteration of the OApIS Method.

Data source	Term
[28]; [3]	Interoperability
[29]	XR
[29]	AR
[29]	MR
[29]	VR

During the third iteration, as shown in Table 3, the Most Popular filter was applied, which highlighted the terms Interoperability, 'Augmented Reality' (AR), 'Extended Reality' (XR), 'Mixed Reality' (MR), and 'Virtual Reality' (VR).

In the subsequent sub-phase, it was observed that AR, MR, and VR are included under the previously selected term XR. Since they were deemed non-essential, these terms were removed, leaving only Interoperability selected.

Accordingly, following multiple iterations, the terms shown in Fig. 8 were chosen for the ontology associated with the Metaverse and Digital Twin (DT).

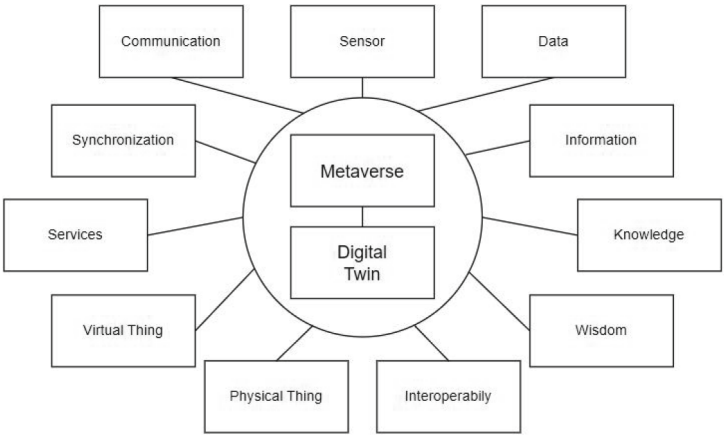

Fig. 8. General Model of Selected Terms Related to Metaverse and Digital Twins.

In addition to the previously recognized terms, it is important to highlight that the communication between DTs, enabled through services, is essentially an 'Interaction'. This interaction involves the continuous exchange of data and information, allowing DTs to synchronize and respond in real-time to dynamic system conditions, improving operational effectiveness.

'Communications', on the other hand, refers specifically to the data exchange between the Physical Twin and Virtual Twin. This exchange is vital, as the Virtual Twin relies on data from the Physical Twin to accurately reflect its state, aiding in real-time monitoring, simulation, and performance forecasting.

Additionally, we include actuators as a key term in the ontology. Sensors collect data from the physical world, but actuators convert control signals into physical actions, allowing the system to interact with the environment.

Table 4 provides a detailed description of the key terms, forming a consistent framework for the ontology's development and aligning with the latest definitions in the field.

Table 4. Description of Selected Terms.

Terms	Description
Virtual Twin	A Virtual Twin is a digital replica of a physical environment, where DTs exist and interact. It facilitates interaction between physical and virtual worlds.
Physical Twin	A Physical Twin represents the tangible world, using sensors and actuators to capture data and send it to the Virtual Twin for analysis.
Interoperability	Interoperability is the ability of DTs to communicate and collaborate, allowing digital objects to interact within the Metaverse.
Services	Services enable modelling, simulation, and real-time predictions, as well as facilitate DT interactions across different sectors.
Data	Data links the physical and virtual worlds, ensuring synchronization and proper responses through real-time exchange between twins.
Information	Information bridges the Physical and Virtual Twins, being processed data exchanged in real time to maintain accurate synchronization.
Knowledge	Knowledge is derived from processed information, applied to make decisions, predict behaviours, and optimise processes in DTs.
Wisdom	Wisdom applies accumulated knowledge to foresee outcomes, solve problems, and improve performance for sustainable solutions.
Interaction	Interaction involves the continuous communication between DTs, ensuring secure and reliable transfer of data, knowledge, and wisdom.
Communication	Communication ensures efficient transfer of data, knowledge, and wisdom between Physical and Virtual Twins to support decision-making.
Synchronization	Synchronization aligns the Physical and Digital Twins, keeping them up-to-date with data, information, and knowledge for reliable interaction.
Sensor	Sensors detect changes in physical variables, converting them into digital signals for analysis and response in real time.
Actuators	Actuators convert digital signals into physical actions, impacting the environment based on control system commands.

As a result of this process, we developed the second phase. In the second phase, "Specification of Information," the properties of the entities and the relationships between them were identified. These were then represented using a UML class diagram created in the Visual Paradigm tool, as shown in Fig. 9.

The Metaverse consists of multiple interconnected DTs. The DT class is associated with Services, Interaction, and Virtual Twin. Services provide essential functions to optimize DT operations and improve user experience.

The Interaction class focuses on the exchange of data, information, knowledge, and wisdom among DTs, enabling real-time coordination. The Virtual Twin manages and stores DTs, allowing real-time simulations and data comparison.

The Physical Twin connects to Sensors and Actuators, which collect data and make adjustments based on the system's needs. Communication facilitates data exchange between the Physical and Virtual Twins.

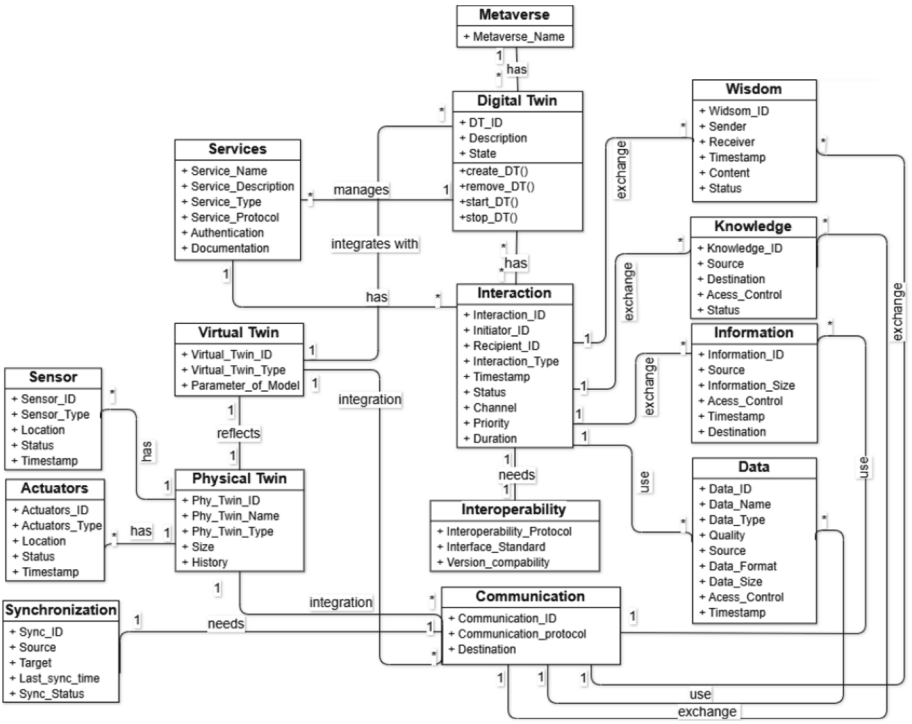

Fig. 9. Metaverse and Digital Twin Ontology Class Diagram.

The Data, Information, Knowledge, and Wisdom classes are connected to Interaction, enabling these exchanges between DTs. The same occurred with the term 'Communication.' Synchronization ensures that data remains up-to-date in real time, supporting effective communication. Interoperability is crucial for seamless DT communication. Services mediate the exchange of data and knowledge, while the relationship between the Physical and Virtual Twins ensures system optimization.

3.3 Application Scenario

Building on the ontological framework, a practical scenario is conducted focusing on deploying DTs using Microsoft Azure. The central objective is to demonstrate how the proposed ontology can be instantiated and managed within an actual cloud platform. First, the ontology is converted into Digital Twin Definition

Language (DTDL), a JSON-based format recognized by Azure Digital Twins (ADT). It preserves the conceptual structure (entities, relationships, and properties) defined in the UML diagrams. Next, these DTDL models are uploaded to ADT, allowing automatic generation and linking of the DT instances.

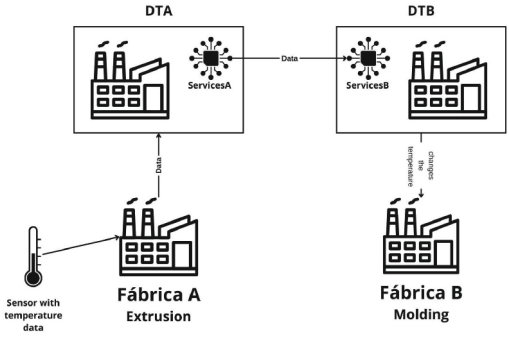

Fig. 10. Application Scenario.

To illustrate the process, two interconnected factories are modelled: "Fábrica A" responsible for extruding plastic, and "Fábrica B" dedicated to moulding. Each facility is monitored by a DT that reads sensor data (e.g., temperature) through Azure services, as shown in Fig. 10. Whenever the extrusion temperature exceeds a certain threshold, the DT of Fábrica B automatically triggers cooling procedures to ensure optimal conditions for moulding. This real-time data exchange and decision-making is fully supported by Azure APIs, which handle authorization, reading and updating twin properties, and synchronizing both physical and virtual environments. Overall, this case study underscores the feasibility of the approach: the ontology guides the DTDL modelling process, while Azure's cloud infrastructure handles scaling, monitoring, and communication. By merging theoretical constructs with operational cloud components, the scenario demonstrates how ontological rigor and ADT capabilities combine to deliver a robust, adaptive solution for Industry 4.0.

While the proposed approach shows considerable potential for integrating Digital Twins and the Metaverse, several limitations warrant discussion. In scenarios with an expanding number of assets and sensors, scalability may become a key challenge, necessitating robust data management strategies [30,31].

Furthermore, maintaining and updating complex ontological repositories over time can be resource-intensive, especially in rapidly evolving industrial environments [32,33]. Lastly, aligning the proposed ontology with existing standards, such as ISO, W3C, or OPC UA, could require specialized extensions or bridging mechanisms [34], potentially complicating broader adoption.

4 Conclusion

Ontology development follows different methodologies, shaping their application. The MDCP Methodology [15] follows a structured five-stage process, ensuring consistency in formalized ontologies. In contrast, OApIS Methodology [16] adopts a data-driven approach, prioritizing adaptability for dynamic domains.

Protegé-generated ontologies emphasize static structures, defining relationships between key terms (e.g., Digital Environment, Virtual Entity, Sensor). OApIS, however, focuses on real-time interactions, modelling continuous data exchange through terms like Services, Interaction, and Synchronization. Consequently, while MDCP provides a solid foundation for methodical, well-organized ontologies, OApIS excels in scenarios demanding ongoing adaptation—particularly relevant when linking Digital Twins to the Metaverse.

By first applying MDCP and then transitioning to OApIS, we achieved an ontology flexible enough to handle real-time synchronization between physical and digital entities. This approach proved indispensable for bridging the gap between structured representation and real-time adaptability, as demonstrated in the Application Scenario with interconnected factories running on ADT.

The proposed ontology not only promotes seamless interoperability and scalability but also boosts predictive capabilities, ultimately fostering a more robust and efficient Metaverse ecosystem. From an implementation perspective, combining MDCP's structured design with OApIS's dynamic data integration adds both consistency (formal stages) and adaptability (through real-time modelling), as demonstrated in our Application Scenario using ADT. This setup underscores the practical feasibility of deploying the ontology in cloud-based infrastructures, offering tangible benefits in monitoring, decision-making, and synchronization.

Looking ahead, an important step is to validate the ontology empirically in a real industrial setting, collecting operational data to refine the model and test its performance under large-scale conditions. Furthermore, exploring integrations with blockchain or other decentralized technologies may bolster trust, traceability, and identity continuity across diverse Metaverse platforms.

Overall, our findings show that unifying Metaverse and DT concepts into a single ontological framework successfully addresses pressing interoperability and real-time challenges, paving the way for broader industrial adoption and more immersive virtual-physical interactions.

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