Ontology Creation for Water Treatment Plant Asset Management

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Abstract

Effective water asset management is crucial for ensuring the reliable and sustainable delivery of water services. However, the diverse and complex nature of water infrastructure often poses challenges in managing, exchanging, and retrieving asset information. To address these challenges, this paper proposes the development of an ontology-based approach for standardised water asset management, operations and maintenance (O&M), leveraging the Water Environment Research Foundation (WERF) and the International Infrastructure Management Manual (IIMM) as foundational references. The ontology aims to provide a structured representation of the domain knowledge and relationships between different entities of a water treatment plant (WTP) to enhance information requirements for water asset O&M, promote seamless information exchange between disparate systems, facilitate efficient information retrieval through structured queries, and sets the foundation for future integration with Large Language Models (LLMs) and BIM models to optimize decision-making processes and improve water asset management practices. The paper presents the ontology's design, development methodology, and validation method to assess its effectiveness.

Keywords: Ontology, Asset Management, Water Treatment Plant, BIM

1 Introduction

Water treatment plants (WTP) are complex infrastructure systems responsible for delivering clean and safe drinking water. Maintaining and optimizing these facilities requires efficient management of a vast array of assets, from pumps and pipes to tanks and treatment mechanisms. This critical function necessitates effective asset management and operations and maintenance (O&M) practices within WTPs. These plants rely on a complex network of infrastructure and equipment that demands thorough monitoring, data collection, and analysis to ensure optimal performance and water quality (Batac et al 2021).

A key challenge in water treatment plant asset management lies in harnessing the vast amount of data collected from various sources. These data includes asset information, sensor readings, maintenance records, and sometimes Building Information Models (BIMs). Additionally, managing the vast amounts of information associated with water assets – their characteristics, operational data, and maintenance schedules – presents another significant challenge. Traditional data and information management methods often struggle with the inherent diversity and complexity of water infrastructure data. This can lead to inconsistencies, siloed information, and difficulties in retrieving critical details for informed decision-making (Suprun et al. 2022).

Ontologies have emerged as a powerful tool for overcoming these information management hurdles. Defined as a structured framework for capturing and representing the relationships between entities, concepts, and properties within a specific domain (Brewster 2004), ontologies offer a standardized vocabulary and data structure to ensure consistent information representation across different systems and applications. In the context of WTP asset management, an ontology can establish a common language for water treatment plant data, facilitating seamless information exchange and retrieval for improved decision-making throughout the asset lifecycle. By structuring asset information in a standardized and semantically rich format, ontologies enables LLMs to effectively learn and understand the domain, leading to improved analysis and decision support (Hadi et al. 2023).

This paper proposes the development of an ontology-based approach for standardized water asset management. To ensure scalability, it is crucial to leverage established industry frameworks as a foundation. The proposed ontology is designed with alignment to the Water Environment Research Foundation (WERF) and the International Infrastructure Management Manual (IIMM) as foundational references, so that the core principles and functionalities can be adapted for wider use across various water treatment plant management practices globally. WERF, a renowned organization focused on innovation and research in wastewater and water reuse, and IIMM, which provides comprehensive guidance on infrastructure asset management best practices, offer strong industry credibility. Aligning the ontology with these frameworks ensures its core principles and functionalities resonate with the needs of water treatment professionals and can be adapted for various water treatment plant management practices globally.

To address the challenges of information management in water treatment plants, this research proposes the development and evaluation of a water asset management ontology (WAM-ONTO). The paper will detail WAM-ONTO's design and development methodology, along with a proposed validation method to assess its effectiveness in:

- Enhance information requirements for water asset O&M by ensuring all relevant data points are captured and represented consistently.
- Promote seamless information exchange between disparate systems by establishing a common vocabulary and data structure, enabling smooth data flow across various software and hardware platforms used in water treatment plants globally.
- Facilitate efficient information retrieval using structured queries. Users can leverage the ontology's structure to formulate precise queries, enabling them to retrieve the specific information needed for informed decision-making.
- Laying the foundation for the integration of Large Language Models (LLMs) and Building Information Models (BIM) to analyze asset information and generate insights.

The research will present the design and development methodology for the water asset management ontology. Additionally, it will explore a proposed validation method to assess the effectiveness of the ontology in improving information retrieval and decision-making processes within water treatment plants.

2 Literature review

Effective water treatment plant asset management necessitates standardized data management due to the complexity and diversity of information involved (equipment characteristics, operational parameters, maintenance schedules). However, traditional data management systems often struggle with this complexity, leading to inconsistencies and siloed information (Carriço 2020). This fragmented data landscape hinders information retrieval and can lead to suboptimal decision-making during asset management, operation and maintenance processes.

A number of ontologies are built in the area of infrastructure management and asset management to support development of applications for asset inventory management, maintenance management, work order management and communication management. Several studies have explored the application of ontologies in water treatment plants. For instance, El-Diraby and Osman created the infrastructure product ontology (IPD-Onto) to represent infrastructure product knowledge (such as pipes, valves, pumps, etc.) in sectors such as water, electrical, telecommunication, and gas (El-Diraby and Osman 2011). Similarly, Zeb developed a tangible capital asset ontology (TCA_Onto) to depict tangible capital assets in transportation, water, and solid waste management, leading to the creation of an asset information integrator system for smooth exchange of tangible capital asset information between municipal and provincial governments (Zeb 2020). These ontologies primarily focus on engineered or man-made assets in the built environment. While they contribute significantly to standardizing data management and facilitating asset inventory management, maintenance, and communication, they have limitations in addressing the comprehensive needs and tailored data representation required for water treatment plant asset management (Farghaly et al. 2023).

Frolov et al. (2010) developed an asset management ontology to integrate product (physical assets) and process (asset management best practices) knowledge to ensure effective asset management. In the realm of condition assessment, knowledge representation has been developed to monitor the condition of industrial assets for effective maintenance management (Campos 2007). El-Gohary (2008) devised the infrastructure and construction process ontology (IC-Pro-Onto) to model construction-related process knowledge across four areas: design and construction processes, management processes, knowledge integration processes, and support processes. To enable seamless information exchange between the information systems of infrastructure or utility organizations, a transaction domain ontology has been developed (Zeb 2020). Similarly, organizations and individuals within the construction industry are represented in the actor ontology to illustrate the various roles played in the realm of infrastructure management (Zhang and El-Diraby 2009). Trento and Fioravanti (2013) introduced a method for linking process and product ontologies to enhance interoperability between planning and design information systems. In addition, Existing ontologies like BrickSchema, IFCOwl, Project Haystack, Real Estate Core (REC), and SAREF, used in BIM and facility management, provide valuable frameworks for representing building-related information (Brick 2021)

These ontologies focus on improving asset management processes and practices to achieve operational efficiencies, but lack the knowledge required to develop a decision support system for the selection of condition assessment technologies for WTP. This requires the need to develop a knowledge model to support the development of applications for asset management.

While existing research demonstrates the value of integrating ontologies and BIM, there is a need for further investigation into the development of standardized ontologies specifically tailored to water treatment plant asset management. This paper addresses this gap by proposing a Water Treatment Plant Asset Management Ontology (WAM-ONTO) specifically tailored to this domain, leveraging established industry frameworks.

3 Research Method

To develop the ontology, we followed the Linked Open Terms (LOT) methodology (Poveda-Villalón et al. 2022). LOT is a well-known and mature lightweight methodology for the development of ontologies and vocabularies that has been widely adopted in academic and industrial projects. The process followed a structured approach, guided by the key phases depicted in Figure 1. First, information about asset hierarchy and relationships were gathered from WERF and IIMM, then it was transformed into a machine-readable spreadsheet, then it was copied to Protégé to create the instances for types, object and data properties, and semantic rules, finally we ran assessments within Protégé to validate it.

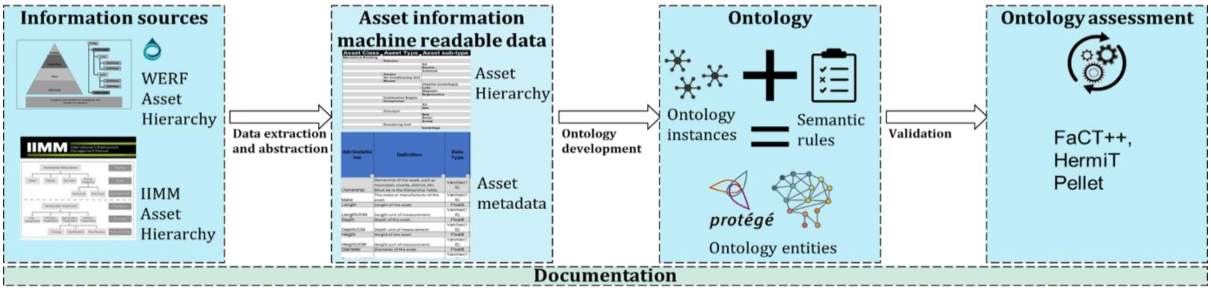

Figure 1 The proposed framework based on ontology for WTP AM

3.1 Ontology Requirements Specification

This section outlines the key specifications of the WAM-ONTO. It describes the purpose, the scope, the intended use cases and knowledge resources.

Table 1. Ontology specification document

Requirements	Descriptions
Domain	Asset Management for WTP
Purpose Identification	Capture the knowledge, concepts, and relationships relevant to managing assets within a WTP context, facilitate efficient data integration, exchange, and retrieval, enabling better decision-making processes in the management of water assets. Provide a structured and standardized framework for organizing and querying asset-related information, facilitating effective asset management practices.
Scope Identification	All physical assets and related information within water treatment plants, distribution networks, and associated facilities. It covers aspects such as asset classification, and metadata such as maintenance history, specifications, risk management, and lifecycle management.
Use case specification	Enhance information requirements for water asset O&M Promote seamless information exchange between disparate systems Facilitate efficient information retrieval using structured queries.
Knowledge Source	Industry standards WERF Asset Hierarchy and IIMM Asset Hierarchy

3.2 Implementation

In this phase of ontology development, knowledge is structured in a conceptual model and follows three steps that are ontology conceptualization, encoding, and evaluation. This section details the implementation process for the WAM-ONTO, drawing upon the established high level asset hierarchy from the IIMM and the WERF. The IIMM and WERF asset hierarchy served as a foundational framework for defining classes and subclasses within the ontology.

3.2.1 Ontology Conceptualization: Using existing ontologies

The development of WAM-ONTO leveraged existing ontologies in the domain of asset management and infrastructure. The following ontologies were considered:

- Semantic Data Model for Operation and Maintenance of the Engineering Asset (Koukias et al. 2013)
- An ontology-based approach for developing data exchange requirements and model views of building information modelling (Lee et al. 2016)
- An ontology for asset management (Campos 2007)
- Domain Ontology for Utility Infrastructure: Coupling the Semantics of CityGML Utility Network ADE and Domain Glossaries (Xu and Cai 2021)
- Ontology-based modelling of lifecycle underground utility information to support operation and maintenance (Wang 2021)

An analysis of these ontologies focused on identifying relevant classes, properties, and relationships applicable to water treatment plant asset management. This analysis informed the conceptual design of WAM-ONTO, ensuring it incorporates established knowledge representation practices within the domain.

Figure 2 shows how we systematically translated asset categories from the hierarchy into top-level classes in Unified Modeling Language (UML). Subsequently, we identified subcategories and established inheritance relationships (subclasses) between them, reflecting the inherent hierarchical structure of water treatment plant assets. For example, the "Buildings" class might encompass subclasses like "PumpStation" and "TreatmentBuilding." Here's a sample set breakdown of the key elements:

3.2.2 Classes:

Treatment Unit: This class represents the overarching category for all units involved in the water treatment process. Examples include:

- Clarifier
- Filter (e.g., Sand Filter, Membrane Filter)
- Disinfection Unit (e.g., Chlorination System, Ozonation System)
- Storage Tank
- Mechanical Static

Infrastructure Component: This class encompasses essential infrastructure elements supporting treatment operations. Examples include:

- Pipe Segment (further specified by material, diameter)
- Valve (including manual, pressure-regulating, or check valve types)
- Sensor (categorized by measurement type: pressure, flow rate, turbidity, etc.)
- Meter (distinguished by measured parameter: flow, level, etc.)

Building: This class represents structures within the plant, further categorized by function (e.g., Pump House, Administration Building).

3.2.3 Relationships:

- **is-a:** This relationship captures hierarchical relationships between classes. For example, "Sand Filter" is-a "Treatment Unit".
- **connects-to:** This relationship defines physical connections between infrastructure components. For instance, "Pipe Segment A" connects-to "Pipe Segment B".
- **located-in:** This relationship establishes the spatial context of a component within a building. For example, "Pressure Sensor" located-in "Pump Station".
- **has:** This general relationship represents various possession-like associations. For example, "Treatment Unit" has-part "Pump", "Pipe Segment" has "property Material"
- **determines:** This relationship indicates a causal influence between entities. For example, "Condition Monitoring" determines "Condition"

3.2.4 Properties:

Each class will have a set of properties relevant to its function. Here are some examples:

- **Treatment Unit:** Capacity (m^3), Treatment Process (e.g., coagulation, filtration)
- **Pipe Segment:** Material (e.g., PVC, cast iron), Diameter (mm), Length (m)
- **Valve:** Type (manual, pressure-regulating, check), Size (mm)
- **Sensor:** Measurement Range, Calibration Date
- **Building:** Year Built, Floor Area (m^2)

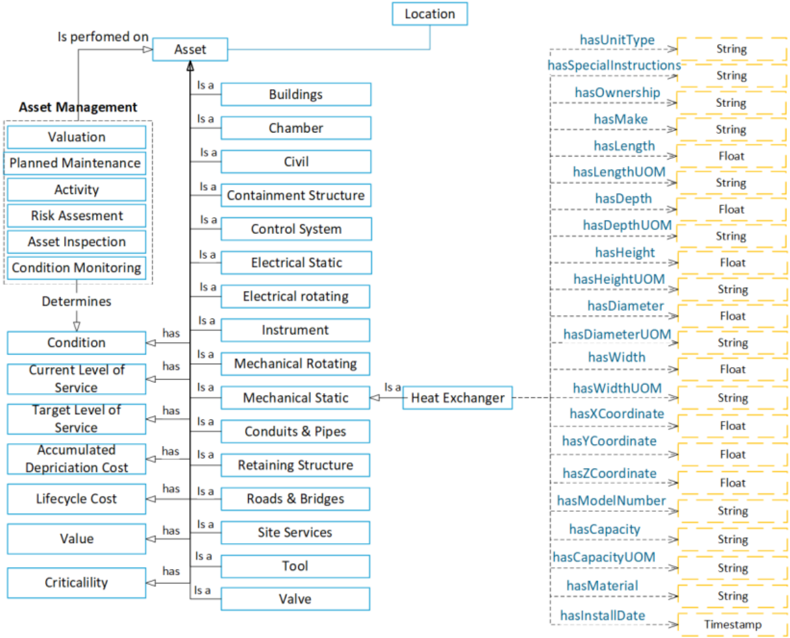

Figure 2 Concepts in of Water Treatment Plant presented in UML diagram showing Heat Exchanger properties

3.3 Ontology encoding:

The next phase in the ontology development was implementing the ontology in a formal language. The web ontology language (OWL) was used to implement the ontology. OWL can represent the meaning of terms and the relationship between terms in a machine-interpretable language. Protégé 5.6.1[1], an open-source application, was used as the development environment to create the OWL file. The following section will describe the ontological model that we named WAM-ONTO).

3.3.1 From Spreadsheets to OWL Classes:

The initial stages of WAM-ONTO development involved utilizing spreadsheets to organize the concepts identified during the conceptualization phase. These spreadsheets captured details like classes, subclasses, relationships, properties, and data types. This structured approach facilitated the translation of these concepts into a machine-readable format suitable for Protégé.

3.3.2 Building WAM-ONTO in Protégé:

Once the elements were organized in spreadsheets, Protégé was used to create the formal OWL file for WAM-ONTO. Within Protégé, we mapped the defined classes from the spreadsheets into OWL classes. Object properties were established to capture relationships between classes (as identified in the conceptualization phase), and data properties were created to represent the characteristics (properties) of each class. Additionally, individuals (specific instances of classes) could be populated within Protégé, allowing for the representation of real-world water treatment plant assets.

3.3.3 Visualizing the Ontology Structure:

Figure 3 provides a visual representation of a portion of the developed class hierarchy, object property hierarchy, and data property hierarchy within WAM-ONTO. This figure helps illustrate the relationships and structure encoded within the ontology.

By following these steps and leveraging the functionalities of Protégé, we successfully implemented the WAM-ONTO in OWL, transforming the conceptual model into a machine-readable format that can be utilized by various applications and systems for effective water treatment plant asset management.

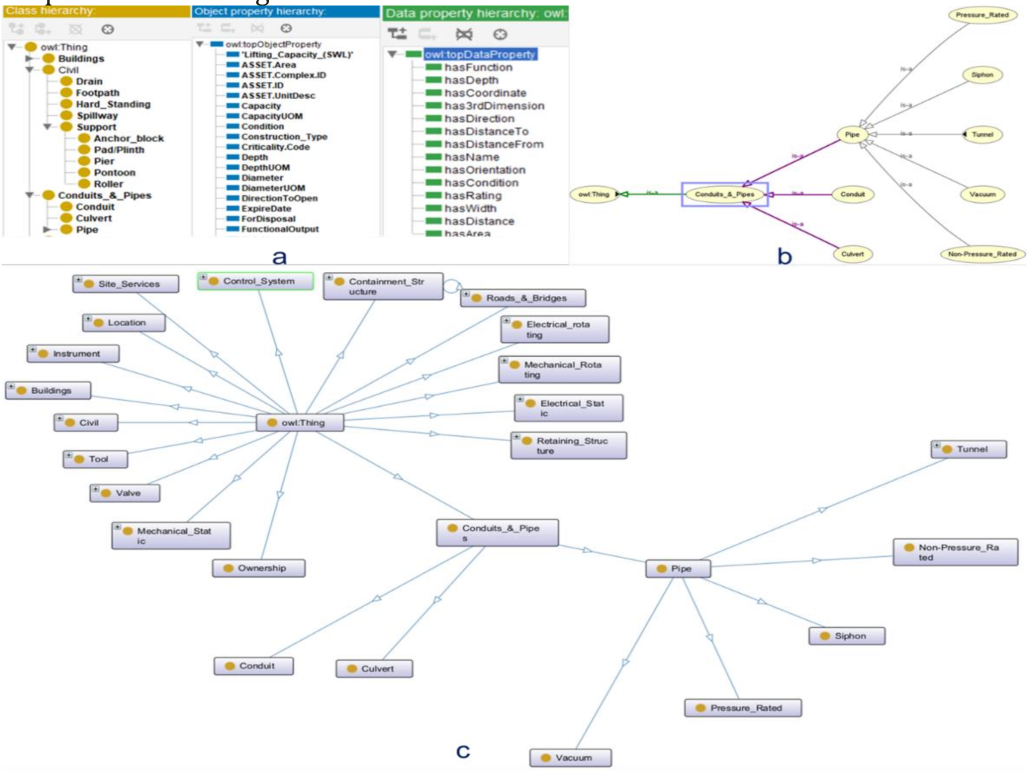

Figure 3 a. Part of the developed class hierarchy, object property hierarchy and data property hierarchy in the ontology, b. Graph representation of pipes using OWLViz, c Visualization using OntoGraf

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[1] https://protege.stanford.edu/

3.4 Ontology Evaluation and Validation

A robust validation process is essential for ensuring the effectiveness of the developed WAM-ONTO. This section outlines the methodology employed to evaluate the quality and suitability of the completed ontology. The level of consistency is about semantic terms and relationships used in the ontology to verify and validate whether the ontology threshold still has inconsistencies, or all semantic terms and relationships have reached a level of consistency. The evaluation and validation of the ontology is performed using the reasoner feature in the Protégé tool.

3.4.1 Automated Reasoning for Consistency and Coherence:

Developing a robust and reliable ontology requires ensuring its internal consistency and coherence. To achieve this, we leveraged automated reasoning tools to evaluate WAM-ONTO's logical structure. These tools performed various checks to identify potential issues within the ontology:

- **OWL Reasoners (e.g., HermiT, FaCT++):** These tools enabled us to perform consistency checking. Consistency refers to the absence of logical contradictions within the ontology. Reasoners detected inconsistencies such as conflicting class definitions or subclass relationships that lead to unintended consequences.
- **Fact++ Reasoner:** Fact++ goes beyond consistency checking and delves into reasoning about the satisfiability of concepts. In simpler terms, it checks if there can exist instances (specific examples) that satisfy the defined properties of a particular class. This helped us identify overly restrictive class definitions that might unintentionally exclude valid asset types.

3.4.2 DL Query for Targeted Validation:

In addition to automated reasoning, we employed the DL Query functionality available within the Protégé environment. This functionality had allowed us to formulate specific queries in a Description Logic (DL) language to test the knowledge encoded within WAM-ONTO. Below an explanation on how DL Query contributed to the validation process is provided:

- **Verifying Class Relationships:** We constructed DL queries to verify the relationships between defined classes in WAM-ONTO. For instance, a query might ask "Are all Pumps part of a Treatment Building?" The results of such queries helped identify inconsistencies and missing relationships within the ontology's class hierarchy.
- **Validating Property Constraints:** We tested constraints associated with properties. Queries were formulated to check if specific property values are within the permissible range defined for a class. This helped ensure data quality and consistency by identifying potential constraint violations within the ontology.

By employing DL Query alongside automated reasoning tools, we achieved a more comprehensive and targeted validation of WAM-ONTO. This combined approach helped us identify logical inconsistencies, verify relationships and constraints, and ultimately ensure a robust and expressive ontology for water treatment plant asset management.

3.5 Ontology Publication

The documentation process is a continuous activity that was conducted from the beginning of the first phase in WAM-ONTO until the end. Following the LOT methodology's emphasis on Linked Open Data (LOD) principles, we aimed to publish WAM-ONTO online to maximize its reusability and accessibility. This involved creating a designated release candidate of the ontology after thorough evaluation and documentation. The ontology's human-readable documentation, including class descriptions, usage guidelines, and diagrams, can be found on the project's GitHub repository (Zabin 2024).

4 Case Study: Applying WAM-ONTO to a BIM Model

This section illustrates the practical application of the developed WAM-ONTO on a real-world BIM of a WTP. The objective of this case study was to test the effectiveness of WAM-ONTO in representing and managing asset information within a BIM context.

4.1 Target System: Clean-In-Place (CIP) Section

We focused on the Clean-In-Place (CIP) system of the WTP BIM model for this case study (Figure 4). The CIP system is a crucial component responsible for the automated cleaning and sanitation of various equipment and piping within the water treatment process.

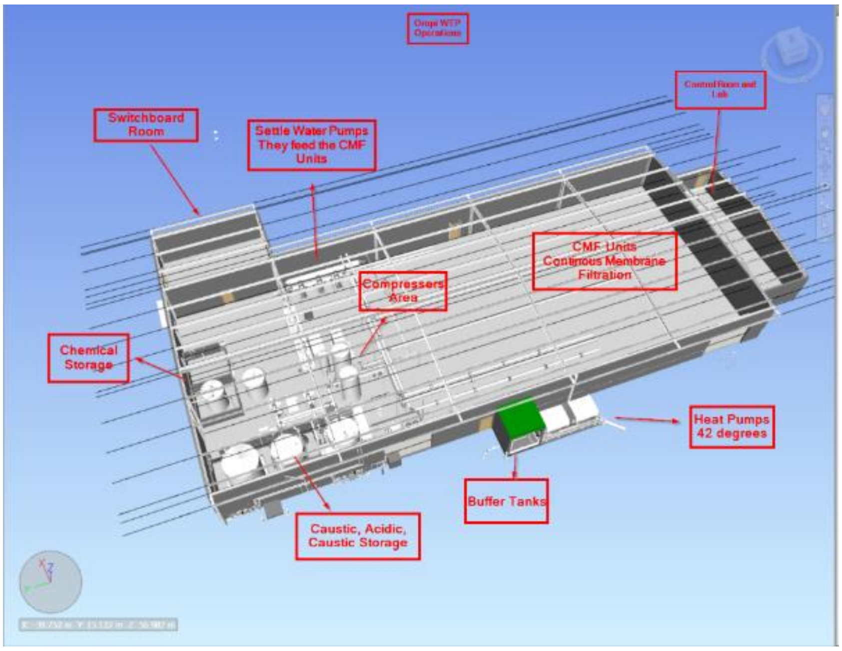


Figure 4 BIM Model – WTP Clean In-Place (CIP) Section

4.2 Ontology Mapping and Instance Population

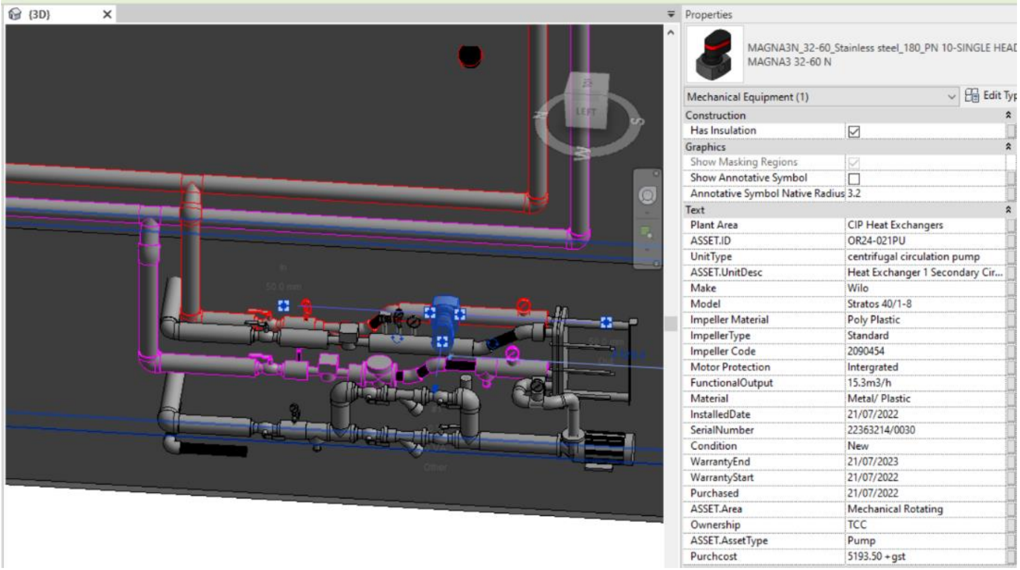
Effectively utilizing WAM-ONTO necessitates mapping it to existing data sources, such as the Clean-In-Place (CIP) system of a water treatment plant's BIM model. To achieve this, we conducted a comprehensive mapping process between WAM-ONTO's classes, relationships, and properties, and corresponding elements within the CIP section of the BIM model. This involved identifying relevant BIM entities (e.g., objects, properties) that closely aligned with the concepts defined within the ontology.

The mapping process resulted in the successful linkage of 16 classes from WAM-ONTO to corresponding BIM object types within the CIP system. Additionally, 23 WAM-ONTO properties were mapped to relevant BIM property fields. These mappings are illustrated in Figure 5.

By establishing these connections, we bridged the gap between WAM-ONTO's knowledge structure and BIM's granular details. This enables seamless data exchange and integration, ultimately leading to better decision-making for water treatment plant asset management.

5 Discussion and Future Activities

The development of the WAM-ONTO presented in this paper highlights the value of a structured approach to ontology engineering. WAM-ONTO's application to the CIP section of the BIM model successfully demonstrated its practical value. The mapping process linked WAM-ONTO classes (e.g., Pump) to BIM object types, enabling the transfer of asset information (capacity, model number) into WAM-ONTO instances. WAM-ONTO's relationships (e.g., connects-to) further allowed modeling connections between CIP equipment (pipes to pumps). This comprehensive representation in WAM-ONTO lays the groundwork for functionalities like automated maintenance scheduling or critical component identification. Overall, the CIP case study highlights WAM-ONTO's potential to bridge the gap between BIM data and water treatment plant asset management needs. Here, we delve deeper into the strengths and limitations of WAM-ONTO, compare it to existing work, and explore future activities for further development.



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Mechanical Equipment (1)

Construction	
Has Insulation	☑
Graphics	
Show Masking Regions	☑
Show Annotative Symbol	☐
Annotative Symbol Native Radius	3.2
Text	
Plant Area	CIP Heat Exchangers
ASSET.ID	OR24-021PU
UnitType	centrifugal circulation pump
ASSET.UnitDesc	Heat Exchanger 1 Secondary Cir...
Make	Wilo
Model	Stratos 40/1-8
Impeller Material	Poly Plastic
ImpellerType	Standard
Impeller Code	2090454
Motor Protection	Intergrated
FunctionalOutput	15.3m3/h
Material	Metal/ Plastic
InstalledDate	21/07/2022
SerialNumber	22363214/0030
Condition	New
WarrantyEnd	21/07/2023
WarrantyStart	21/07/2022
Purchased	21/07/2022
ASSET.Area	Mechanical Rotating
Ownership	TCC
ASSET.AssetType	Pump
Purchcost	5193.50 + gst

Figure 5 Ontology Mapping and Property Population

5.1 Limitations and Challenges:

The current version of WAM-ONTO focuses on representing core assets within the Clean-In-Place (CIP) section of the water treatment plant. While this scope proved successful for the case study, future iterations can be expanded to encompass a broader range of equipment types and functionalities across the entire treatment process.

Another key challenge lies in ensuring standardized integration methods across different BIM platforms. While the initial mapping to the specific BIM software used in the case study was successful, broader applicability requires addressing platform-specific variations.

To achieve seamless integration across different BIM platforms, future work on WAM-ONTO should leverage IFC (Industry Foundation Classes). IFC is a vendor-neutral data exchange format for BIM, promoting interoperability between various BIM software applications. By aligning WAM-ONTO's data structures with IFC entities and properties, we can ensure that the ontology can effectively integrate with diverse BIM platforms used in water treatment plant design and management.

5.2 Comparison to Existing Work:

Several ontologies exist within the water treatment domain. However, WAM-ONTO offers a more specific focus. It targets the detailed characteristics and relationships of water treatment plant assets, catering specifically to the needs of information management and decision-making within this particular context. By providing a more granular level of detail, WAM-ONTO can support more targeted information retrieval and analysis tasks related to water treatment plant operations and maintenance.

6 Conclusion

This study contributes to the body of knowledge in several keyways:

- **Formalized Knowledge Representation for Water Treatment Assets:** WAM-ONTO provides a formal and machine-readable ontology for representing the key concepts, relationships, and properties of water treatment plant assets. This standardized knowledge structure facilitates improved information management and exchange within the water treatment domain.
- **Systematic Development and Validation Methodology:** The application of a LOT-inspired approach ensures the systematic development and rigorous validation of WAM-ONTO. This methodology can serve as a valuable guide for future ontology development efforts in the water treatment industry or other engineering domains.
- **Enhanced BIM Integration and Future Applications:** The effective application of WAM-ONTO to a BIM model paves the way for future integration with BIM systems and Large Language Models (LLMs). This integration has the potential to significantly improve

information retrieval and decision-making processes within water treatment plant operations and maintenance. By enabling users to query the BIM model using natural language powered by LLMs, WAM-ONTO can contribute to a more efficient and user-friendly approach to information access.

Overall, WAM-ONTO presents a significant advancement in knowledge representation for water treatment plant assets. By laying the foundation for improved information management, data integration, and future applications with emerging technologies, this study contributes to a more efficient and data-driven future for the water treatment industry.

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