DATA MODELING FOR OPERATION AND MAINTENANCE OF UTILITY NETWORKS: IMPLEMENTATION AND TESTING

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ABSTRACT:

The organisational data models that support the information needs of utility network managers are proprietary and domain-specific, while the emerging national standards in this field often lack lifecycle data representation capabilities. However, multiple types of utility networks can be comprehensively represented with the free and open-source Utility Network Application Domain Extension (ADE) of the international standard CityGML. The Operation & Maintenance (O&M) Domain Ontology is a proposed extended version of the Utility Network ADE that allows for consistent and comprehensive processing, storage and exchange of O&M-related utility network data. So far, this ontology has not yet been implemented in a spatial-relational database. Consequently, the support it offers during routine utility asset management tasks has remained untested. This paper, therefore, tests the support of the O&M domain ontology for asset management and proposes a database implementation of this data model. To this end, it models and loads two utility networks from the campus of the University of Twente, the Netherlands. It tests the ontology’s support for asset management by simulating a street reconstruction project and retrieving necessary project information in relation to a utility’s (a) maintenance history and performance, and (b) site conditions and valve locations. Results show that the implemented model supports projects with rapid, comprehensive, and consistent information about semantic details of utilities. Such data needs yet to be collected and registered systematically to enable future data-driven asset management practices.

1. INTRODUCTION

The supply and disposal of the commodities that sustain society are realized through utility networks. The lifecycle management of utility networks is fragmented vertically, horizontally, and longitudinally. First, vertical or inter-functional fragmentation happens as companies focus on their core competences and outsource specialized tasks (Steenhuisen et al., 2009). In-house integrated ownership, management and execution of Operation & Maintenance (O&M) of utility networks thus becomes increasingly infrequent. Second, horizontal or inter-disciplinary fragmentation occurs because utility networks transporting distinct commodities are owned by different parties, and they are constructed with the combined efforts of several trades (e.g. design, piping, surveying, systems, etc.). Finally, longitudinal fragmentation exists while in knowledge and about a utility network and its components do not flow seamlessly through the different life phases and stakeholders that manage the network. This may be because of the inability to integrate historical asset records.

As a result, asset information is dispersed among multiple organizations and captured in different data models, which are often proprietary and, possibly, closed-source. There is a great number of such models at national, industry and organizational level, and each has its own conceptualization of reality (Becker et al., 2011) and specific data storage format. Consequently, utility data are often not interoperable, and organizations must transform formats (e.g. shapefile to CAD to database) and semantics (i.e. ontology to ontology) when exchanging asset information. Because of longitudinal fragmentation, asset information is not easy to retrieve and sometimes even lost. An example of this is the scarce availability of the z dimension in utility datasets, due to the lack of a placeholder in the 2D-oriented historical cadastres (Osko, 2002).

These fragmentation issues form a barrier to the growing societal pressures to safeguard the reliability of public infrastructure. Therefore, infrastructure owners increase levels of service, maintain aging infrastructure, and reduce costs by moving towards the lifecycle asset management (AM) paradigm (Wijnia & Herder, 2010). This paradigm requires that asset owners make decisions that increase infrastructure quality while also minimizing costs. It requires them to mindfully register their utilities’ lifecycle data in comprehensive models.

Comprehensive data models can integrate asset data and minimize integration issues with disparate datasets, to eventually support data-driven AM-decisions. Examples of data models are the IMKL, which is the underground utility standard for the Netherlands (Geonovum, 2019), and the one in development in Singapore (Yan et al., 2019). These models do not, however, include the detailed information needs that asset owners and managers have while making decisions about Operation and Maintenance of a utility. Models, for example, lack support for representation of performance or maintenance history. Further, the models do not support the representation of the surrounding soil and groundwater levels that are necessary to plan the trenching and dewatering tasks. We thus posit that the sector

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lacks a standardized data model that supports lifecycle asset management of utility networks.

One solution to this problem may be the open-source and free O&M Domain Ontology. This model is an improved version of CityGML Utility Network ADE 0.9.2 as it adds asset management concepts to the base model (ter Huurne, 2019). All of CityGML, the Utility Network ADE and the O&M Domain Ontology are based on the ISO 19100 standards family. The content of the O&M-model is based on different data models that practitioners currently use to represent Dutch utility networks, and it incorporates elements of IMKL, such as related party and component identifiers. The model, however, lacks a technical database implementation and testing and hence has not demonstrated its practical value as a standard for asset managers.

To address this, we present (a) the workflow that implements the O&M Domain Ontology in a PostgreSQL-based database, (b) the data pre-processing steps, (c) the workflow that semantically transforms and enriches the data and populates the database, and (d) the formalization of database queries. We demonstrate a test case of two utility networks that are located at the campus of the University of Twente to show how the model supports a typical street reconstruction project. We show the planning support that the O&M Domain Ontology enables with its Utility-Network- ADE-inherited topological module.

2. THEORETICAL BACKGROUND

Utility network asset information is typically stored digitally using formats varying in complexity (e.g. scanned records, pdf files, CAD files, geo-databases, etc.). The representation and storage of the utility networks requires the use of ontologies to achieve a standardized output (Xu and Cai, 2020). An ontology can be described as an underlying data modelling standard that is specific to a domain. In the past two decades, several technologies have been developed to help bridge interoperability issues through unifying ontologies.

One of these technologies is associated with the Geographic Markup Language (GML). GML is a vendor-neutral standard from the Open Geospatial Consortium (OGC). It defines the way in which spatial features should be represented digitally, without describing specific features (Lake et al., 2004). CityGML is an application schema of GML that digitally represents cities, including a great variety of above-ground objects (buildings, bridges, tunnels, etc.), their appearance, geometry, and other semantic attributes (Gröger and Plümer, 2012). CityGML currently has three encodings, namely GML, JSON, and a SQL-based spatial-relational database called 3D City Database or, in short, 3DCityDB (3DCityDB Development Team, 2016).

The CityGML data model can be extended modularly to add concepts from the utilities domain by using the Application Domain Extension (ADE) mechanism. Several ADEs exist (Biljecki et al. 2018), ranging in energy (Agugiaro et al., 2018) to augmented reality (Zamyadi et al., 2013). The Utility Network ADE is an extension of CityGML that provides the necessary classes and relations to represent different utility network types (e.g. water, electricity, gas, etc.) both topographically and topologically (Becker et al., 2012).

Further, the Utility Network ADE has a database encoding that extends the 3DCityDB. The latest version of the 3DCityDB tools allow for an automatic derivation of the ADE-related database using the ADE’s XSD (XML Schema Definition) file (Yao et al., 2018). By spring 2020 the Utility Network ADE is still in development and has no formal documentation. The consequence is that there are no clear recommendations on best practices to model network topology.

As the Utility Network ADE is not developed for Asset Management specifically, it lacks operation & maintenance concepts. Similarly, those O&M related attributes also lack in the IMKL data model of the KLIC-WIN program in the Netherlands (ter Huurne, 2019). Table 1 compares the most important capabilities and supported features of Utility Network ADE, the O&M Domain Ontology, and IMKL. We based the selection of elements on the requirements for the Utility Network ADE, as specified by Becker et al. (2011), and on the identified lifecycle asset management needs from the empirical observations that ter Huurne (2019) conducted in a utilities contractor firm. We established if a capability is covered by checking the presence of a class and its attributes that capture the knowledge about the properties / capabilities as listed in the table. For example, we checked whether the models supported multiple utility types by checking whether their classes included representation of water, data, etc. The table shows that the Utility Network ADE can represent network and component hierarchies, store topographies, represent topology in detail, and connect to city models. IMKL can represent attributes such as depth, related party, physical labels, and precautionary measures. The O&M ontology includes most of the representation capabilities of both the Utility Network ADE and IMKL. Topography is only considered partially supported by IMKL 1.2 because this model only stores the topography of the utility network components, and not a Digital Elevation Model (DEM) of the terrain’s surface. Topology is also considered only partially covered by IMKL 1.2 because it lacks the ‘feature graph’ concept used by UN ADE. Mapping components to feature graphs allows for more faithful representations of the topology of a network (Becker et al., 2011).

Table 1. Comparison of Utility Network ADE 0.9.2, Utility Network O&M and IMKL 2015 v1.2.

| Property / capability         | Supported? |
|-------------------------------|------------|
| Open (extensible)             | Y Y Y      |
| Multiple utility networks     | Y Y Y      |
| Network hierarchies           | Y Y P      |
| Topography                    | Y Y P      |
| Topology                      | Y Y P      |
| Connection to city objects    | N N N      |
| Maintenance activities        | N N N      |
| Performance properties        | N N N      |
| Impact                        | N N N      |
| Depth                         | N Y Y      |
| Related party                 | Y Y Y      |
| Component labels / annotations| N N N      |
| Surrounding soil properties   | N N N      |
| Indication of precautionary   | N N N      |

* 1 UN ADE can store topographies (because CityGML can). IMKL must store them separately.
* 2 UN ADE has a more advanced topological module.

Table 1. Comparison of Utility Network ADE 0.9.2, Utility Network O&M and IMKL 2015 v1.2.

In addition, the O&M Domain Ontology adds new classes and relations that provide additional capabilities for the missing asset management concepts. Figures 1 and 2 provide an example of a selection of these classes, and serve as visual aid for readers unfamiliar with the Utility Network ADE:

- ‘RelatedParty’ (Figure 1) is a new class that is related to ‘Network’, ‘AbstractNetworkFeature’, and ‘Maintenance Activity’. This class stores the name of an organisation and...
individual, their contact information, and the role of this party in the maintenance of the network or its components.

- ‘MaintenanceActivity’ (Figure 1) allows the standardized storage of the maintenance records related to components such as pipes, cables, and appurtenances.
- ‘SurroundingSoilProperties’ and ‘GroundWaterProperties’ (Figure 2) characterise the soil surrounding a utility using terms like type, strength, permeability, and groundwater level. With this data the cost and safety measures during trenching can be estimated.

Additional classes and attributes store: the milestones in the lifecycle of a component; its colour, tags and other visual information to help practitioners onsite to recognize a component; quantified environmental, societal and economic impacts of a component; and how components perform based on types (e.g. engineering and environmental), service level target scores, and actual scores. Finally, ‘MeasuredDepthProperties’ adds the possibility of recording surveyed depth, measurement location, the reference level and the survey date.

To date, the new classes from the O&M Domain Ontology have been, however, neither implemented nor tested. Thus, their asset management support has remained untested.

3. CASE STUDY AND METHODOLOGY

Approximately 300 km of utility networks lie in the 146-hectare park-like campus of the University of Twente, the Netherlands. Its department Campus & Facility Management (C&FM) manages them. C&FM consolidated all its real-estate assets into a spatial-relational database using PostgreSQL/PostGIS as backend and QGIS as frontend. This system substituted their old 2D CAD files holding all their utility data. Even though the GIS database system is a substantial improvement over the previous, C&FM still lacks a broader database to store their O&M-related information. This spurred the development of the O&M Domain Ontology (ter Huurne, 2019). This case study offers the chance to encode the O&M Domain Ontology into a database to populate and test it. In order to facilitate the reading and understanding of the several steps defined by the proposed methodology, the theoretical part and the implementation part based on the case study are presented and described together in the following.

The proposed approach consists of four steps. First, we derived the spatial-relational database that serves as backend of the system using the Unified Modelling Language (UML) class diagram of the O&M Domain Ontology (Section 3.1). Second, we pre-processed C&FM’s utility shapefiles to correct digitization mistakes and draped these over a Digital Elevation Model (DEM) of the campus (3.2). Third, we transformed the data semantically and loaded them into the database (3.3). Finally, we formalized queries related to two use cases — and visualized the results in a GIS application (3.4).

3.1 Database derivation from the class diagram

The O&M Domain Ontology’s original class diagram contains an unnecessarily large number of many-to-many relationships between classes. To avoid complexity due to an overload of association tables in the proposed database, we first simplified the defined relationships of the class diagram based on preliminary tests and dialogues with stakeholders. We enforced stricter rules on how to derive new classes from the featureType or dataType stereotypes to reduce the cardinality of many-to-many associations. This was expected to lead to a minimal loss of functionality.
The automatic database derivation with the 3DCityDB tooling resulted in a too complex output, so we derived database tables manually as a next step. Thus, we created (a) an empty database in PostgreSQL, (b) extended it with PostGIS, (c) installed the 3DCityDB v.3.3, and (d) installed the database utilities package and metadata module of 3DCityDB “Plus” (Agugiaro, 2019) to add stored procedures to 3DCityDB.

Then, we adapted the database encoding of the Utility Network ADE.9.2 by extending it with O&M-related relations. To this end, we designed the database manually following the general principles of 3DCityDB (3DCityDB Development Team, 2016), and the ADE-specific guidelines available for the database encoding of Energy ADE (Agugiaro and Holcik, 2017). In order to keep the number of tables in check we merged classes and relations into one table where reasonably possible. Figure 2 provides an example of this, where the classes ‘SurroundingSoilProperties’ and ‘GroundWaterProperties’ are mapped to the table ‘uom5_soil_and_groundwater’. We also created stored procedures to facilitate data insertion and deletion.

3.3 Semantic transformation and database populating

We created an FME workbench that transforms the utility network data to the O&M data model and imports these in the extended 3DCityDB. It also transforms and imports data representing the streets and trees at the campus. This is possible because the department C&FM also manages a database with topographic features such as buildings, trees and streets. The O&M-database can store a representation of those objects natively because it extends the 3DCityDB of CityGML. The workbench contains circa 300 transformers and writes data into both the “normal” CityGML tables and O&M-derived ones. This process assigns IDs and maps the input attributes to the corresponding ones in the O&M Domain Ontology and performs the transformation processes that are explained below.

Given the relative sparse documentation regarding the Utility Network ADE on how to generate topology and the different topological configurations from existing datasets, some of the steps that we followed in this work are listed and documented here. We generated and stored the connectivity of the network according to the structure of the O&M (and of the underlying Utility Network ADE) data model. The Utility Network ADE allows to use internal nodes and auxiliary interior feature links to model a single pipe, which in turn permits the use of complex multi-element ‘feature graphs’ while keeping the pipes in the original system unpartitioned (Figure 4B). However, we decided to partition the geometries representing pipes (Figure 4A) at every node and at every intersection with another pipe before generating the topology and obtained a simplified topological representation with fewer links and nodes (Figure 4C). The practical processing steps in FME are:

1. Partitioning pipes into independent segments at intersections with other pipes and at intersections with nodes by generating one node at the beginning of every loose end and at every intersection;
2. (2) matching existing appurtenances to the generated nodes, and classifying unmatched nodes (those with no information available in the original dataset) as auxiliary appurtenances;
3. multiplying the nodes corresponding with appurtenances to generate external nodes of pipes;
4. generating interior feature links between the exterior nodes of each pipe;
5. generating inter-feature links between exterior nodes of pipes and nodes corresponding to appurtenances;
6. finally, draping all 2D...
features onto the DEM to give them an elevation, and adding an offset to the underground by -1 m. We left the geometrical representation of the links and nodes of the topology at 0 m elevation (Figure 5), as suggested by Boates et al. (2018).

Figure 4. A) Pipe and appurtenance representation in the input shapefiles. B) Complete topological representation possible in Utility Network ADE (Kutzner et al., 2018). C) Simplified topology, adopted in this work

Figure 5. Geometric (red) and topological (blue) representations of the gas low pressure network at different heights.

3.4 Use-cases and derivation of queries

A typical and recent operation and maintenance case for C&FM is a street reconstruction project. C&FM decomposes such a project into two phases, each associated with different information needs. These are as follows:

1. Phase I. Identification & Decision: What network components are in the project area? What actions should be taken with respect to the existing utilities?
2. Phase II. Execution. What are the site conditions? Where are the relevant valves of each network?

Due to the lack of values for maintenance, surrounding soil, measured depth, related parties and performance we first enriched the dataset with dummy (but realistic) attributes. We chose QGIS as database frontend for data inspection and visualisation, and prepared SQL queries as follows.

3.4.1 Simulation of a street reconstruction

In the first step of phase I, we define the extents of the construction area by selecting a street at the University of Twente campus in QGIS. The second step performs a spatial query using the QGIS plugin ‘DB Manager’ to retrieve the pipes and appurtenances located inside the street, and to load the result as a QGIS layer (Figure 6). The results of this “identification” part of phase I match the type of information that would be obtained via a KLIC-request, the compulsory system for requesting utility location information in the Netherlands. Next, we retrieve the records needed by C&FM to decide whether to inspect, rehabilitate, replace or do nothing with the existing components within the construction area.

Phase II represents a planned maintenance work. The asset manager uses the system to extract relevant data stored in the model and send detailed assignments to the contractors that are responsible for the street and utility reconstruction work. The addition of operational on-site aspects such as the soil type and the presence of groundwater allows the contractor to better estimate the costs and plan the works, in terms of employing adequate shoring for the laterals of the trenches and estimating dewatering requirements. Furthermore, a priority in this stage is to avoid excavation damages and minimizing the consequences of an eventual pipe strike. Thus, to reduce the chances of a pipe strike the asset manager needs to identify the pipe location and depth, and the colour of the pipes. Further, to minimize the consequences of a pipe strike the asset manager needs to determine which valves must be closed to isolate the components from the source of the commodity.
4. RESULTS

The results of phase I are summarized in tables 2 to 4. Table 2 shows data that allows to characterize pipes, such as id, colour, diameter, depth, etc. A similar query could be done for appurtenances.

The next queries exemplify the case when the asset manager uses supporting maintenance and performance records to decide on the future actions on the existing infrastructure. As the maintenance history and performance information are non-geometrical, they are presented in simple tables. Table 3 presents how the maintenance history results from the query. It contains the components’ ID, maintenance timeline, the type of maintenance, the executed maintenance activity, task, dates, and the related party. Table 4 shows performance information such as the dates of installation and of performance measurement, the required and actual performance, an indication on whether the performance is sufficient, and extra information.

To obtain the information necessary during phase II, we developed two queries. The first one retrieves the site conditions, location, depth and pipe characteristics (colour, shape, size) that are necessary for the contractor to better estimate the costs and to execute the work safely. Table 5 shows the non-graphical part of the query’s output, which also includes the geometric representation of the elements in a map. The second query exploits a variant of the common Dijkstra algorithm in the pgRouting extension of PostgreSQL to locate the first valve in all the different paths that lead back to the source of the commodity (Figure 7). The query (shown in the appendix) selects the distinct valve appurtenances that are located in the 100 shortest paths from the pipe to the source by using the pg_KSP (Dijkstra with ‘K’ shortest paths) function. It looks for the connectivity information in the custom views uom5_view_pipe_topology and uom5_view_appurtenance_topology.
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APPENDIX

SELECT DISTINCT sq.appurtenance_id, sq.class, sq.geom
FROM (SELECT DISTINCT ON (pgr_KSP.path_id) appt.apppurtenance_id, appt.class, appt.geom
FROM pgr_KSP('SELECT id, start_node_id::int4 AS source, end_node_id::int4 AS target, 1 AS cost FROM citydb.uom5_link', (SELECT start_node_id FROM citydb.uom5_view_pipe_topology WHERE id=4800), (SELECT start_node_id FROM citydb.uom5_view_appurtenance_topology WHERE apurtenance_id=3257), 100,directed := FALSE)
LEFT JOIN citydb.uom5_view_appurtenance_topology WHERE apurtenance_id = appt.apppurtenance_id)
ON appt.class = 'appt.geom' WHERE app.geom

ORDER BY pgr_KSP.path_id, pgr_KSP.geom

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.

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