A Review of Utility Network Data Models

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# 1 Introduction

## 1.1 Urban Data Modelling

The modern urban citizen's expected standard of living, together with the trend of populations shifting to urban centres has made clear the necessity of careful planning and distribution of limited resources. When a person turns on the tap, water is expected to flow. When they turn on the light switch, electric current is expected to illuminate the light bulb. These kinds of services are in most cases made possible via utility networks, assemblages of physical components such as pipes, cables and other distribution elements which connect production facilities to end consumers. There are also functional elements in utility networks, which control the status and operation of the utility network. It is easy to take these systems for granted, but the truth is that these conveniences are merely the end result of a carefully-planned system, spanning entire networks at differing scales, constantly balancing network load while anticipating future demand, twenty-four hours a day, seven days a week.

## 1.2 3D Data in Urban Data Modelling

Urban data models can be designed to model any aspect of the urban environment. With the recent increases in computational capacity and availability of 3D spatial data, it has become feasible to perform simulations on urban environments that take into account physical & geometrical properties of the urban structures themselves. A popular area of research in this regard has been to use 3D building models to calculate energy losses and gains due to solar irradiance (Simons, 2014), (Quan et al., 2015), (Pili, Desogus & Melis, 2018).

# 2 Semantic City Models

A semantic city model is one which stores not only the physical and geometrical properties of the objects, but also information that is not inherently spatial, such as the age of a building, the species of tree, the type & nature of doors or windows in a building, etc. Such semantical properties are important - useful assumptions can be made from the age of a building regarding its heat loss, for instance.

## 2.1 CityGML

CityGML is a standardized storage and exchange format for 3D city models based on Geographic Markup Language (GML) and developed by the Open Geospatial Consortium (OGC). It is designed to provide a common framework for geometric and semantic information about objects found in cities at multiple levels of detail (OGC 2012). It has become a popular choice for base data intended to be used in urban simulations. This is because its standardized definitions allow for simulation models to be designed to be reusable and reproducible, while maintaining enough flexibility to suit most needs in creating customized 3D city models.

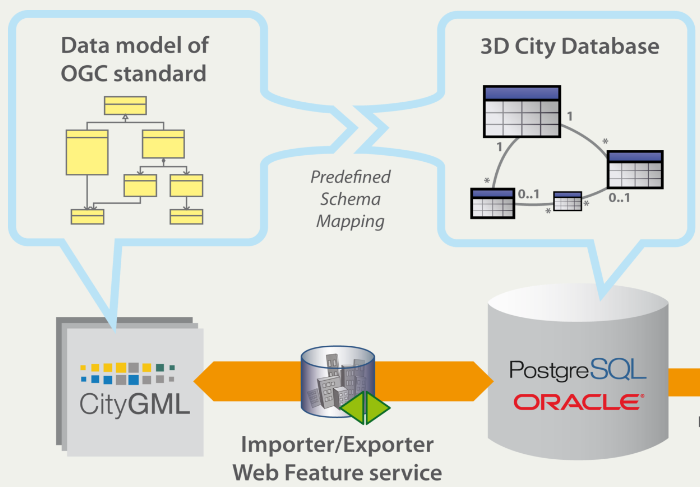
## 2.2 Application Domain Extension (ADE)

An application domain extension is an expansion of the existing CityGML schema to enable a similarly-standardized model for a specific theme (CityGML, 2018). By using the abstract *"CityObject"* class, from which all CityGML classes derive themselves from, an entirely new family of classes can be defined via an XML schema definition file (.xsd). Each ADE has its own namespace to separate them from core CityGML classes, as well as other ADE classes. In this way, multiple ADEs can be added to a single CityGML file without interfering with each other. Figure 1 depicts the modular expansion-like relationship between ADEs and CityGML.

  
Figure 1: ADEs connect to CityGML to expand their ability to model specific thematic properties of city objects. From (Nichersu, 2017)

## 2.3 3DCityDB

The 3D City Database (3DCityDB) is a pre-defined relational database schema that provides a simplified mapping of the CityGML data structure specification in a relational database context (TU Berlin, 2011). It is available for (PostGIS enabled) PostgreSQL and Oracle Spatial databases. Using 3DCityDB as the basis for an urban data model leverages the speed and transactional integrity of a relational database management system (RDBMS) while maintaining the familiar basic parts of the CityGML data model. It has enjoyed many implementations in the domain of urban modeling and simulation, including development of a 3D city model for Berlin (Stadtler et al., 2009), cloud-based storage & distribution of 3D city models (Herreruela, Nagel & Kolbe, 2012) and development of a 3D city model for New York and subsequent rendering using the Cesium web-based rendering engine (Kolbe, Burger & Cantzler, 2015). Figure 2 depicts the relationship between CityGML and 3DCityDB.

  
Figure 2: Relationship between the CityGML data model and the table schema in the 3DCityDB. From (Kunde, 2014)

# 3 Utility Networks

Utility networks are officially defined by the European Infrastructure for Spatial Information in Europe (INSPIRE) as “Node-link-node structured networks for collection, transmission and distribution, including electricity, oil/gas and chemicals, sewer, thermal, water or (not mandatory) telecommunications networks” (INSPIRE, 2018). It is a very broad definition that covers many different types of utility network types, however each network is crucial in modern urban infrastructure. The different networks can be completely different in how they operate, for example, a water network vs. an electrical network, but the “node-link-node” structure is a recurrent theme throughout all of them.

Similar to how the physical & geometrical properties of urban buildings play an important role in determining resource demand & distribution, the physical & geometrical properties of utility network structures are also important considerations, in addition to their functional connectivity. Further to this, the increasing complexity of modern utility networks introduces interdependencies. For instance, given a water processing facility that is connected to an electrical network, its operational status is therefore dependent on the operational status of the water network. In the event of an electrical network component breakdown, the water network dependent on this water processing facility may cease to have water flowing through it, or at the very least will have its flow rate otherwise affected. These kinds of interdependencies are difficult to model, given the differences in network type-specific modeling systems.

## 3.1 Modelling with Utility Networks

Utility network modeling is a broad topic with varying levels of informational requirement. The different kinds of information that could be modeled about a utility network are:

* Physical location & extent of network features (topography)
* Physical & conceptual properties of individual network features (semantics)
* Functional connectivity of network features (topology)
* Ordinal relationships of groups of network features to each other (scale)

It is not necessary to have all of these kinds of information in every instance of a utility network model. For example, for a model designed primarily for simple inventory management of network components, only the topography and semantics may be required. A model designed primarily for determining network outages due to valve shutoffs may only require the topology. For a fully comprehensive model, however, all of these kinds of information would be important.

### Water Network Modeling

Swiss Water Model???

### Common Information Modelling

The Common Information Modelling (CIM) system provides a standardized definition of typical electrical network components for use in network state & behaviour modelling. In addition, the functional connectivity of components is modelled (DMTF, 2018). In (Zhou et al., 2018), a network state & behaviour model is developed by mapping the CIM components and their relationships into a graph database representation in an electrical network context. The nodes and edges of the network are used as information storage units, as well as the means of communicating information from one part of the network to another. An algorithm is also presented that describes how topological connectivity is used to evaluate how different substations may interact with each other during network operation.

The emphasis in the CIM model (and this graph database implementation of it) appears to be on representing the state of network components and their connectivity, which is a useful standard to have when wanting to model the behaviour of a network over time, e.g. during a simulation. This information in the CIM standard could be related to geographical features for managing the network at a component scale.

### Use Case: Eco-industrial parks

Maximization of efficiency in industrial parks has been married to ecological responsibility by means of the concept of the "eco-industrial park". By using network infrastructure to connect different industrial facilities together, the by- or waste-products of one facility can be used directly as the input to another. According to (Boix et al., 2015), this promotes the development of eco-industrial parks, as they are efficient to the industries themselves, as opposed to punitive "end-of-pipe" solutions, which are often expensive and mandated by a political decree. The authors provide a comprehensive review of optimization methods used to design eco-industrial parks with maximum efficiency. However, most of the methods described are theoretically-defined, offering very little or no information about the model that could manage such complex network datasets. In order to facilitate the development of accurate and precise eco-industrial park network models, a data format is required that can model physical network component properties, their semantic properties, their functional topological connectivity. Networks for different transported media must be able to be stored together and indeed be able to interact with each other. Such a data format would allow for development of simulations that could be quickly adapted for new network datasets and / or up- or down-scaling.

### Use Case: Distributed Power Generation

(Georgilakis & Hatziargyriou, 2015) presents distributed power generation ias a hallmark of modern power distribution planning. The reductions in cost of power generation on the individual level (e.g. from photovoltaic cells and wind turbines) is significant and must be accounted for when planning electric network load balancing. A data format is therefore required that is able to model sources and sinks of electricity on low, medium and high voltage networks simultaneously, and at the same time allow spatial calculations on energy production. Algorithms designed to use such a data format as input would therefore be re-usable for different networks, and would facilitate simulation of network modifications & expansions.

### Use Case: Energy Reclamation using Another Network's Existing Infrastructure

With the increase in prevalence of district heating networks (DHNs) in Europe, it is not unexpected that some of them are beginning to integrate "waste heat" produced by commercial and/or industrial equipment (Sayegh et al., 2017). Such a coupling between individual networks further reiterates the usefulness of a standardized data format that can model the interdependencies between networks, where the output of an element in one network can serve as the input to another.

Another case of network coupling with existing infrastructure is that of (City of Nanaimo (1), 2018), wherein water flowing through pipes down a slope gains kinetic energy, which is recovered by turbines and converted to electricity for the local electric grid before being deposited into the nearby reservoir. It is clear that in order for accurate modelling and simulations to be performed, a uniform data model is required that can model topographical, topological and semantical properties, as well as the ability to store different networks and their interdependencies.

## 3.2 Visualizing Utility Networks

Given that quite often the majority of the components that comprise a utility network are underground or otherwise hidden, visualizing them becomes a top priority. The most common way of visualizing utility networks is in a GIS software. Networks can be visualized either as realistic portrayals of their physical layouts, or as simplified topological diagrams. An overview of the differences between topographical and topological visualization of utility networks, as well as an exploration of the importance of both is provided in (Semm, Becker & Kolbe, 2012). Figure 3 shows the difference between a topographical and topological visualization of the same network.

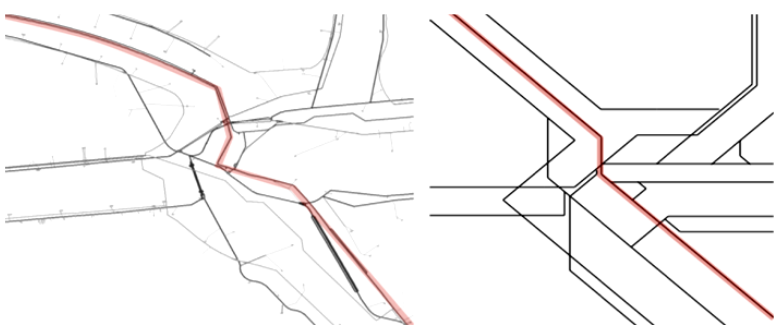
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Figure 3: Topographical (left) and topological (right) visualizations of the same network. Topography offers a clearer picture of spatial position and extent of network features, while topology offers a clearer picture of topological connectivity. From (Semm, Becker & Kolbe, 2012).

Complications arise, however, when the source data for different networks is only available in different formats, each of which tailoured for use in a specific GIS, relevant to its network type. A preferable solution would be a utility network data model that uses the same core fundamentals to model all types of utility networks at all scales. This would allow for any arbitrary GIS to easily render the network features, no matter the semantic differences between them.

### Augmented Reality

The recent advances in augmented reality (AR) technology bring exciting possibilities in the context of visualization of hidden utility network features. Devices such as tablets and AR/VR goggles are coming into the realm of affordability for industry and even personal use. It was found during a survey of people who routinely work with utility networks by (Gustafsson & Berg, 2017) that 88.9% of respondents believed that 3D visualizations of utility network data (including AR visualizations) would improve their field work. (Blut, Blut & Blankenbach 2017) have explored in great detail the feasibility and best practices of visualizing large-scale CityGML datasets for rendering on portable computers and indeed in AR applications. Given other recent successes in the field visualization of CityGML / 3DCityDB & urban simulations (Wendel, Nuñez & Simons, 2017), (Heuveline, Ritterbusch & Ronnås, 2011), a standardized, CityGML-based model for utility networks would be a valuable asset for facilitating visualization of hidden utility network components themselves, as well as the results of urban simulations thereupon.

# 4 The UtilityNetwork ADE

## 4.1 Overview

An ADE, currently under development, of particular interest for the development of urban data models involving utility networks is the UtilityNetwork ADE. It extends the CityGML schema to enable storage of features related to utility networks, including their geometry, semantic properties and topological connectivity. It was developed as a response to a lack of comprehensive support for all necessary facets of utility network modelling.

### Alternatives identified by Becker, Nagel & Kolbe in 2012

(Becker, Nagel & Kolbe, 2012) assessed the existing alternatives to utility network modelling at the time and identified several shortcomings, which prompted the development of the UtilityNetwork ADE.

The first model, the ArcGIS Network Model, was found only to be able to represent 2D topography and connectivity information. Any 3D representation would be therefore decoupled from the model. Additionally, it was limited to only water, electricity and gas networks, with no common model shared between them.

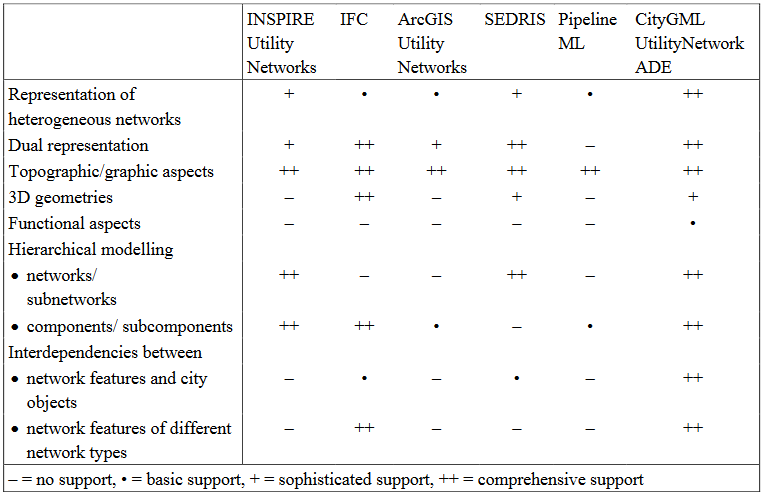
The second model, the Industry Foundation Classes (IFC) Utility Model, was found to be restricted to a local engineering reference frame, making it only relevant to individual buildings, and not feasibly able to scale up to urban scale.

The final model, the INSPIRE Network Package, was found to lack the capability to decompose features into smaller features in a hierarchical way, as well as explicit 3D topographic representations of network features. It was also found that the functionality of network features was not obvious, and that the emphasis of the model was on describing topography and not on modeling functionalities of individual features.

### Alternatives identified by Kutzner & Kolbe in 2016

(Kutzner & Kolbe, 2016) once again assessed the existing alternatives, this time after the UtilityNetwork ADE development had begun. Additionally assessed this time was SEDRIS (Source of Environmental Data Representation and Interchange), which was found to have too little software support and too much ambiguity of the format at runtime. Also assessed was Pipeline ML, which focused only on 2D geometries, and did not support topological representation of networks. A table (see Table 1) was also produced, summarizing the coverage of the alternatives in comparison with the then in-development UtilityNetwork ADE.

Table 1: Summary of levels of support for network modelling alternatvies to the UtilityNetwork ADE (from Kutzner & Kolbe, 2016).



### Other Alternatives

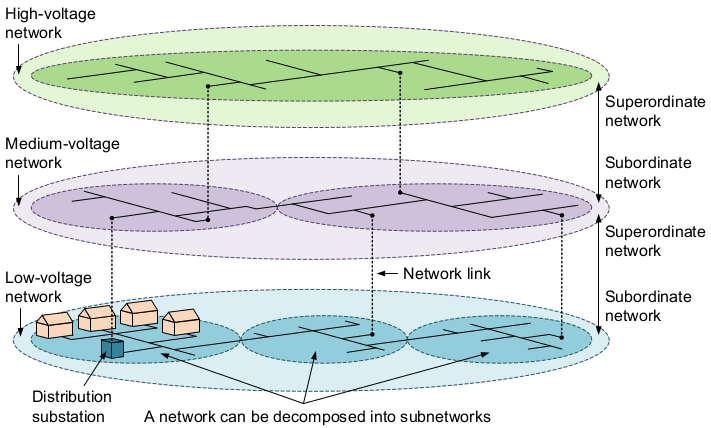
EPANET, developed by the United States Environmental Protection Agency (EPA) is a system used for modelling drinking water networks (EPA, 2018). It is however rather old, and only focuses on water networks. Furthermore, there is no explicit representation of topography and topology, which is offered by the UtilityNetwork ADE.

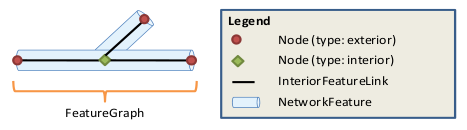
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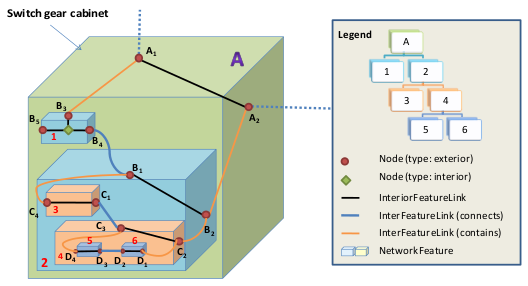
### Description of the UtilityNetwork ADE

Consequently, the UtilityNetwork ADE was designed so as to model any kind of network, at any or indeed multiple hierarchical scales (see Figure 4) with explicit definitions of the function of network components. A topographical and topological structure of networks and their constituent components allows for a simultaneous dual-representation of topography and topology. The functional linkages between network components are also modeled explicitly (see Figure 5). Network components can be aggregated into hierarchical complex features (see Figure 6). The goal was to have a data model which could store any information from the three previously mentioned data models with no information loss (Becker, Nagel & Kolbe, 2012).

The concept of recursively defining network component feature hierarchies, as well as the "dual representation concept is further elaborated on in (Becker, Nagel & Kolbe 2011). Furthermore, the need for further research into the nature of how exactly to model dependencies between networks is expressed.

  
Figure 4: Multiple networks modeled in a hierarchy. From (Kutzner & Kolbe, 2016).

  
Figure 5: Dual representation (topographical & topological) of network components with explicitly modeled linkages. From (Becker, Nagel & Kolbe, 2011)

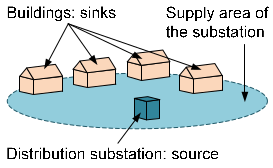
  
Figure 6: Multiple network components modeled in a hierarchy. From (Becker, Nagel & Kolbe, 2011).

## 4.2 Functional Modeling with the UtilityNetwork ADE

Functional modeling remains one of the more unexplored areas in the UtilityNetwork ADE, at least in terms of published applications. Most of the work at the time of writing is purely theoretical, and so it is important for functional modelling techniques to be applied and documented. Given the UtilityNetwork ADE’s emphasis on compatibility with all possible utility network types, functional modeling concepts must be defined as abstractly as possible, making use of terms and methods that are independent of specific network types.

### Supply areas, suppliability and suppliedness

In (Kutzner & Kolbe, 2016), the concept of the "Supply Area" is introduced, which provides an alternative for connecting consumption elements in the network. It is a geographical region, which is a property of the network, and it is considered an extent inside of which all consumption elements are inherently connected to that network's production element(s) (see Figure 7). It provides an alternative for creating functional models when little or no information is available regarding the actual layout of the network.

  
Figure 7: Distribution area for a network, connection a source network feature (production) to its sink features (consumption). From (Kutzner & Kolbe, 2016).

The concepts of "Suppliability" and "Suppliedness" are also introduced, which are intended to be measures of how much of the network's transported medium can be consumed by a consumption element, and what is at the current moment being consumed by the consumption element. These concepts are valuable in developing functional simulation models to evaluate the changes in the flow of the network's transported medium.

## 4.3 UtilityNetwork ADE in 3DCityDB

Using the same principles as how CityGML schema has been mapped to a relational database schema via the 3DCityDB (see section 2.3), there are also efforts to map the UtilityNetwork ADE schema as an extension to the 3DCityDB default schema. Following recent successes in doing so for the Energy ADE (Agugiaro & Holcik, 2017), there is such a schema mapping that has been recently completed and is undergoing testing (Agugiaro, 2018). A specific point of interest is the inclusion of so-called "smart insert functions". Relational databases often rely on complex relationships to minimize data storage requirements and increase computational efficiency, which come at the cost of ease of viewing and understanding. These "smart insert" functions allow a developer to insert individual network elements with a simple and human-readable PostgreSQL function, which takes care of the complex data relation mapping automatically to maintain database integrity. These functions make it quite simple to convert CityGML files with the UtilityNetwork ADE extension to a standardized relational database format, based on the already-familiar 3DCityDB schema.

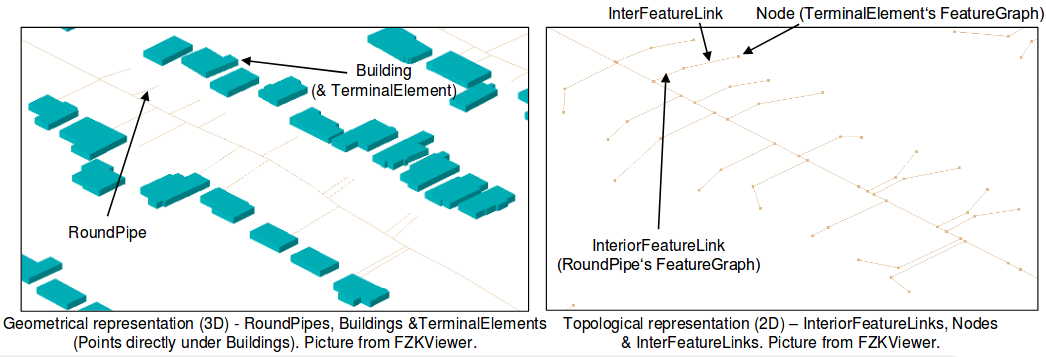
## 4.4 Applications & Examples

### Cascading Failures with SIMKAS-3D

The Simulationen von intersektoriellen Kaskadeneffekten bei Ausfallen von Versorgungsinfrastrukturen (SIMKAS-3D) project was the first use of the UtilityNetwork ADE in practice. Its goal was to model the cascading effects & failures due to an initial failure in a different, but dependent utility network. A multi-utility network complete with internetwork dependencies was developed for the city of Berlin (Bundesministerium für Bildung und Forschung, 2012). Unfortunately, the data was not made publicly available.

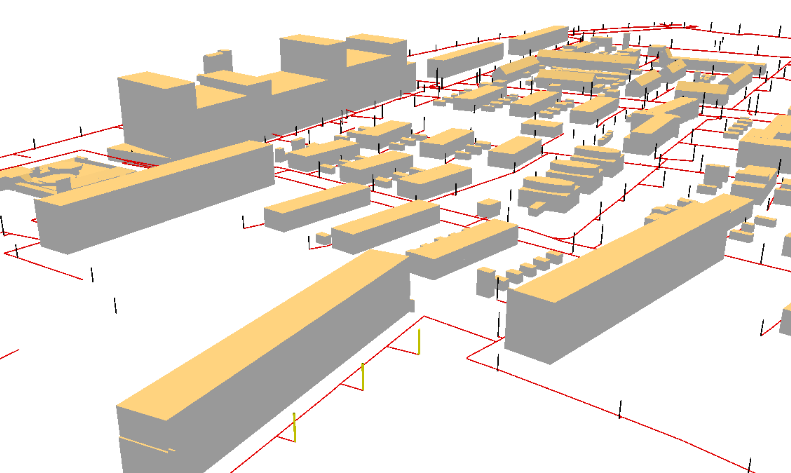
### Dual Representation with the Nanaimo Water Network

The city of Nanaimo in Canada has released various utility network data to their Open Data Catalogue (City of Nanaimo (2), 2018). (Boates, 2017) converted parts of the water network into a network dataset with functional connectivity in the UtilityNetwork ADE. Attention was given specifically to the ability to model differences between the topographical and topological representations, in accordance with the "dual representation" principle outlined in (Becker, Nagel & Kolbe, 2011). A lack of specific information about how the water pipes connected into the houses themselves led to a solution in which only the known pipes are modeled, but an abstract link is added to the topological structure to complete the functional connection (see Figure 8).

1.   
   Figure 8: Leveraging the "dual representation" principle to only model what is known about the physical network components (left), while adding abstract links to complete the functional connection to the buildings (right). From (Boates, 2017).

### 3DCityDB Implementation and Topological Routing Analysis with the Rotterdam Electric Network

The city of Rotterdam in the Netherlands has recently released their sewer and electrical network as part of an open data initiative. (Den Juin, 2017) translates this data into a functional utility network model in the UtilityNetwork ADE. Of particular interest was the subsequent conversion of the CityGML dataset to the associated 3DCityDB schema in a (PostGIS-enabled) PostgreSQL database. In doing so, the capability for the use of the pgRouting library (pgRouting, 2018) was enabled, which allowed for topological routing algorithms to be used to identify streetlights that were affected by a breakage at a specified point (see Figure 9). This proves that it is feasible to perform topological network connectivity modeling using the UtilityNetwork ADE 3DCityDB schema.

  
Figure 9: The electrical network in Rotterdam modeled in the UtilityNetwork ADE. The three yellow features are streetlights that have been identified as being affected by a network break, by using the pgRouting topological routing algorithms.

# 5 Conclusion

Utility network data models suffer from silo-ization. There is not yet a suitable unified data model that is capable of modelling all aspects of arbitrary utility network systems and modeling the interactions between the different networks in a standardized way. Despite this, existing utility networks are extremely complex, and the interdependencies between them are constantly increasing. A unified data model is needed that is able to model utility networks physically, semantically and functionally, as well as on arbitrary scales. Such a data model would be of great value for developing simulation models for extremely complex utility networks, as well as the visualization thereof.

The UtilityNetwork ADE, once finished with development, will these capabilities. As an extension of the CityGML data model, it will be able to interface well with existing semantic city models. The mapping of its schema to an extension for the 3DCityDB also allows for the leveraging of the speed and transactional integrity of an RDBMS. The work conducted so far in building models with it is promising and offers exciting possibilities in visualizing, developing urban simulations on and modeling interdependencies between utility networks.

There is, however, very little published that has to do with functional modelling using the UtilityNetwork ADE, and consequently, very few public examples. It would be very useful to have a public example demonstrating the advantages of the UtilityNetwork ADE when it comes to such modelling, both for future research and for raising awareness and interest in its development.

# 6 Bibliography

**Simons, 2014:***"Development of a CityGML infrastructure for the implementation of an energy demand method with different data sources"*. Master Thesis at Hochschule Karlsruhe Technik und Wirtschaft.

**Quan et al., 2015:** *"A GIS-based Energy Balance Modeling System for Urban Solar Buildings"*. Energy Procedia (75). Elsevier.

**Pili, Desogus & Melis, 2018:** *"A GIS tool for the calculation of solar irradiation on buildings at the urban scale, based on Italian standards"*. Energy and Buildings 158. Elsevier.

**OGC 2012:** *"OGC City Geography Markup Language (CityGML) Encoding Standard"*. Accessed 2018-03-04. <https://www.citygml.org/>

**TU Berlin, 2011:** *"CityGML DBMS storage 3DCityDB Implementation"*. Powerpoint Presentation. Accessed 2018-03-04. <https://www.3dcitydb.org/3dcitydb/fileadmin/downloaddata/Delft\_3DCityDB.pdf>

**Stadler et al., 2009:** *"Making interoperability persistent: A 3D geo databased based on CityGML"*. Proceedings of the 3rd International Workshop on 3d Geo-Information, Lecture Notes in Geoinformation & Cartography. Springer.

**Herreruela, Nagel & Kolbe, 2012:** *"Value-added services for 3D City Models using Cloud Computing"*. Geoinformatik 2012 "Mobilität und Umwelt", Konferenzband zur Tagung Geoinformatik. Shaker.

**Kolbe, Burger & Cantzler, 2015:** *"CityGML goes to Broadway"*. Photogrammetric Week '15. Wichmann.

**INSPIRE, 2018:** “Utility and governmental services”. Website. Accessed 2018-04-16 <http://inspire.ec.europa.eu/theme/us>

**CityGML, 2018:** *"Application Domain Extensions (ADE)"*. Website. Accessed 2018-03-04. <https://www.citygml.org/ade/>

**Nichersu, 2017:** *"Common Workshop of the Utility Network ADE and the Energy ADE"*. Agenda and Results of the CityGML UtilityNetwork ADE workshop 2017 December - Karlsruhe, Germany. Powerpoint Presentation. Accessed 2018-03-27 <https://en.wiki.utilitynetworks.sig3d.org/index.php/Agenda\_and\_results\_of\_the\_CityGML\_Utility\_Network\_ADE\_workshop\_2017\_December\_-\_Karlsruhe,\_Germany>

**Kunde, 2014:** *"3DCityDB V3.0"*. VirtualCitySystems. Powerpoint Presentation. Accessed 2018-03-27. <http://slides.com/fxku/3d-city-database#/>

**Gustafsson & Berg, 2017:** *"2D and 3D Visualization to Support Fieldwork in the Area of Utility Networks"*. Degree Project in Civil Engineering and Urban Management. KTH Royal Institute of Technology School of Atchitecture and the Built Envrionment.

**Blut, Blut & Blankenbach 2017:** *"CityGML goes mobile: application of large 3D CityGML models on smartphones"*. International Journal of Digital Earth. Taylor & Francis.

**Wendel, Nuñez & Simons, 2017:** *"Urban Energy Modeling - Semantic 3D City Data as Virtual and Augmented Reality"*. GIM International. Online. Accessed 2018-03-05. <https://www.gim-international.com/content/article/urban-energy-modelling>

**Heuveline, Ritterbusch & Ronnås, 2011:** *"Augmented Reality for Urban Simulation Visualization"*. The First International Conference on Advanced Communications and Computation.

**Semm, Becker & Kolbe, 2012:** *“Simultaneous Visualization of Different Utility Networks for Disaster Management”*. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume 1-2, 2012. XXII ISPRS Congress in Melbourne, Australia.

**City of Nanaimo (1), 2018:** *"Reservoir No. 1 and Energy Recovery Facility"*. Website. Accessed 2018-03-05. <https://www.nanaimo.ca/your-government/projects/projects-detail/reservoir-no-1>

**DMTF, 2018:** *“Common Information Model”*. Website. Accessed 2018-04-16. < https://www.dmtf.org/standards/cim>

**Zhou et al, 2018:** *“CIM/E Oriented Graph Database Model Architecture and Parallel Network Topology Processing”*. To be published in the Proceedings of the Power and Energy Society General Meeting (PESGM), Portland, Oregon. Cornell.

**Boix et al., 2015**: *"Optimization methods applied to the design of eco-industrial parks: a literature review"*, Journal of Cleaner Production (87). Elsevier.

**Georgilakis & Hatziargyriou, 2015:** *"A review of power distribution planning in the modern power systems era: Models, methods and future research"*. Electric Power Systems Research (121). Elsevier.

**Sayegh et al., 2017:** *"Trends of European research and development in district heating technologies"*. Renewable and Sustainable Energy Reviews (68). Elsevier.

**EPA, 2018:** *“Model for Water Distribution Piping Systems”.* Website. Accessed 2018-04-16. <https://www.epa.gov/water-research/epanet>

**Becker, Nagel & Kolbe, 2012:** *"Semantic 3D modeling of multi-utility networks in cities for analysis and 3D visualization"*. Selected papers from the 3D GeoInfo Conference 2012 in Quebec City. Springer.

**Becker, Nagel & Kolbe, 2011:** *"Integrated 3D modeling of multi-utility networks and their interdependencies for critical infrastructure analysis"*. Advances in 3D Geo-Information Sciences, Lecture Notes in Geoinformation in Cartography, Springer.

**Kutzner & Kolbe, 2016:** *"Extending Semantic 3D City Models by Supply and Disposal Networking for Analyzing the Urban Supply Situation"*. Dreiländertagung der DGPF, der OVG under der SGPF in Bern, Schweiz (25). DGPF.

**Agugiaro & Holcik, 2017:** *"3D City Database extension for the CityGML Energy ADE 0.8 PostgreSQL Version Documentation"*. Online. Accessed 2018-03-05. <https://github.com/gioagu/3dcitydb\_ade/raw/master/02\_energy\_ade/manual/3DCityDB\_Energy\_ADE\_0.8\_Documentation.pdf>

**Agugiaro, 2018:** *"3D City Database extension for th CityGML Utility Network ADE"*. Github repository. Online. Accessed 2018-03-05. <https://github.com/gioagu/3dcitydb\_ade/tree/master/03\_utility\_network\_ade>

**Bundesministerium für Bilding und Forschung:** *"Simulationen von Kaskadeneffekten bei Ausfällen von Versorgungsinfrastrukturen"*. Online. Accessed 2018-03-05. <https://www.sifo.de/de/simkas-3d-simulation-von-intersektoriellen-kaskadeneffekten-bei-ausfaellen-von-1820.html>

**City of Nanaimo (2), 2018:** Open Data Catalogue. Online. Accessed 2018-03-05. <https://www.nanaimo.ca/open-data-catalogue>

**Boates, 2017:** Nanaimo Water Pipes Utility Network ADE Sample. PowerPoint Presentation. Online Accessed 2018-03-05. <https://en.wiki.utilitynetworks.sig3d.org/images/upload/2017-12-08\_UtiltyNetworkADE\_Karlsruhe.pdf>

**Den Juin, 2017:** *"A 3D modeling approach for integrated management of below and above ground utility network features"*. PowerPoint Presentation. Online. Accessed 2018-03-05. <https://en.wiki.utilitynetworks.sig3d.org/images/upload/UtilityNetworkADE\_Karlsruhe\_XanderdenDuijn.pdf>

**pgRouting, 2018:** *"pgRouting Project"*. Online. Accessed 2018-03-05. <http://pgrouting.org/>