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Semantic Modelling of 3D Multi-Utility Networks for Urban Analyses and Simulations:

The CityGML Utility Network ADE

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ABSTRACT

Current data models for representing, exchanging, and storing utility networks often meet the needs of specific domains only, i.e. they do not consider the integration of different network systems, mutual relations between networks and the embedding into 3D urban space. These important prerequisites for urban analyses and simulations are met by the CityGML extension Utility Network ADE. Originally developed for disaster management, this article presents the further development of the ADE by new and revised concepts that result from an extensive analysis of relevant use cases. A catalogue of requirements is presented, current data models are evaluated against these requirements, and the recent developments and refinements of the ADE are explained in detail. This includes the concepts of inter-feature links and network links, the linking of network components with city objects, the modelling of functional characteristics, a refined network components module, and a new electricity network package. In addition, an overview of projects that successfully have applied the ADE is provided.

KEYWORDS

3D City Models, 3D Data Models, 3D Utility Networks, CityGML, Multi-Utility Networks

1. INTRODUCTION

Semantic 3D city models represent city objects, such as buildings, bridges, tunnels, roads, and vegetation, that mainly constitute the visible parts of a city. Cities, however, also exhibit a large number of city objects that are not apparent at first sight, but that are crucial to the functioning of the city as a system. These city objects, which are (often) hidden below ground, contribute to the infrastructure of a city in the form of networks for water, electricity, sewage, gas, telecommunication, and other public utilities. Modern society depends on a stable and complex array of these networks to deliver the various commodities. Utility network infrastructures require a sophisticated model for managing the networks and their relations to other network systems and for providing an integrated view to understand the interaction between city entities and utility networks.

One well-known standard for representing 3D city models is the international OGC standard CityGML (Gröger et al., 2012). However, Utility Networks are not included in the standard. CityGML allows for systematically extending the core model with application-specific attributes and object

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types by means of so-called Application Domain Extensions (ADE), to enable representing city objects within 3D city models which are not part of the CityGML core model. A comprehensive list of ADEs that have been created over the past years for diverse applications is given in (Biljecki et al., 2018). Specifically, for applications dealing with supply and disposal networks, the CityGML Utility Network ADE (Becker et al., 2011; Becker et al., 2012b; Kutzner & Kolbe, 2016) provides concepts that allow for modelling different types of networks.

The CityGML Utility Network ADE was originally developed based on the use case of disaster management. The development started in 2009 as part of a project called SIMKAS 3D that aimed at identifying and analyzing the mutual interdependencies of critical infrastructures and simulating cascading effects in the failure of supply infrastructures (Becker et al., 2012a). The development was further continued in 2015 as part of the project Risk Analysis Supply Infrastructure that studied the possibilities of utilizing supply infrastructures in training simulators for crisis scenarios and for simulating the impact of failures on the population.

In 2016, an international and interdisciplinary working group formed that systematically analyzed a broad variety of use cases beyond disaster management, collected requirements to make the Utility Network ADE usable for a wider range of use cases and evaluated the ADE against these requirements to be able to provide a well-grounded rationale for the concepts defined in the ADE. As a result of this work, the ADE was revised and shortcomings were fixed. Concepts that are required by specific use cases, but are not yet supported by the ADE or are not yet elaborated in detail, have been added. Already existing concepts that proved to be modelled not semantically precise enough have been refined. In addition, test data sets have been developed and used in evaluating the concepts defined in the ADE based on selected use cases.

This paper presents the results of the use case analysis and the new developments of the Utility Network ADE. Several use cases in the context of utility networks are introduced, a catalogue of requirements specific to utility networks is presented, and it is shown that each use case has differing requirements to be fulfilled. In addition, several data models prevalent in the geospatial domain for representing utility networks are evaluated against these extensive requirements to analyze to which extent they cover the needs; the evaluation shows that the CityGML Utility Network ADE provides the best coverage. Afterwards, the paper explains the new and revised concepts of the ADE; this includes network links, a refined network components module, the modelling of functional characteristics, and a new electricity network package. In addition, existing concepts which turned out to be easily misunderstood when applying the Utility Network ADE in practice are explained more precisely; this includes inter-feature links and the linking of network components with city objects such as buildings, hydrants, or street lights. In addition, the paper gives an overview of projects that successfully have applied the Utility Network ADE and which also offer publicly accessible test data.

The paper is subdivided into six sections. Section 2 discusses use cases for utility networks and their requirements. Section 3 reviews different utility network data models and evaluates them against the requirements identified. Section 4 describes the new and revised concepts of the CityGML Utility Network ADE, section 5 presents projects that have successfully applied the ADE, and section 6 concludes this paper.

2. USE CASES AND THEIR REQUIREMENTS

2.1. Utility Network Use Cases

The exploration of the information requirements for utility network applications was completed with a group of 20 persons from different firms and organizations. The persons are dealing with a wide range of utility network tasks from different domains such as storm drainage, water, electricity, energy planning, and facility management. During the workshops a list of use case areas which include electricity grid planning and simulation, waste water network planning and operation, navigation within utility networks, urban facility management and city system simulation and smart cities was compiled. In the following, specific use cases from these areas are discussed. We were especially interested in those use cases requiring an integration of 1) utility networks with city models, or 2) multiple types of utility networks, or 3) functional modeling within utility networks.

2.1.1. Storm Drainage Network

Water authorities have the responsibility to plan and manage storm drainage networks, to reduce the overflow in storm drainage systems, and to secure the city from flooding. Water authorities need to know the building sites (area/volume, private/public), building roofs and sewer systems that are connected to the storm drainage network, the areas of roofs and the land surface type. This will allow the city to estimate the amount of water that will be discharged into the storm drainage system. Therefore, there is a need to calculate the building roof areas, the different built up areas and their covering materials. Moreover, this information is of great importance to the city in order to calculate the fees they need to charge from citizens (Ofwat, 2019). The use case is an example of (1) integration of utility networks with city models.

Water authorities do not yet have a tool that allows them to search the network and quickly access the information that enables them to connect to the buildings and get information about its roof properties; also, they need to get information about built-up areas that are used as parking or asphalt yards. The water authority needs to be able to get the area of buildings and non-permeable surfaces that are connected to specific parts of the network. Retrieval of the relevant information about the roofs and other surfaces is important in order to take actions to change these surfaces to a permeable one where water can soak in. Also, a textual description that is providing a reference to the locations of the building and their owners would be useful. Information about the area of the roofs, surfaces and building uses is of great importance (Hao et al., 2012; Sohail et al., 2005).

2.1.2. Clean Water Act

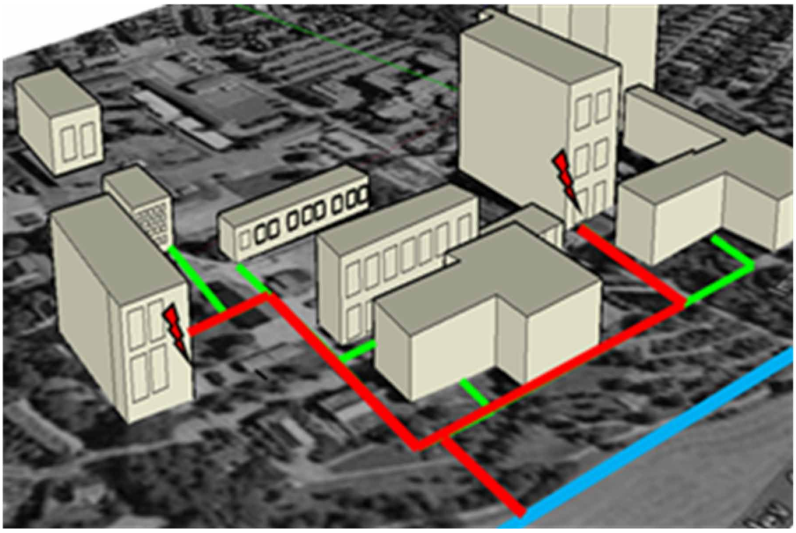
The second use case refers to the inspection of waste water (Figure 1). City authorities perform regular inspections of some buildings in the city (e.g. chemical labs, factories) to ensure that the water discharged from these buildings does meet the safety standards of public water resources (EPA, 2019). The inspection team needs to find the location of these elements inside these buildings to test whether they are working properly. Also, there is a need to establish a linkage to natural water resources such as streams. A method that provides the water authority with the ability to force rules on the network that can be linked to the natural water resource is useful in this use case. Using connectivity rule techniques, the network authority can control how to connect to other systems (Hijazi et al., 2012). This use case provides an example of (1) and (2); it requires the connection between utility networks and city models as well as between multiple types of utility networks.

2.1.3. Vulnerability Assessment and Disaster Management Emergency Response

This use case refers to disaster management in different stages, i.e., vulnerability assessment and emergency response. The use case is an example of (3), i.e. it requires functional modeling within utility networks. Vulnerability assessment is of great importance, as cities need to know the effects of natural or man-made disasters on utility networks. Important information to know is the area that can be affected and how this can affect specific network systems. The city needs to know the buildings and city facilities that will be out of service based on a natural or man-made disaster. Above the interdependency between a specific network system and other network systems is of great importance. Having the different network systems and the city objects linked in one data model (cf. Figure 2) will facilitate vulnerability assessment of the city infrastructure in order to develop mitigation plans.

In emergency situations, when the precise location of a shut-off valve and the response in a timely manner are key issues, e.g. during fire incidents, the crew team should be able to disconnect any part(s) of the service system. In addition, damage in network systems can affect accessibility to the city and can therefore affect city life (Becker et al., 2012a; Ouyang, 2014).

Figure 1. Building discharge into the storm drainage network, flash signs represent buildings that need to clean the water before it is discharged into the storm drainage network, red pipes represent the parts of the network that are connected to the building under investigation, blue color represents the natural resource that the network discharges into (Hijazi et al., 2012)



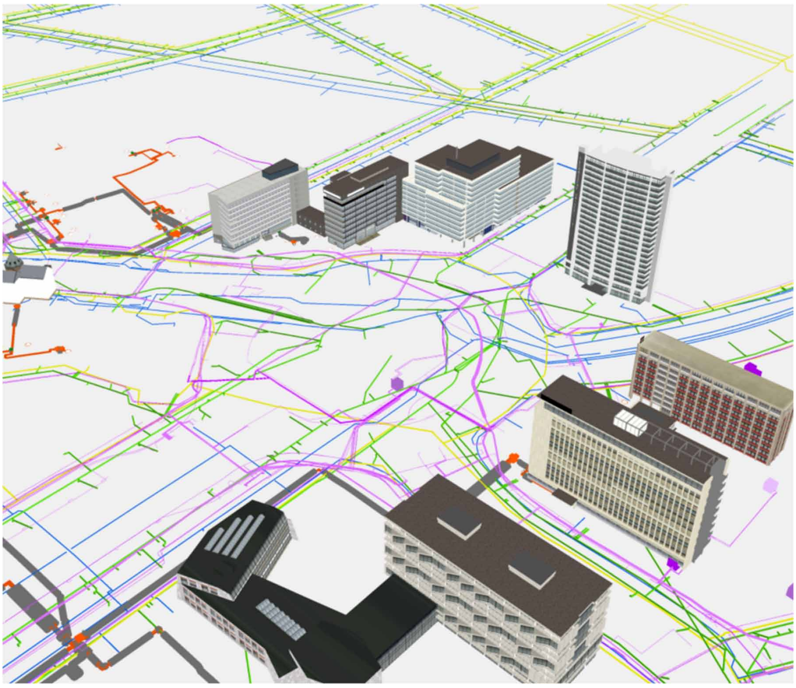
2.1.4. Maintenance Operations and Facility Management

This use case focuses on notifying residents about a scheduled or unscheduled maintenance. Facility managers need to perform maintenance operations, which can either be caused by a failure in the network or by planned (preventive) operation (due to date of expiration or cleaning). Both cases will cause an outage of service, because replacing of elements is required. Therefore, occupants of private buildings or public facilities need to be notified. The operational workflow starts by announcing the maintenance operation prior to its date after which the location of the shut-off valve must be defined and submitted to the field crew. The process in the field starts by closing the shut-off valve. In some cases, there is more than one option, and the best one to select will be that which affects the least number of occupants and city facilities (although this is not easy to define in the current system). The team needs to be able to input the location of the maintenance and have the GIS return an information product that includes a 3D view that describes the location of the shut-off and provides a textual description of the location of the shut-off in a human-oriented form. The view should provide a perspective of the space where the shut-off is, including the structure elements (e.g. manholes, walls, or slabs) and the network segments under suspicion, the segments being connected to the structure elements both upstream and downstream, as well as any other structure elements that immediately surround the shut-off location. Finally, the team needs to define the network elements and their contained space, or city objects that would be out of service when there will be a shut-off. Also, a textual description is needed providing a reference to the location of the space within the city feature (e.g. building or a long street) (Hijazi et al., 2012; Hao et al., 2012; Sohail et al., 2005). The use case is an example of (2) and (3), as the connection of multiple types of utility networks and the functional modeling within utility networks is of great importance here.

2.1.5. Smart Energy Planning, Simulation and Operation

This use case provides an example of (1), (2), and (3); it illustrates the need for a connection between utility networks and city models and for a connection between multiple networks. The use case considers co-simulation of electrical grid, heating and cooling networks as well as energy demand estimation use cases as listed in (Biljecki et al., 2015). Electricity planners and energy authorities

Figure 2. Integrated representation of city objects and different network systems at the Ernst-Reuter-Platz in Berlin as realized in the SIMKAS 3D project (Becker et al., 2012a)



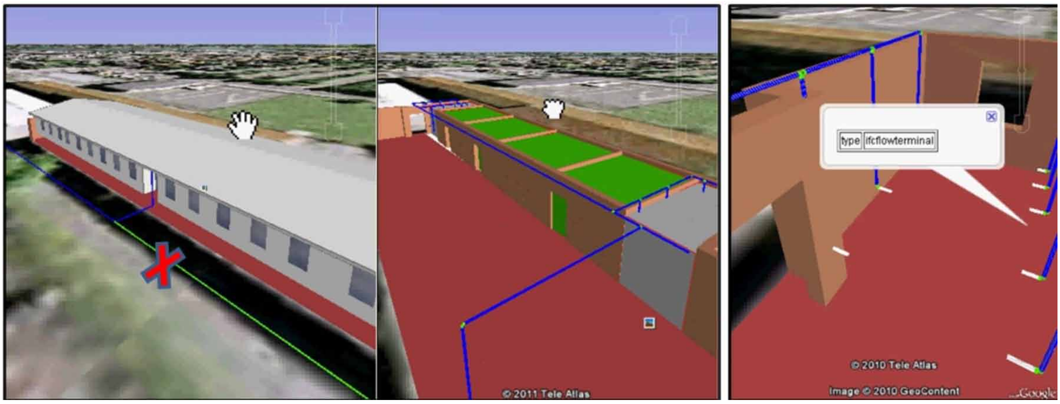
need to know how a change in land use can affect the energy consumptions and production. Also, there is a need to model interdependencies between different networks. In many cases, the state and functionality of elements in one network are directly influenced by changes in another. There is a need to provide modelling capabilities of these dependencies. Connecting network with smart city models will enable the planners to know the volume of network connected to specific electricity generators. In order to enable the accumulation of the load in the network at different scales, i.e. building to specific block and block to city or district. Therefore, network elements can be evaluated based on the stress they have. Cascading effects associated with the change in the network or a new connection can be directly evaluated. Moreover, linking smart city models to the network will enable planners, for instance, to select the best location to fix solar cells in the network (IBPSA, 2019).

Another important information is related to the ability to perform network analyses of the different utilities considering different scale levels. For simulation purposes, the ability to provide network objects themselves with information about the potential and current supply of commodities to them is important. In addition, as the issue of security is of great importance, the availability of supply areas can be important in this matter, because supply areas are in particular useful when the detailed modeling of the supply lines is not available (Kutzner & Kolbe, 2016). This use case also requires that energy planning authorities can define rules of how to connect network features to city entities and other network types. Furthermore, there is a need of coupling smart grids with buildings to simulate various issues concerning energy production, consumption, and distribution (Widl et al., 2018; Agugiaro et al., 2015).

2.2. Utility Network Requirements

On the basis of the use cases presented in the previous section, key aspects that are important to these use cases are identified. These aspects can be considered as modeling criteria or data modeling requirements regardless of the application or the final goal. These aspects will be used for the evaluation

Figure 3. Outdoor and indoor network integrated with 3D building features (Hijazi et al., 2012)



of selected network models that will be discussed in the next section. A set of 18 generic and sub-generic requirements were identified in total and subdivided into five groups:

- Spatial scope: The use cases provide us with the spatial extent that is required to facilitate the workflow in the use case. Some of the use case operations need to be modeled on city block level, others on city level or district level. Providing a modeling mechanism to aggregate or disaggregate the models to different scopes and extents is of importance.
- Spatial representation: Topographic representation is one of the most important aspects for 2D and 3D representation of network objects. Ability to operate with different geometric representations as complexes of objects is indicated as an important consideration for a GIS (Frank, 1991; Flick, 1996). In this part of the requirements investigation, we consider the following aspects:
    - Levels of detail as another method used to decrease the complexity of 3D representations.
    - Resolution and 2D and 3D representation of network objects and other city objects.
- Semantic representation: Most of the use cases require a semantic categorization of the network objects based on their role in the network. Moreover, other semantic information related to the dimensionalities, materials, volume, functions, and geometric properties of network objects are required. Utility network objects need to receive semantic specifications in order to achieve interoperability (Montello & Freundschuh, 2015; Mark & Turk, 2003).
- Spatial and logical relationships: The investigation of the operation to be performed on the different use cases provides us with the relationships that should be preserved. These spatial relationships are relationships between network objects themselves within the same network, between different networks, or between network objects and other city features. Topological data structures are required as a framework for the management of 3D spatial relationships, i.e., the 3D spatial querying is one of the key issues of a functional 3D GIS (Boguslawski & Gold, 2008; Coors, 2003; Egenhofer, 1995; Ellul, 2007). These relationships can be summarized as follows:
    - There is a need to link at the data level network fixtures (e.g. lamps, sinks) and city features (e.g. space, street) in order to select the spaces – or part of buildings or city features – that would be out of service.
    - There is a need for a link between network elements themselves in order to be able to trace the commodities that are moving through the network objects.
    - There is some network-to-network linkage that must be made between the network systems; i.e., the logical relationship between the hot water and the electricity network that needs to be maintained in the network.
    - The relation between the exterior and interior networks needs to be maintained.

  - Finally, there is a need to force constraints on how to establish the different relationships mentioned above.
  - Network for indoor navigation to routing to get to the location of failure in the utility network, i.e. easy access point.
- Visualization: Realism and interaction are necessary for information to be understood quickly. Many authors (Kofler et al., 1998; Raper et al., 1998; Tempfli et al., 1996) recommend utilization of real images to texture the model instead of comprehensive methods for illumination and shading. In this part of the requirements investigation, we consider the representation methods such as iconic and realistic visualization.
- Connection to sensors – time series data: Some of the decisions related to network management or planning requires up-to-date/real-time information about the status of the network elements or the amount of stocks (e.g. water level in a basin, energy level of a battery) available at a specific time.

The methodology to determine the importance of the above requirements to the different use cases was based on the authors thorough analysis of the use cases, the features required by each use case and their properties. The requirements were ranked using ordinal scale: not needed, basics, needed and very much needed. The results of the analysis are provided in Table 1. It clearly shows that the information requirements strongly depend on the application. Emergency response poses the highest requirements in total. To be able to support emergency and disaster management and perform rescue, response, and navigation in timely manner, there is a need to have a linkage between different network systems and also to have a connection to city objects. Therefore, in the evaluation it gets "very much needed," but the storm drainage network use case got the "not needed." Geometrical, topological (connectivity and adjacency), and semantic information shall be available. Many applications need a time component indicating the status of the network objects, e.g. the availability of commodities, either through the supply line or through storage, at a specific point in time. Maintenance operation needs information about the status of the commodities in the network at a specific location at the time of the maintenance operation, but facility management needs more matured representation of time data including time series in order to support predicative maintenance operations. All applications need semantic information to be able to address the network operations in the best possible way. Although not of general interest, connectivity rules (how network objects connect to each other or other network types) are critical for planning and simulation of different scenarios. Therefore, it gets the highest level of importance, but it needs basic capabilities to support maintenance operations. The table shows that several applications need real-time information and connection to sensors.

3. REVIEW OF RELATED DATA MODELS

A range of data models for representing, exchanging, analyzing, and storing utility network infrastructures exist already. In the course of the development of the CityGML Utility Network ADE, several of these data models have already been discussed in detail in Becker et al. (2011) and Becker et al. (2012b). This section provides a short overview of those models which are currently most relevant in the geospatial domain.

- The EU Directive INSPIRE provides the *INSPIRE Utility Networks* model (JRC, 2013a) which is based on the INSPIRE Generic Network Model (JRC, 2013b). The INSPIRE Utility Networks model defines a 2D topological relationship between network objects and allows for representing five different types of networks (water, electricity, waste water, district heat, and oil/gas/chemicals). However, the semantic categorization of network objects is basic, i.e., the data model defines, for instance, pipes and cables, but does not provide a further domain-specific classification of these network elements. Links between different types of networks cannot be represented.

Table 1. Requirements relevant to different use cases

		Storm Drainage Network	Clean Water Act	Vulnerability and Emergency	Maintenance Operation	Facility Management	Smart Energy
Spatial Scope	• City	++	++	+	•	--	+
	• Block	+	•	++	+	++	++
	• Building	•	•	++	++	++	+
Spatial Representation	• LOD	++	++	+	+	+	+
	• 2D utilities	++	++	++	++	+	•
	• 3D utilities	++	•	++	++	++	•
	• 2D city features	++	•	+	+	+	+
	• 3D city features	+	+	++	++	++	•
Semantics		++	++	++	++	++	++
Spatial and Logical Relationships	• Indoor to outdoor network	•	+	+	+	++	++
	• Connectivity rules	+	++	+	•	++	++
	• Network to City features	+	++	++	+	+	++
	• Network itself	+	+	+	+	+	+
	• Network to Network	--	+	+	+	+	+
	• Network for indoor navigation	--	•	++	+	+	--
Vis	• Realistic	+	+	+	++	++	•
	• Iconic/Symbols	--	+	+	+	•	+
Sensors/Time series data		•	++	+	•	++	++

– = no needed, • = basics, + = needed, ++ = very much needed

- The *Industry Foundation Classes* (IFC) is an ISO standard (ISO, 2013) which is predominantly used in Building Information Modeling. IFC provides a 2D and 3D representation of network objects. Relationships between network objects are described using a connectivity concept, which comprises both the physical and logical connectivity. Thus, with the IFC data model it is possible to establish a linkage between different network types. IFC provides a rich semantic categorization of network objects based on their role in the network. However, the IFC data model was developed with the intension to provide a way to model utilities at the building level. The integration of city scale network on small scale (large areas) is not supported.
- ArcGIS provides two sets of network data models to manage the logical and physical relations in a network. The *ESRI Geometric Network* model (Esri, 2017a) represents the basic structure for any utility network type. The network is composed from nodes and junctions which can be generated automatically by ArcGIS based on the physical connectivity of network objects that are represented as points and lines in the database. *ArcGIS Schematics* (Esri, 2017b) provides a mechanism to represent the logical relations in a network. Using a relationship class that represents associations between network objects, it is possible to generate a graph representing the linkage between different network objects. ArcGIS has a set of industry-specific domain data models for gas, water, and electricity that are customized based on the Geometric Network model. However, the model is lacking the topographic representation of network objects in 3D and also managing the logical relation between network objects is a challenge.
- Another ISO standard, which allows for representing utility networks, is *SEDRIS* (Synthetic Environment Data Representation and Interchange Specification) (SEDRIS, 2006). SEDRIS focuses on the representation and exchange of synthetic environments and allows for modeling networks for electricity, water and wastewater as well as for oil, gas, and chemicals. SEDRIS was developed for training simulation and is to date only applied in the military domain.

Disadvantages, however, are the high representational ambiguity of the format at runtime and the limited software support.

- *PipelineML* is a GML-based data interchange standard for the exchange of pipeline data focusing on the oil and gas industry which is currently under development by the OGC (OGC, 2016). In its current stage of development, the standard focuses on distribution components and 2D geometries only, terminal elements such as pump stations are not considered, neither is a topological representation of networks.
- *MUDDI (Model for Underground Data Definition and Integration)* is a conceptual model proposed as engineering report by the OGC which aims at representing subsurface network infrastructures including the subsurface environment (OGC, 2017). The data model defines classes, but also uses interfaces which allow for integrating concepts from other data models such as IFC or CityGML. In this way, MUDDI is interested to serve as a unified model at the granularity required to address various utility network use cases.

The different data models were analyzed regarding their support of the requirements defined in Section 2. Table 2 provides an estimation of the fitness of the different data models for the requirements under consideration. Although the introduction of the CityGML Utility Network ADE will follow in the next section, this comparison already includes the Utility Network ADE to be able to better identify advantages and disadvantages of the different data models.

The methodology for evaluating the data models was based on the authors revisions of the data models specifications for gathering capabilities. The data models were evaluated according to the criteria defined in the previous section. An ordinal level of measurement was used, i.e. no support, basic support, sophisticated support and comprehensive support. For example, the INSPIRE data model does not support LOD, therefore, it gets “no support”. On the other hand, it provides a sophisticated support of 2D utilities, but the ESRI utility network data model gets “comprehensive support”, because of its extra ordinary capabilities to represent utilities network in 2D.

4. THE CITYGML UTILITY NETWORK ADE

The CityGML Utility Network ADE provides concepts which allow for modelling different types of networks, such as electricity, freshwater, wastewater, gas or telecommunication networks, which is in particular important for 3D city model applications dealing with supply and disposal networks. Becker et al. (2011) and Becker et al. (2012b) provide a detailed introduction to the design principles of the Utility Network ADE as well as background and motivation behind its initial development. In the following, the main characteristics of the Utility Network ADE will shortly be summarized. Afterwards, a detailed description of the new and revised concepts that have been added to the ADE in the course of its further development is provided with reference to the requirements from Section 2.2 that are supported by these concepts.

4.1. Design Principles

The following list summarizes the main characteristics of the Utility Network ADE:

- **Representation of Heterogeneous Utility Networks:** The Utility Network ADE is not restricted to specific network types; various utility networks of a region can be represented simultaneously which allows for modeling multi-utility scenarios.
- **Dual Representation:** Each network component and each network can be represented topographically and topologically in 3D within the same application.
- **Hierarchical Modeling at the Feature and Network Level:** Network components can be represented as aggregations of individual parts that make up the internal structure of a network

Table 2. Support of requirements by different data models

		INSPIRE Utility Networks	IFC	ArcGIS Utility Networks	SEDRIS	Pipeline ML	MUDDI	CityGML Utility Network ADE
Spatial Scope	City	+	–	++	+	+	+	++
	Block	+	–	++	+	+	+	++
	Building	–	++	•	•	–	•	++
Spatial Representation	LOD	–	•	–	•	–	–	++
	2D utilities	+	+	++	+	+	+	+
	3D utilities	–	++	–	+	–	++	++
	2D city features	++	–	++	+	–	–	++
	3D city features	–	–	+	+	–	–	++
Semantics		+	++	•	+	•	+	++
Spatial and Logical Relationships	Indoor to outdoor network	–	–	–	•	–	•	+
	Connectivity rules	–	•	++	–	–	–	•
	Network to City features	–	•	–	•	–	•	++
	Network itself	+	+	++	++	+	+	++
	Network to Network	–	++	–	–	–	+	++
	Network for indoor navigation	–	•	–	–	–	•	•
Visualization	Realistic	•	++	–	+	•	•	++
	Iconic/ Symbols	•	–	++	–	•	•	•
Sensors/Time series data		–	•	–	+	–	•	•

– = no support, • = basic support, + = sophisticated support, ++ = comprehensive support

component and that, in turn, represent components of the network themselves. Networks can be split up hierarchically into subnetworks, superordinate and subordinate networks.

- **Representation of Different Levels of Detail:** Networks and their network components can be represented at various levels of granularity, i.e., as line and point representations or as volumetric objects, they can comprise only the most important components to build up a connected network or include every single component to obtain a detailed representation of the network.
- **Representation of Functional Aspects:** The ADE supports the modelling of supply areas and the characterization of city objects and network features according to functional roles (e.g. source and sink) which are necessary for representing supply and disposal tasks and for analyzing the impact of failures on regions.
- **Linking of Utility Networks with 3D City Models:** Since the Utility Network ADE is defined as an extension of the CityGML standard, utility networks can easily be linked with 3D city models. This allows for performing comprehensive analyses that require an integrated modelling of cities and their utilities.
- **Usage as Integration Platform and Information Hub:** The ADE does not aim at replacing other models or systems, but at providing a common basis for the integration of the diverse models in order to facilitate joint analyses and visualization tasks, e.g. by mapping data which is based on the IFC or ArcGIS model to the ADE. In addition, the ADE can serve as information hub for various stakeholders and various use cases. Data conforming to the ADE can be shared and integrated seamlessly with other utilities, without loss of information or functionality.

- **Usage Beyond City Boundaries:** The ADE can not only be applied in urban areas, but also in suburban and rural areas to represent the transmission of resources from generation plants, wells and reservoirs located outside urban areas.

The Utility Network ADE is structured into five thematic modules as is also shown in Figure 4:

- **Network Core:** The most important module of the ADE, it defines the topographic model (feature and network) and the topological / functional model (feature graph and network graph) (cf. sections 4.2-4.5).
- **Network Components:** Provides the individual components of utility networks including distribution elements, protection elements, and functional elements (cf. section 4.6).
- **Feature Material:** Defines the exterior, interior and filling materials of network components.
- **Network Properties:** Defines the liquid, gaseous, solid, electrical, and optical commodities transported by networks and their characteristics (e.g. temperature, electric conductivity, pressure, flammability).
- **Functional Characteristics:** Provides the functional concepts supply area, functional roles, and suppliability / suppliedness of city objects (cf. section 4.7).

These five modules define concepts which are relevant to all types of utility networks. Above that, concepts may exist which are required by individual network types only. For this purpose, individual network-specific packages for district heating, electricity, gas, freshwater, etc., are foreseen as part of the Utility Network ADE, as is exemplified in Figure 4 by the packages *DistrictHeatingNetwork*, *ElectricityNetwork*, and *FreshWaterNetwork*. These network-specific packages facilitate the detailed spatial representation and visualization of network-specific components as well as a more precise modelling of spatial and logical relationships in many of the use cases analyzed in section 2.2. Section 4.8 provides more details on the Electricity Network package which is the first network-specific package defined for the ADE.

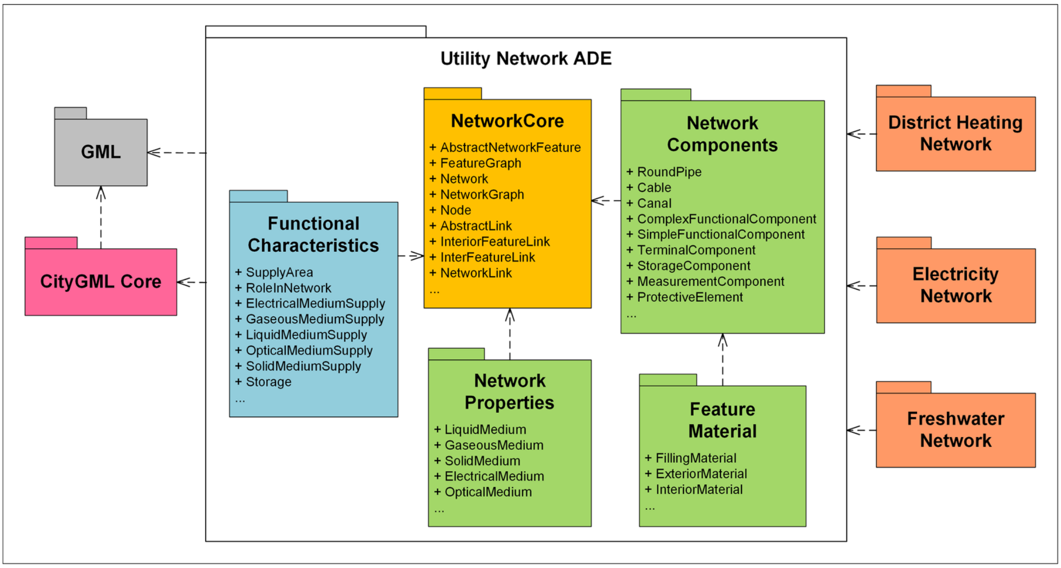
4.2. Network Core Module

The *Network Core module* shown in Figure 5 defines the central concepts for representing utility networks. Topographically, a network is represented as an aggregation of network features, i.e., of the individual components the network is constructed from. Topologically, a network is represented through a network graph, which is composed of the feature graphs of the individual network features. These concepts are defined in the data model by the classes *Network* and *AbstractNetworkFeature* as well as *NetworkGraph* and *FeatureGraph*. An in-depth introduction to the concepts defined in the data model are presented in Becker et al. (2011) and Becker et al. (2012b).

Application of the Utility Network ADE to various use cases revealed that the aspects of precise semantics of networks and the representation of relationships between different networks and between networks and city objects, as stated in section 2.2 and required by these use cases, are not sufficiently represented in the original data model. To overcome these deficits, the following refinements were realized:

- Originally, the class *Network* supported the definition of subnetworks only in the sense of subordinate and superordinate networks. Since the concepts of subordinate and superordinate network differ from the concept of subnetwork, a new bi-directional association with the role names *subOrdinateNetwork* and *superOrdinateNetwork* was added to be able to explicitly distinguish subordinate and superordinate networks from subnetworks. Section 4.4 further describes these concepts.
- Following the attribution of feature classes in the CityGML specification, the attributes *class*, *function*, and *usage* are added to *Network* as well. The attribute *class* allows for denoting the

Figure 4. Modules of the CityGML Utility Network ADE (UML Package diagram)



type of a network. The attribute *function* can be used to denote the intended usage of a network, whereas the attribute *usage* should be used to denote the actual usage of a network.

- Sometimes, different types of commodity can be transported simultaneously within a network. Power lines, for instance, cannot only distribute electricity, but they can also be used for transferring data simultaneously, which is referred to as powerline communication. To allow for the transport of more than one commodity within the same network, the multiplicity of the association *transportedMedium* between *Network* and *AbstractCommodityType* was changed from 0..1 to 0..* (not shown in Figure 5).
- Originally, a composition between *Network* and *NetworkLink* existed allowing for explicitly expressing links between networks of different network types, such as between a medium-voltage and a low-voltage network. Since *NetworkLink* represents a topological concept and *Network* a topographical concept, the composition should rather link the network topologies of the corresponding networks. Furthermore, network links are always realized by individual network components which exhibit connections to two or more different networks. For this reason, the composition is now modelled between *NetworkGraph* and *NetworkLink*. Section 4.4 provides a more detailed description of the network link concept.
- The class *Network* extends now the class *AbstractCityObject* instead of *AbstractFeature*, since not only the individual network components represent city objects, but also the networks themselves.
- Network features can be linked to city objects defined in the CityGML standard such as buildings or street lights via the attribute *connectedCityObject* in the class *AbstractNetworkFeature*. The type of the attribute was originally provided as URI, however, to specify more explicitly that the referenced city objects are city objects defined by the CityGML standard, the attribute was changed into an association referencing the class *AbstractCityObject*. Section 4.5 provides further information on how to link network features with city objects.

4.3. Inter-Feature Link Concept

When representing networks by their network topologies, traditional approaches usually map the complete network structure onto one single network graph, i.e., linear objects are mapped to edges and point-like objects to nodes. This mapping approach brings about several disadvantages: 1) Point-like objects, even when they are of considerable height or length, cannot be represented as edges. 2) Point-like objects can have several points of connection to other linear objects. These connection points cannot be represented topologically when the point-like object is mapped to a node. 3) When removing objects from the topological network, the graph can become disconnected or even invalid, when edges do not start or end with a node any more. This is shown in the upper part of Figure 6. The network consists of two pipes that are connected via a T-fitting, the pipes are represented as edges and the T-fitting as node. Removing the T-fitting results in a network graph, where the edges of the left and right pipe are no longer terminated by start and end nodes and, thus, the topological validity of the whole network graph can no longer be maintained.

To overcome these disadvantages, the Utility Network ADE uses a different approach to represent networks topologically: each network component is represented by its own feature graph and the whole network graph is an aggregation of the individual feature graphs. A feature graph consists of exterior nodes, interior nodes, and interior feature links that are represented by the classes *Node* (the attribute *type* indicates whether the node is exterior or interior) and *InteriorFeatureLink* (cf. Figure 5). The exterior nodes represent the connection points to other objects, the interior nodes can be used to model structural or logical aspects inside the network component, and the interior feature links represent edges that connect the exterior and interior nodes (cf. Becker et al. (2011) for a more detailed introduction to the feature graph representation of network components). The network graph of the whole network is created by connecting the exterior nodes of the different feature graphs via so-called inter-feature links, represented in the ADE by the class *InterFeatureLink*. This is shown in the lower part of Figure 6. The pipes are now represented as individual feature graphs, each feature graph consists of two exterior nodes that are connected by one interior feature link. The feature graph of the T-fitting consists of three exterior nodes and one interior node that is located at the intersection of the two axes of the T-fitting, all nodes being connected via interior feature links. The connection between the feature graphs is established via inter-feature links. When the T-fitting is now removed, the pipe segments still have a valid graph representation, maintaining also the topological validity of the whole network graph in this way.

The *InterFeatureLink* concept is comparable to the *Port* concept used in IFC and the concepts *ConnectivityNode* and *Terminal* used in CIM (Common Information Model, cf. section 4.8) (EPRI, 2015). Representing the network topology based on feature graphs and inter-feature links might at first sight look unnecessarily complex, however, only in this way use cases which require extensive topological analyses can be dealt with in a satisfactory way (cf. the requirement on spatial and logical relationships in section 2.2). Furthermore, with this approach it is still possible to represent network graphs according to the traditional approaches described above, supporting interoperability between systems following the traditional approach (e.g. ArcGIS) and the Utility Network ADE.

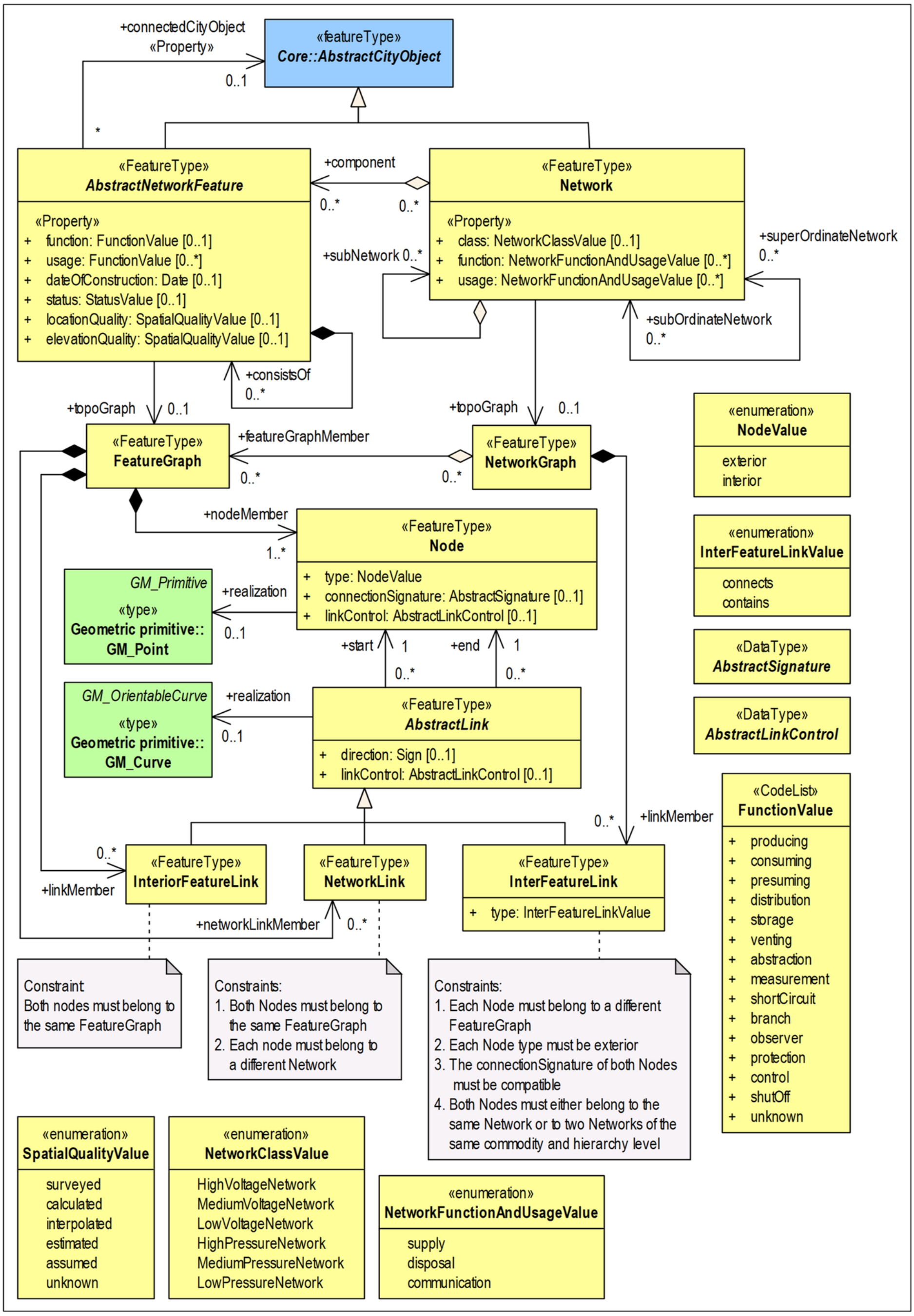
4.4. Network Link Concept

By means of network links, the Utility Network ADE allows for expressing topological and functional relationships between networks transporting the same type of commodity and between networks transporting different types of commodity. The network link fulfils the network-to-network relationship requirement of section 2.2. The relationships are established through specific network components which represent points of contact or interfaces between two or more networks. In the following, these relationships are discussed in more detail and are illustrated by common examples of network components acting as network links.

4.4.1. Network Links Between Networks Transporting the Same Type of Commodity

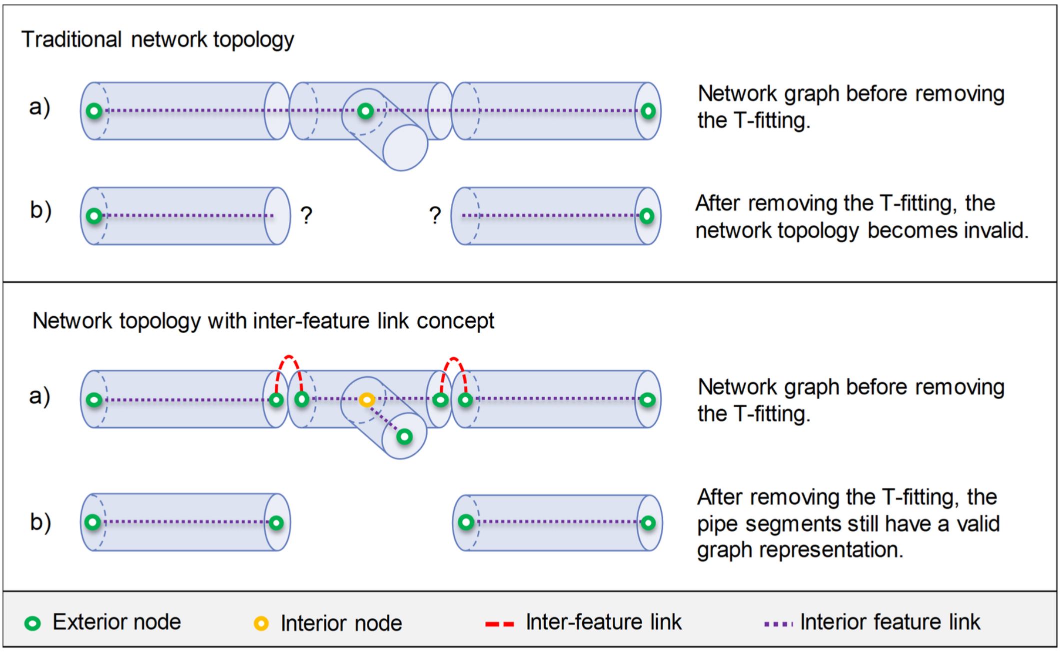
A transformer represents a common example of a network component acting as network link between a primary electrical circuit and two or more secondary electrical circuits to transfer electrical energy between them. A transformer consists of two or more coils of wire, called windings, which are wrapped

Figure 5. Refined UML model of the Network Core module. (Blue classes are CityGML classes, yellow classes are defined by the Utility Network ADE, green classes are geometry classes from ISO 19107)



around an iron core, see Figure 7(a). The winding connected to the primary circuit is called primary winding, the windings connected to the secondary circuits are referred to as secondary windings. In addition, the iron core can be considered a network of its own which transports the magnetic flux. Within circuit diagrams, specific symbols are used for representing transformers. Figure 7(b) shows

Figure 6. The role of the inter-feature link in network topologies



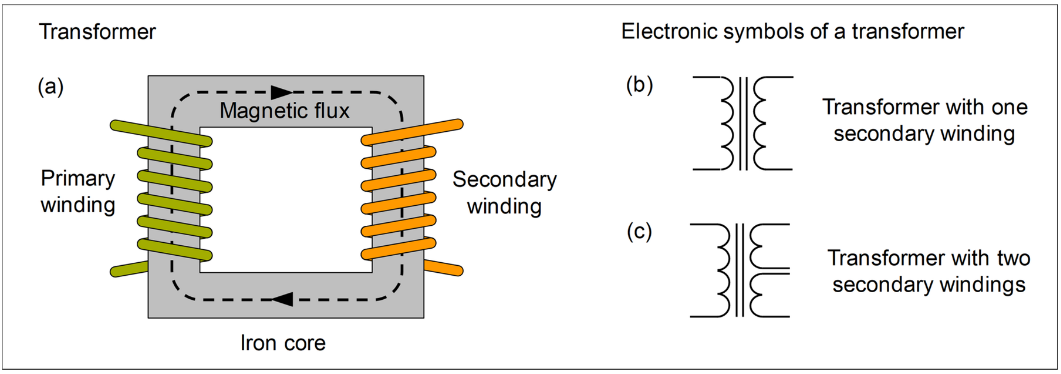
the symbol of a transformer with one primary and one secondary winding, Figure 7(c) with two secondary windings.

From these transformer symbols, the topological representation of a transformer in the Utility Network ADE can be derived. As is shown in Figure 8, each component of the transformer, i.e., primary winding, secondary winding, and iron core, is mapped to an exterior node. The nodes of the primary and the secondary windings are connected to the network graphs of the primary and secondary circuits, respectively, and the node of the iron core is connected to the network graph of the iron core network (the graphs are indicated by circles here). The actual network link between the primary and the secondary circuit can be represented in two ways. In Figure 8(a), two network links are used, one network link connects the primary circuit with the iron core network, the other network link connects the secondary circuit with the iron core network. This representation explicitly shows that it is the iron core, that establishes the functional relationship between the two circuits. In addition, the network links explicitly model the transformation of electrical energy into magnetic flux and vice versa. Alternatively, a single network link can be used to connect the primary and the secondary circuits directly, as is shown in Figure 8(b). A transformer containing two secondary windings can be represented in the same manner in the ADE as is illustrated in Figure 9. Using network links, we can now easily express that by switching off the primary network, no electrical power is induced any more in the secondary network(s).

Network links between networks transporting the same type of commodity often relate networks that can be classified hierarchically into superordinate and subordinate networks, whereas subnetworks are rather linked by inter-feature links:

- A subnetwork is part of a more extensive, interconnected network, all subnetworks being located at the same horizontal level. An example in the field of power supply are wide-area synchronous grids such as the European electricity transmission network (www.entsoe.eu) which interconnects the transmission networks of 42 electricity transmission system operators, the individual

Figure 7. Transformer representations



transmission networks being subnetworks of the interconnected European network. Similarly, a distribution network operated by a certain distribution system operator can be split up into several subnetworks, each subnetwork distributing power from a certain distribution substation to the connected end users (cf. Figure 10).

- Superordinate and subordinate networks, in contrast, represent separate networks which are located at different vertical levels. All networks transport the same commodity, however, the commodities may exhibit different parameters, such as different pressure levels, different voltage levels, or different signal frequencies. Power, for instance, is transmitted and distributed based on different voltage levels. High-voltage networks are used to transmit power across large distances, e.g. from power stations to supply regions, whereas medium-voltage networks distribute power within a supply region. By means of distribution substations, medium voltage is transformed to low voltage and distributed via low-voltage networks to the end users (cf. Figure 10). Hierarchically, the low-voltage network represents a subordinate network and the medium-voltage network its superordinate network; the medium-voltage network, in turn, is subordinate to the high-voltage network. In the same way, gas networks transmit and distribute gas based on different pressure levels, commonly distinguishing between high-pressure, medium-pressure, and low-pressure networks. Another example are cable-television networks, which commonly operate on four network levels, the content network, the headend network, the distribution network, and the home network, the signal frequency varying between the different networks.

4.4.2. Network Links Between Networks Transporting Different Types of Commodity

Several network components establish relationships between networks transporting commodities of different types. Common examples of such components are electrical pumps and heat exchangers. An electrical pump is used to move fluids by means of an electrically powered impeller; thus, the pump establishes a relationship between a fluid commodity network and an electricity network. Heat exchangers are used to transfer heat between different commodities, commonly one commodity being liquid and the other one gaseous, or both commodities being either gaseous or liquid. Heat exchangers are used in district heating to transfer heat, which is transported in district heating networks in the form of hot water, to the heating systems of buildings to heat up drinking water and radiators.

These network components can be represented in the same way as the transformers above. Figure 11 exemplifies this for the electrical pump. Relevant parts of the pump to be represented as nodes are the motor, which is connected to the electricity network, the impeller, which is connected to the fluid commodity network, and the shaft, which transfers the energy from the motor to the impeller. Similar to the transformer, where the iron core establishes the functional relationship between the

Figure 8. Representation options of a transformer acting as network link between a primary and a secondary electrical circuit

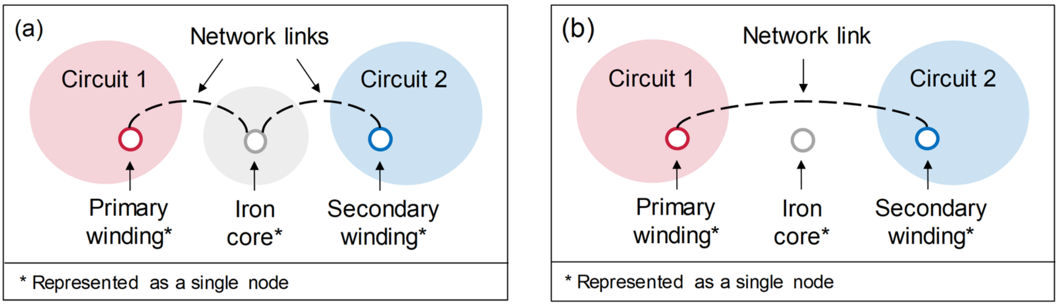


Figure 9. Representation options of a transformer acting as network link between a primary and two secondary electrical circuits

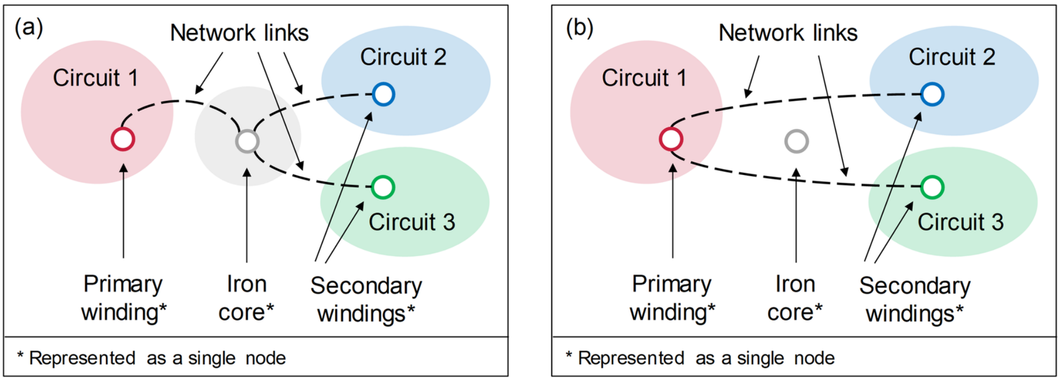
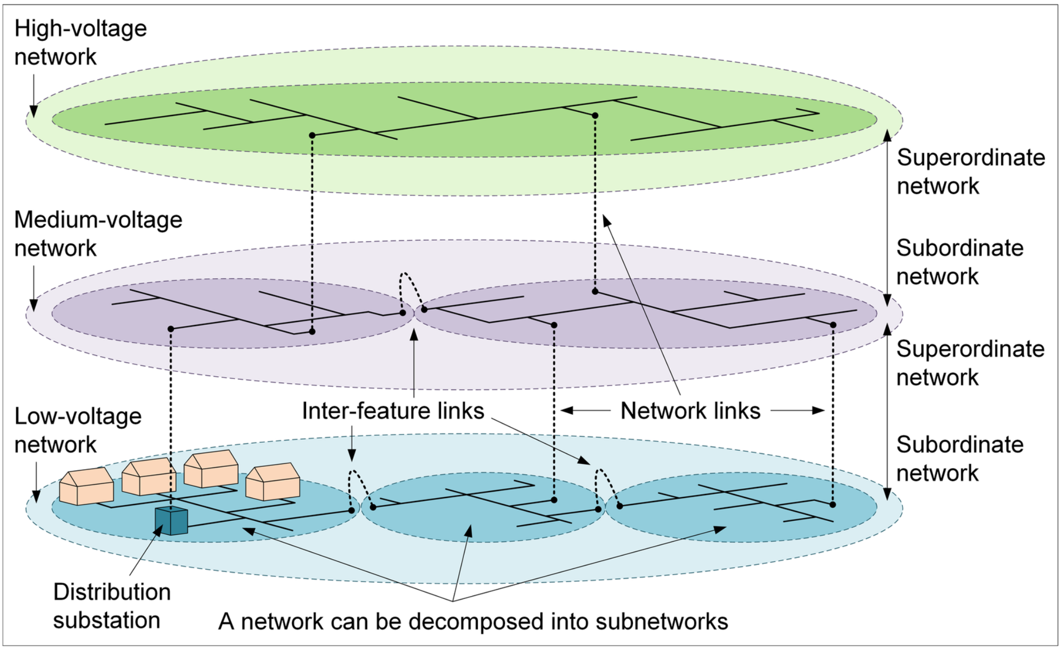


Figure 10. Decomposition and hierarchical structuring of networks in the context of power supply (Kutzner & Kolbe, 2016, modified)



different networks, it is the shaft that establishes this relationship in electrical pumps. In the ADE, this can either be expressed explicitly again, by connecting the motor and impeller nodes with the shaft node through network links, or implicitly, as shown here, by creating a direct network link between the motor node and the impeller node.

A heat pump represents a common example of a network component linking three different networks. A heat pump is a device that extracts heat from one commodity (source) and transfers it to another commodity (sink). Heat pumps are used for space heating, however, the same principle is applied in reverse order for space cooling such as in air conditioners or refrigerators. A heat pump consists of an evaporator, a compressor, a condenser, an expansion valve, and a refrigerant as is shown in Figure 12(a). The evaporator is connected to the network providing the heat source (usually air, ground, or water), the compressor is connected to the electricity network, and the condenser is connected to the network representing the heat sink (usually heating systems in buildings). The refrigerant circulates within a closed circuit of the heat pump and acts as transmitter of the heat. The evaporator extracts heat from air, ground, or water, and passes it on to the refrigerant, the refrigerant changing its state of matter from liquid to gaseous. Next, the compressor increases the pressure of the gaseous refrigerant, which further increases the temperature of the refrigerant. In the condenser, the heat of the refrigerant is then transferred to the heating system of the building, the refrigerant cooling down and becoming liquid again. Finally, the expansion valve further reduces the pressure and temperature of the refrigerant, before the cycle repeats again. The heat pump is also a good example showing that commodities can change their state of matter while circulating within a network, as does the refrigerant while circulating within the heat pump.

Within the ADE, the evaporator, the compressor, the condenser, and the refrigerant are represented as nodes that are connected to different networks. The connection between the nodes via network links can either be realized identically to the transformer in Figure 9(a), i.e., by connecting the nodes of evaporator, compressor, and condenser with the refrigerant node, or implicitly by creating direct network links between the nodes of evaporator, compressor, and condenser, as shown in Figure 12(b).

4.5. Connection Between Network Elements and City Objects

According to section 2.2, spatial and logical relationships between networks and city objects are considered relevant by all analyzed use cases. The ADE meets this requirement and allows for linking network elements to any city object defined in the CityGML standard. The connection is specified via the association *connectedCityObject* between the classes *AbstractNetworkFeature* and *AbstractCityObject* (cf. Figure 5. The association is particularly relevant for network elements of the type *TerminalComponent* (cf. Figure 15). Terminal components represent end points of a network, e.g. points where a commodity enters or leaves the network (Becker et al., 2012b). Hydrants, for instance, represent such end points in water networks and street lights in electricity networks. The end points, however, are not to be confused with the city objects representing these hydrants or street lights. The end points rather refer to that spot, where the network is connected to the hydrant or street light, i.e. where the water and electricity enter the hydrant and street light, respectively.

This connection is illustrated in Figure 13 between a water pipe and two hydrants that exhibit terminal components where the water enters the hydrants through the openings of the pipe. The pipe and the terminal components are elements of the water network; the hydrants, however, are city furniture objects, and, thus, are part of the city model. The connection from the terminal elements to the hydrants is realized via the association *connectedCityObject*. Topologically, the feature graph of each terminal component is represented by one exterior node. The feature graph of the pipe consists of interior and exterior nodes which are connected via interior feature links. Inter-feature links are used to connect the exterior nodes of the terminal components with those exterior nodes of the pipe representing the opening points to the hydrants.

Figure 11. Electrical pump representations as schematic drawing and acting as network link

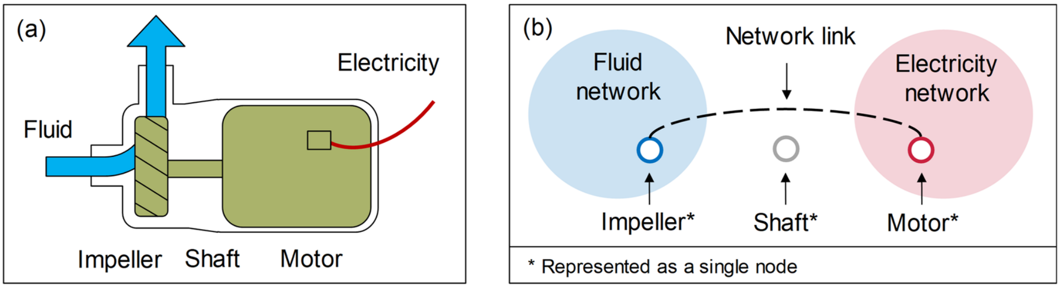
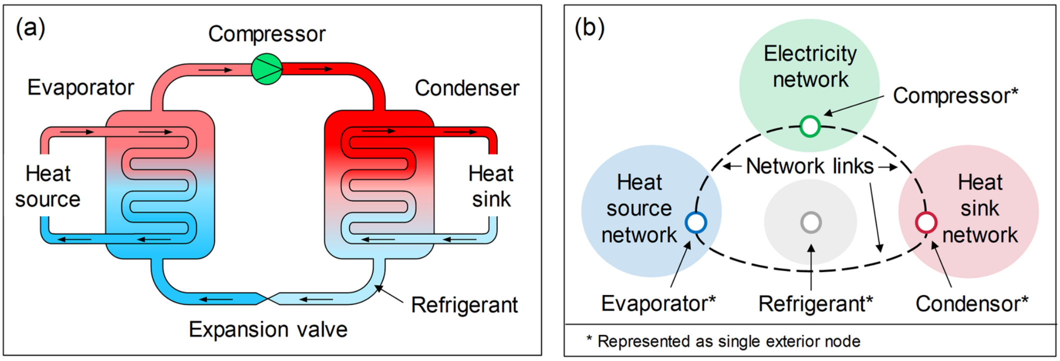


Figure 12. Heat pump representations as schematic drawing and acting as network link



4.6. Network Components Module

The *Network Components module* defines the individual components a utility network can consist of. This includes *distribution elements* for the transport and distribution of a commodity (e.g. cables, canals, pipes), *functional elements* for the linkage, control, maintenance, and observation of a commodity or transport element (e.g. manholes, valves, transformers), and *protection elements* for network security (e.g. beddings, ductwork, protection shells). This classification is represented in the Utility Network ADE through the three classes *AbstractDistributionElement*, *AbstractFunctionalElement*, and *ProtectiveElement* as is shown in Figure 14. The classes are subclasses of the base class *AbstractNetworkFeature*; from these classes, further subclasses are derived that define the individual network elements in detail (cf. Becker et al. (2012b) for an in-depth introduction to the various network components). In this way, every network component inherits the attributes from the base class *AbstractNetworkFeature* and, furthermore, can also be represented through a feature graph.

Originally, the classification was based on six classes as described in Becker et al. (2012b). Subsequent application of the Utility Network ADE to various use cases, however, revealed that this classification is not precise enough and does not allow for unambiguously relating network components from the use cases to these classes. In particular, the relation of network components to functional elements posed some problems, while the structure of the distribution and protection elements proved to be stable. According to Becker et al. (2012b), functional components are required for operating or maintaining a network, but do not represent elements of the network. In practice, however, also these components need to be considered integral part of the network itself. Manholes, for instance, are used for inspecting sewer networks, thus, they have a maintaining role, but at the same time they also connect the individual sewer pipes into a sewer network and are used to change the direction or

Figure 13. Connection between a network element (pipe) and city objects (hydrants)

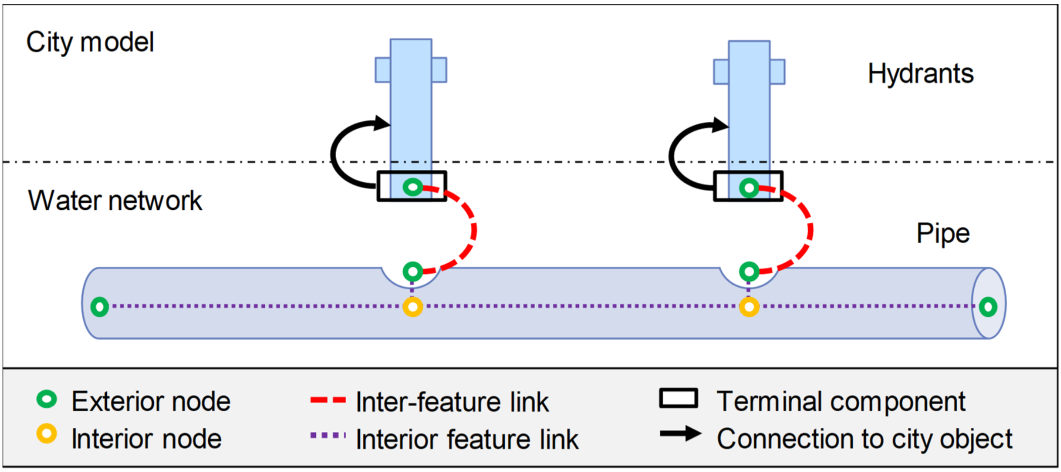
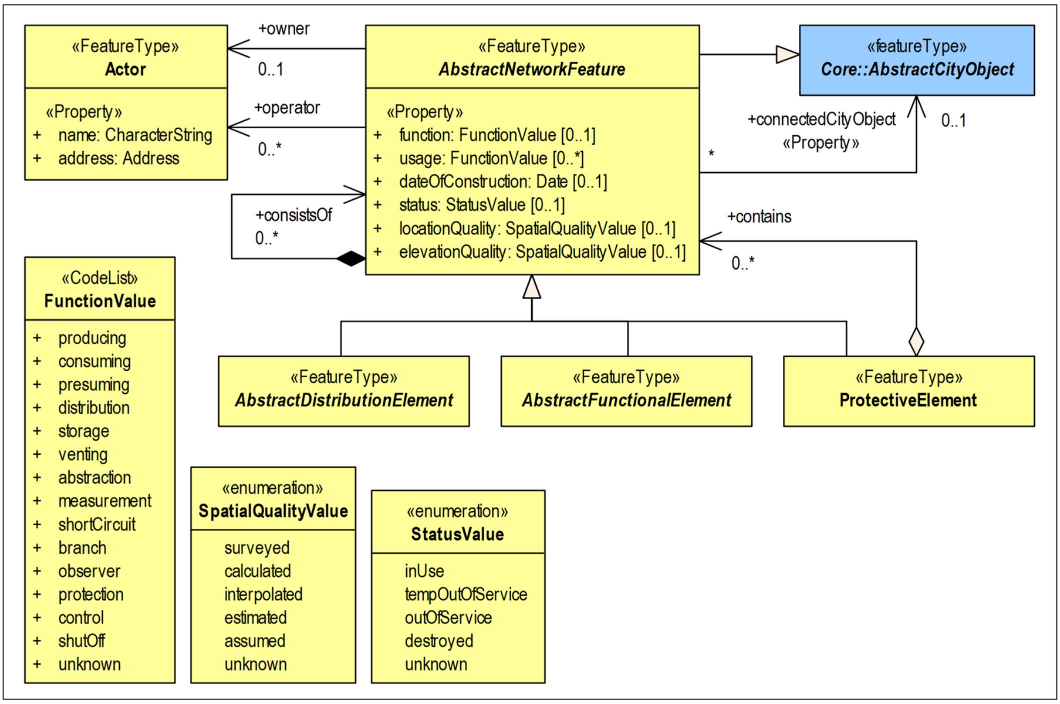


Figure 14. Classification of network components into distribution, functional, and protective elements and provision of information on owners and operators of network components



the material of sewer pipes, which means, they also represent a component of the network themselves (den Duijn, 2018a). Furthermore, topological representations of networks will exhibit gaps when they do not include the functional components. Transformers, for instance, are functional devices, but without including the feature graph of the transformer in the network topology, the network link between the two electrical circuits cannot be represented.

Based on these findings, the functional elements structure of the Network Components module was refined to better meet the demands of these use cases. In particular, this refinement fulfils the requirements on the representation of spatial and logical relationships within the same network and between different networks, indoor as well as outdoor, and on correct semantic and spatial representation and visualization of 2D and 3D utilities at different spatial scopes as defined in section 2.2. Figure 15 presents the new structure that is based on three fundamental classes: *AbstractFunctionalElement*, which acts as superclass for all functional elements, *SimpleFunctionalComponent*, which is the base class for individual functional components, and *ComplexFunctionalComponent*, which represents functional components that are aggregated from simple or complex components recursively. The classes *StorageComponent*, *MeasurementComponent*, *ControllerComponent*, *OtherComponent*, and *TerminalComponent* are reused from the previous model (their suffix *Device* was renamed to *Component* to be consistent with the general naming) and are now modelled as subclasses of *SimpleFunctionalComponent*. In addition, a new subclass *ConnectionComponent* is introduced as suggested by den Duijn (2018a), since they represent one of the most essential components of a network besides distribution elements without which no connected network exists, thus, they should be represented explicitly by their own class.

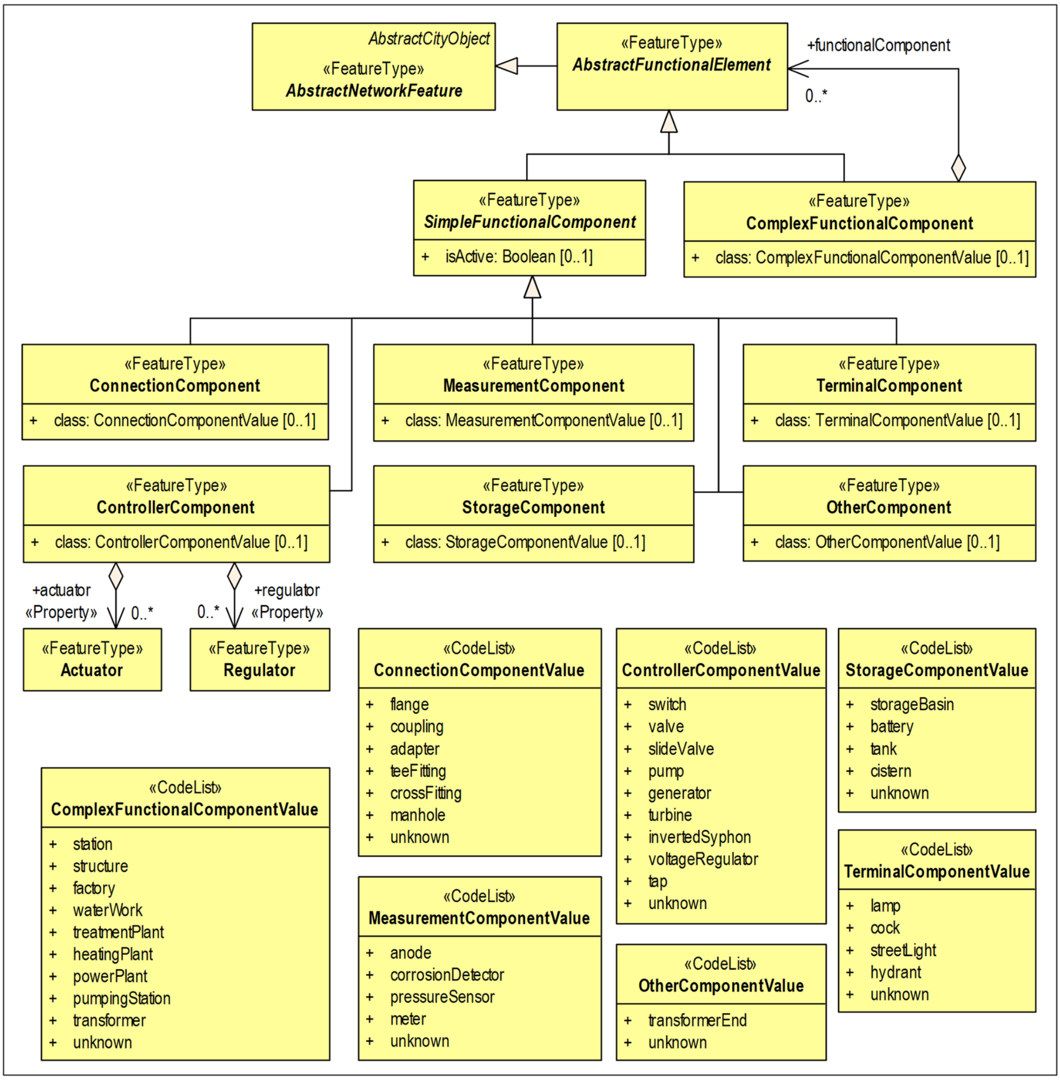
The introduction of the Electricity Network package (cf. section 4.8) requires network elements to be classifiable into passive and active elements. To meet this demand, the attribute *isActive* is added to the class *SimpleFunctionalComponent*. In the context of the Utility Network ADE, active elements are defined as network elements that play an active role in the network (e.g. pump, valve, generator). These elements can generate, process, or amplify a commodity and require some form of power (e.g. electric, manual) to operate. In contrast, passive elements represent network elements that play a passive role in the network (e.g. busbar, resistor, tee fitting). These elements passively support the transport of commodities and do not require power to operate.

The complex functional class and each simple functional subclass define the attribute *class* that can be used to specify the type of the functional element explicitly. For this purpose, code lists with common values of different types of networks are provided (cf. Figure 15). The code lists provided here are not complete, they can be extended by further values or even be redefined depending on the use case. However, if a use case requires a more detailed modelling of a specific functional element, a subclass with additional attributes can be defined instead. In this way, a manhole, for instance, can either be defined using the class *ConnectionComponent*, the attribute *class* holding the value *manhole* in this case, or, a specific class *Manhole* can be introduced as subclass of *ConnectionComponent* which allows for adding additional attributes such as the height and the diameter of the manhole. Creating subclasses of individual functional elements is of particular interest for the modelling of specific network packages as is shown in section 4.8 for the Electricity Network package.

Specific utilities may differentiate more precisely between some of the network components defined in the Network Components module. For instance, the electricity domain differentiates between ‘cables’ and ‘lines’, cables being buried in the ground and lines being above ground, and between ‘transmission’ and ‘distribution’ cables / lines. Within the Utility Network ADE, however, this classification is realized at the level of the *class* attributes and not through individual feature types.

In addition to restructuring the Network Components module, a new class *Actor* is introduced (cf. Figure 14) which can be used to provide information on the owner and operator of network elements. The class is linked with the class *AbstractNetworkFeature* via two associations with the role names *owner* and *operator*. The associations need to be added to the network components and not to the network itself, since different components within one and the same network can be operated by different utility providers and one component can even be operated by several providers. This information is important for various use cases in the context of energy-related analyses and management of utilities.

Figure 15. Refined modelling of the functional network elements



4.7. Functional Characteristics Module

Originally, the Utility Network ADE focused on *topographical* and *structural* aspects that allow for representing in detail the structure of a network together with all the discrete network components the network is composed of and for deriving spatial and computer-graphic-related answers therefrom. For representing supply and disposal tasks, often *functional* aspects are of relevance as well. Functional aspects can be represented through the topological connection of the network components which allows for simulating the propagation of failures across multi-network structures. However, due to data privacy issues or other reasons, no information reflecting the detailed modelling of a network supplying a certain area with a commodity might be available; nevertheless, it must still be possible to analyze the impact a network failure has on a certain region and on the concrete city objects located in that region. For this reason, the *Functional Characteristics module* was introduced which allows for modelling supply areas, defining functional roles, and providing information on commodity supply

(Kutzner & Kolbe, 2016). The concepts can be used at different spatial scopes, provide additional semantics, support logical relationships, and can be coupled with real-time sensor data as defined in the requirements in section 2.2.

4.7.1. Representation of Supply Areas

The supply area represents that geographic region a specific commodity is supplied to by a network. When a failure in one of the network components occurs, a detailed modelling of the network allows for easily analyzing which parts of the network itself and which city objects that are connected to the network are affected by this failure. To be able to perform analyses also without a detailed modelling of the network, a supply area can be specified which is explicitly being related to one or more sources supplying a commodity to that area; furthermore, corresponding sinks can be defined. In the power supply context, for instance, a distribution substation providing electricity to a certain area could be regarded as such a source and the buildings in this area supplied with the electricity as sinks (cf. Figure 16).

The supply area is represented in the Utility Network ADE by the class *SupplyArea* (cf. Figure 17). By defining *SupplyArea* as a subclass of *CityObjectGroup*, each supply area can be provided with a geometry defining the spatial extent of the supply area. The city objects located within a supply area can be determined in two ways: Either implicitly by intersecting the geometry of the supply area with the geometries of the city objects, assuming in this way that all city objects located within the supply area are sinks, or explicitly, by relating a supply area to the city objects located in that area through the association *groupMember* between *SupplyArea* and *AbstractCityObject*. A 1:1 association between *SupplyArea* and *Network* relates each supply area to the corresponding network supplying that area and vice versa.

4.7.2. Characterization of Infrastructure Objects According to their Functional Role

Another important functional aspect is the possibility of representing the flow of commodities in a network by denoting network features and city objects with one of the roles source, sink, distribution, or storage. This information is also required for relating a supply area with corresponding sources and sinks.

The modelling of this aspect was already partially available in the Utility Network ADE. The class *AbstractNetworkFeature* already provides the attribute *function* to state the intended role of a network feature (the values *feeding* and *draining* in the code list *FunctionValue* are representing the roles source and sink, respectively). To allow also for expressing the actual role of a network feature, which might change when a network feature is used differently from its intended usage, the attribute *usage* is newly added (cf. Figure 18). Furthermore, the class *RoleInNetwork* is specified to

Figure 16. The relationship between supply area, source, and sink (Kutzner & Kolbe, 2016)

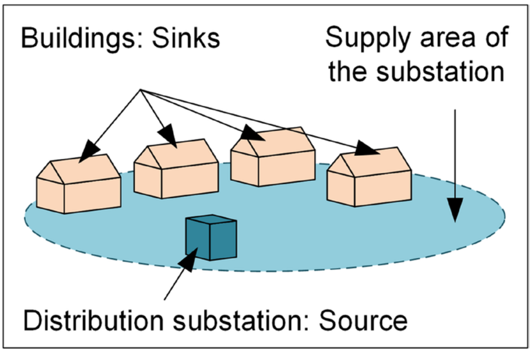
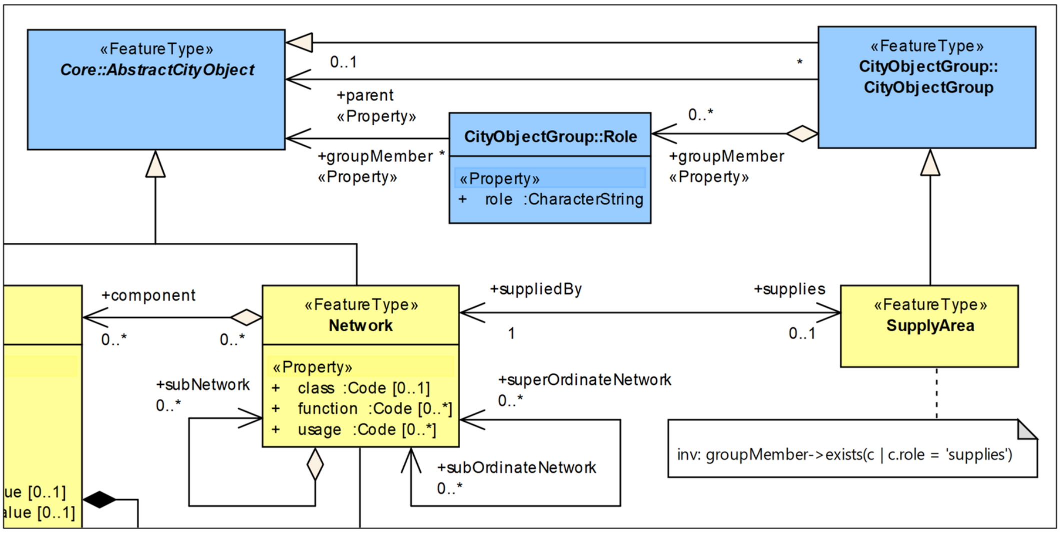


Figure 17. Representation of supply areas in the CityGML Utility Network ADE (Kutzner & Kolbe, 2016)



enable adding these roles to city objects as well. The class defines the attributes *functionInNetwork* and *usageInNetwork* which allow for denoting the intended and actual roles of a city object within a specific network. Each city object can be provided simultaneously with role information specific to different networks, i.e. a building can, for instance, at the same time be denoted as sink in a power network and as source in a wastewater network.

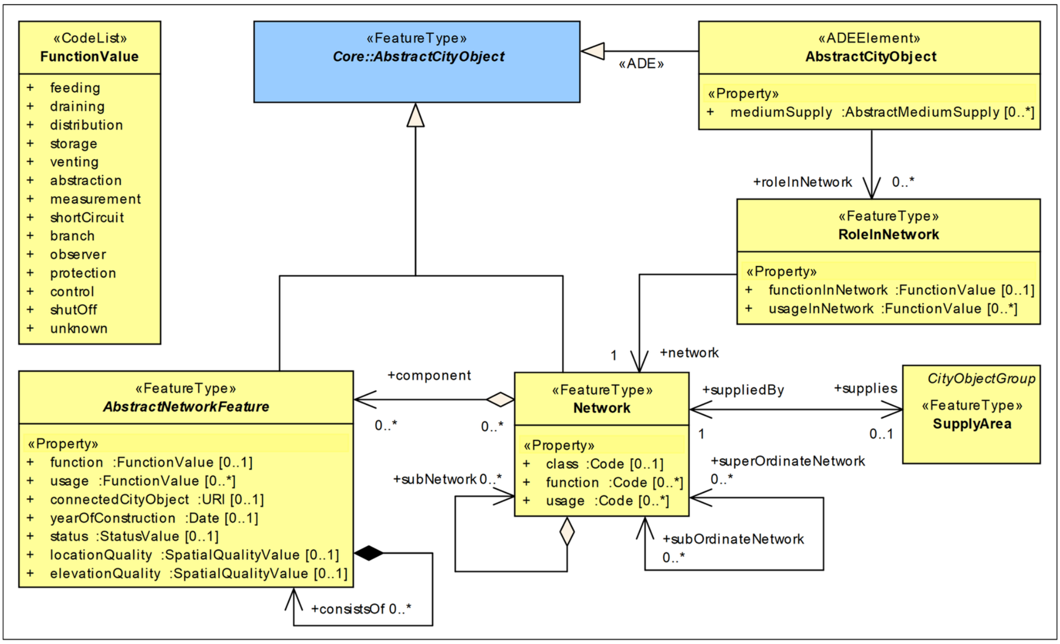
The connection between the supply area and the roles the city objects located in that area play, is established through the transitive relationship between *AbstractCityObject* and *SupplyArea* via the classes *RoleInNetwork* and *Network*. Similarly, the transitive relationship between *AbstractNetworkFeature* and *SupplyArea* via *Network* establishes the connection between the supply area and the roles the network features located in that area play.

4.7.3. Representation of the Potential and Current Supply of Commodities to City Objects

In the context of various simulations, and also in general when no information at all is available on networks, it can be useful to provide the city objects themselves with information on the potential and current supply of commodities to them. The concept *suppliability* defines the *potential supply* of a commodity to a city object, the reliability of the supply and whether storage is available allowing for autonomous supply with a commodity in case the supply via a network is interrupted, for instance due to a natural disaster. The concept s*uppliedness* defines the *actual supply* of a commodity to a city object at a specific point in time as well as the actual reliability of the supply and the actual state of the storage at that point in time. For instance, a building that is connected to an electricity network exhibits a suppliability with electricity. When the electricity network is working, the building also exhibits a suppliedness with electricity; however, when the electricity network is out of service, e.g. due to a thunderstorm, the suppliedness is interrupted.

These concepts are represented in the Utility Network ADE by the class *AbstractMediumSupply* (cf. Figure 19). The attributes *potentialSupply* and *currentSupply* of this class express the suppliability and suppliedness, respectively, and allow for explicitly stating the *flowRate* and the supply reliability of the commodity (*status*), which can be uninterrupted (*inUse*), intermittent (*tempOutOfService*), or unsupplied (*outOfService* or *destroyed*). The attribute *storage* allows for providing detailed information on the *type* of a storage, its potential and actual capacity (*maxCapacity, fillLevel*) as

Figure 18. Representation of functional roles in the CityGML Utility Network ADE (Kutzner & Kolbe, 2016)



well as the rate the commodity is flowing in and out of the storage (*inflowRate*, *outflowRate*). In addition, *AbstractMediumSupply* defines five subclasses to be able to classify the suppliable commodities according to their physical condition: *ElectricalMediumSupply*, *GaseousMediumSupply*, *LiquidMediumSupply*, *OpticalMediumSupply*, and *SolidMediumSupply*. This classification conforms to the classification in the Network Properties module, which defines the commodities that can be transported by networks (cf. Becker et al., 2012b). To be able to add the information on suppliedness and suppliability to a city object, the class *AbstractCityObject* is extended by the attribute *mediumSupply*, the multiplicity 0..* allowing for adding supply information of different commodities to each city object.

4.8. Electricity Network Package

For better support of electricity-related applications, a new *Electricity Network package* is defined as first network-specific package of the Utility Network ADE. In the context of electricity networks, the Common Information Model (CIM) plays an important role. CIM consists of two international standards as well as several profiles published by the International Electrotechnical Commission (IEC) that focus on modelling various aspects related to electricity networks (EPRI, 2015). CIM defines a data model for representing electricity networks including the individual network components and allows for modelling energy management systems, planning and optimization, metering, asset management, enterprise resource planning, and customer information systems.

The CIM base model specifies various electrical and mechanical devices that are referred to as equipment and conducting equipment. These devices were used as starting point for defining the *Electricity Network package*. The aim of this package is not to duplicate the CIM model, but to allow for interoperability between the CIM model and the Utility Network ADE by representing those concepts from CIM that are required for applying relevant use cases in the context of 3D city models on electricity networks.

Figure 19. Representation of the suppliability and suppliedness of city objects in the CityGML Utility Network ADE (Kutzner & Kolbe, 2016). The data types ElectricalMediumValue, GaseousMediumValue, LiquidMediumValue, etc., are defined in the Network Properties module and, thus, are not displayed here.

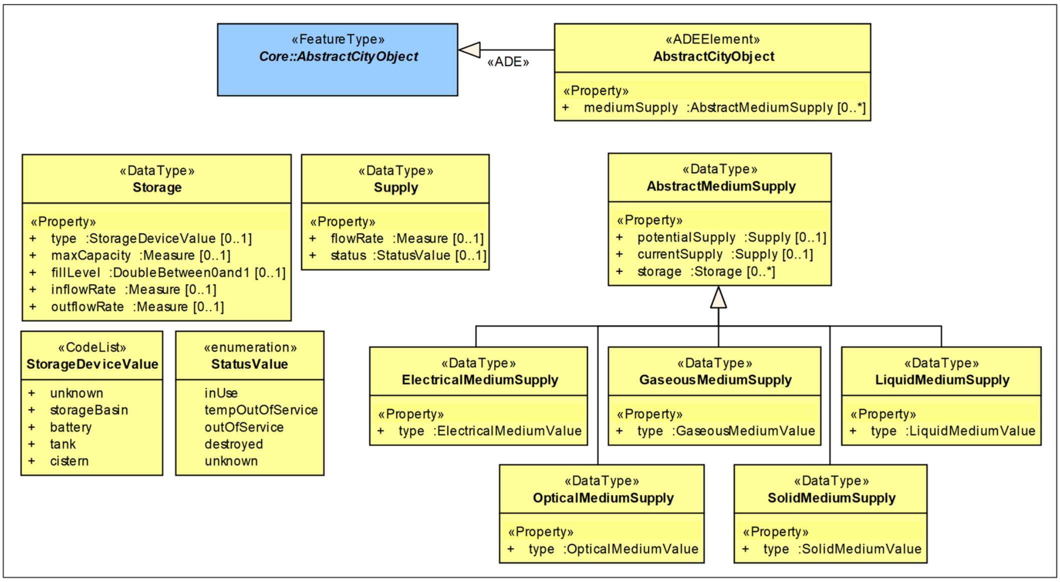


Figure 20 provides an overview of the electricity network elements that are part of the Electricity Network package. The individual elements are defined as subclasses of corresponding network elements from the Network Components package (cf. section 4.6). A transformer and its transformer windings, for instance, are represented in the CIM model by the classes *PowerTransformer* and *TransformerEnd*. These classes are taken over into the Electricity Network package as subclasses of *ComplexFunctionalElement* and *ControllerElement*, respectively. The same is done for the other electricity elements defined in the CIM model. An OCL constraint is added to the *TransformerEnd* class to indicate that the windings are passive elements. Similar OCL constraints can be added to the other classes. In addition, the classes can be complemented by attributes adopted from the respective CIM classes to provide further information on the electrical equipment.

5. APPLICATIONS

The Utility Network ADE has been applied in various research projects and studies, proving its usability and maturity in the context of diverse use cases, the necessity and usefulness of the various concepts defined by the ADE, and its applicability all over the world, also in developing countries.

Within the research project 'Simulation of intersectorial cascading effects caused by a failure of supply infrastructures using the 3D city model of Berlin' (SIMKAS 3D), the Utility Network ADE was applied for the first time to simulate interdependent crisis situations, the linking of situation information with the urban space, and the implementation of a common situation map which also allows for individual views and analyses by each provider. The project involved stakeholders from various research institutions, utility providers, and public authorities. The data of the utility providers (electricity, district heating, gas, fresh water, waste water) were stored in an ArcGIS geodatabase which was implemented based on the Utility Network ADE. Please refer to Becker et al. (2012a) and Becker et al. (2012b) for further information on the project.

The research project 'Risk Analysis Supply Infrastructure' focused on the possibilities of utilizing supply infrastructures in training simulators for crisis scenarios (e.g. evacuation), for simulating the impact of a failure on the population, and for simulating the impact on tactical operations. The project made use of electricity, water, and sewer networks as well as CityGML buildings in LoD 1. The network data was originally provided as DXF and Shapefiles and was transformed to the Utility Network ADE using the software FME. The use case applied in the project simulates the cascading effect of a power failure due to an explosion in a distribution station as can be seen in Figure 21(a) where the street lights are out of service in parts of the city. The power failure propagates by causing a failure of the water works that results in a shortage of water supply to the population, see Figure 21(b). Analyzing the number of people affected by these failures helps in taking suitable actions, e.g. in providing enough drinking water to the population via water tanks, as shown in Figure 21(c).

Den Duijn (2018a) and den Duijn et al. (2018b) analyze how above-ground 3D city objects can efficiently be linked with the below-ground sewer and electricity network of Rotterdam, Netherlands, to facilitate asset management. Furthermore, they perform topological routing on these networks to analyze and visualize which network features and city objects are affected in case of a utility strike (cf. Figure 22).

Boates et al. (2018a) model, simulate, and visualize dependencies between the water network and electrical network at a hydroelectric power generation facility in Nanaimo, British Columbia, Canada (cf. Figure 23). Furthermore, various topological routing tasks such as the calculation of the least-cost path the within the water network are performed.

Gilbert et al. (2018) present a system for BIM-GIS integration of multi-scale network topologies based on IFC and Utility Network ADE models and for enriching the integrated topology network with real-time sensor data describing dynamic resource flows. In addition, the system allows for disseminating states and changes of the network via a message broker for further use in analysis and visualization. They demonstrate the applicability of their system in a case study on electricity demand-supply visualization spanning multiple scales from intra-building circuits to intra-urban electricity distribution feeder networks.

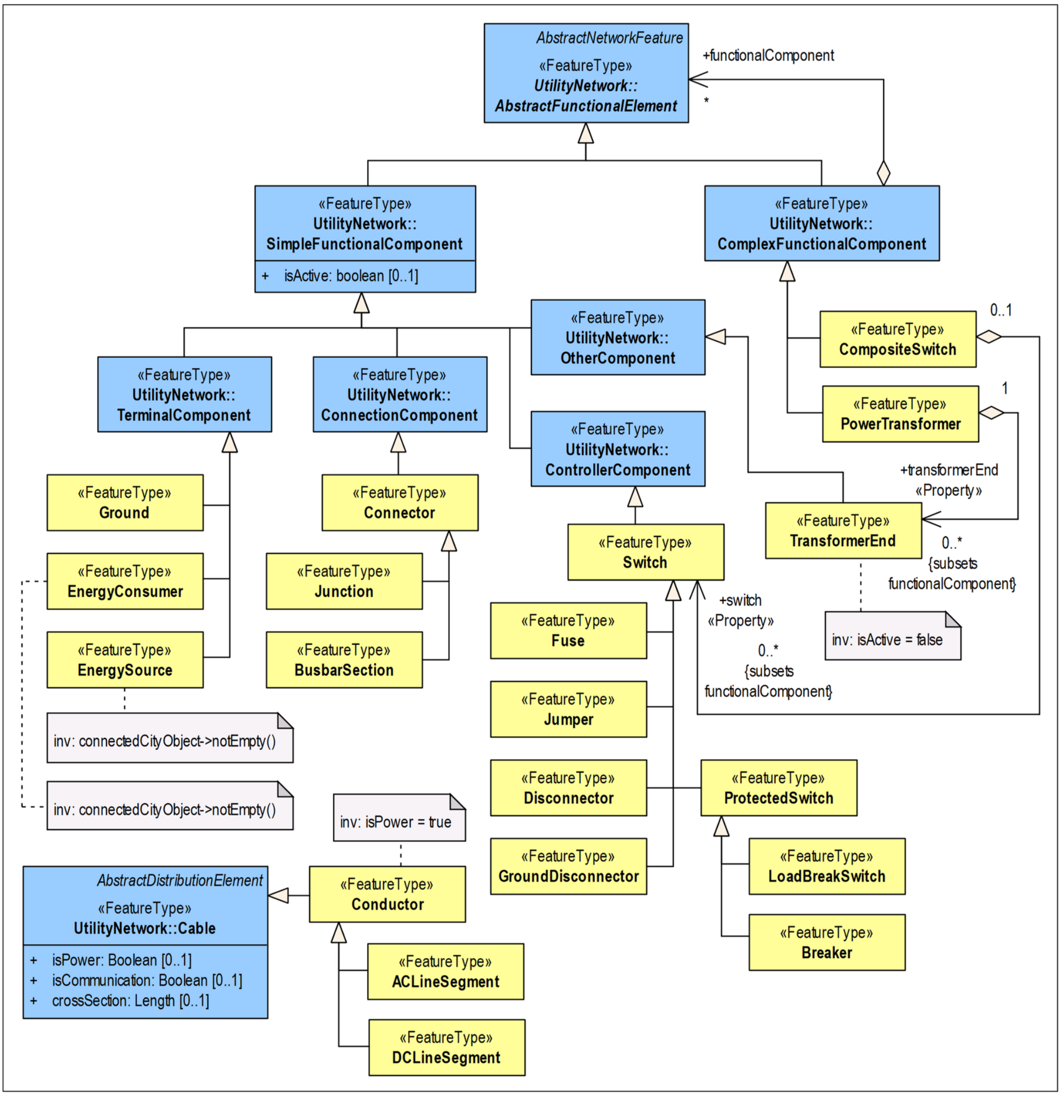
The research of Vishnu & Saran (2018) focuses on using the Utility Network ADE for modelling the water supply network of Dehradun City, India, based on field visits and various secondary datasets as well for applying use cases such as determining the areas affected by network failure or the street space affected by network maintenance.

Publicly-available test data sets have been created in the past months to facilitate the application of the Utility Network ADE in various use cases. This includes waste water network data of the City of Rotterdam, Netherlands (den Duijn, 2018c), and water and electricity network data of the City of Nanaimo, Canada (Boates, 2018b); the data sets can be downloaded via the links provided in the references. Further data sets are currently under development including synthetic data sets of freshwater, electricity, and gas networks. Resources on the Utility Network ADE including the latest UML model and XML schema, links to test data sets as well as information on how to use the ADE with FME are available from the github repository of the Utility Network ADE (Kutzner, 2018). Workshop results of the joint SIG 3D and OCG working group on the CityGML Utility Network ADE are available on the Wiki page of the working group (SIG3D, 2018).

6. CONCLUSION AND OUTLOOK

This paper presents the further development of the CityGML Utility Network ADE by new and revised concepts that result from a systematic analysis of a variety of use cases in the context of utility networks. Several of these use cases, such as ‘maintenance operation’, ‘emergency response’, ‘inspection operation’, ‘storm drainage network’, and ‘energy planning and simulation’, are introduced in the paper. A catalogue of requirements specific to utility networks is presented and several utility network data models commonly used in the geospatial domain were evaluated against these requirements to analyze to which extent the individual data models fulfil the requirements, also in comparison to the CityGML Utility Network ADE. The new and revised concepts that were added to

Figure 20. UML model of the Electricity Network package defining various components of electricity networks. Blue-colored classes are from the Utility Network ADE package.



the ADE are explained in detail. In addition, the paper gives an overview of past and recent projects that successfully have applied the Utility Network ADE.

The Utility Network ADE provides several advantages over other data models for utility networks. While some data models focus on specific types of networks only, the Utility Network ADE has been defined in a such generic way that it can be used for a joint representation of different types of networks and, thus, also for analyses and visualization of multi-utility scenarios. In addition, the ADE fulfils the needs of applications and domains that require a detailed representation of network elements specific to certain network types by providing network-specific packages. An example is the new electricity network package providing network elements specific to the electricity domain to allow for improved use of the ADE in electricity-related use cases and to establish interoperability with the CIM standard. Ongoing work focuses on the specification of a sewer network package that improves interoperability with ISYBau, a German standardized exchange format for sewer networks.

Figure 21. Power failure and water failure, making water supply by tanks necessary

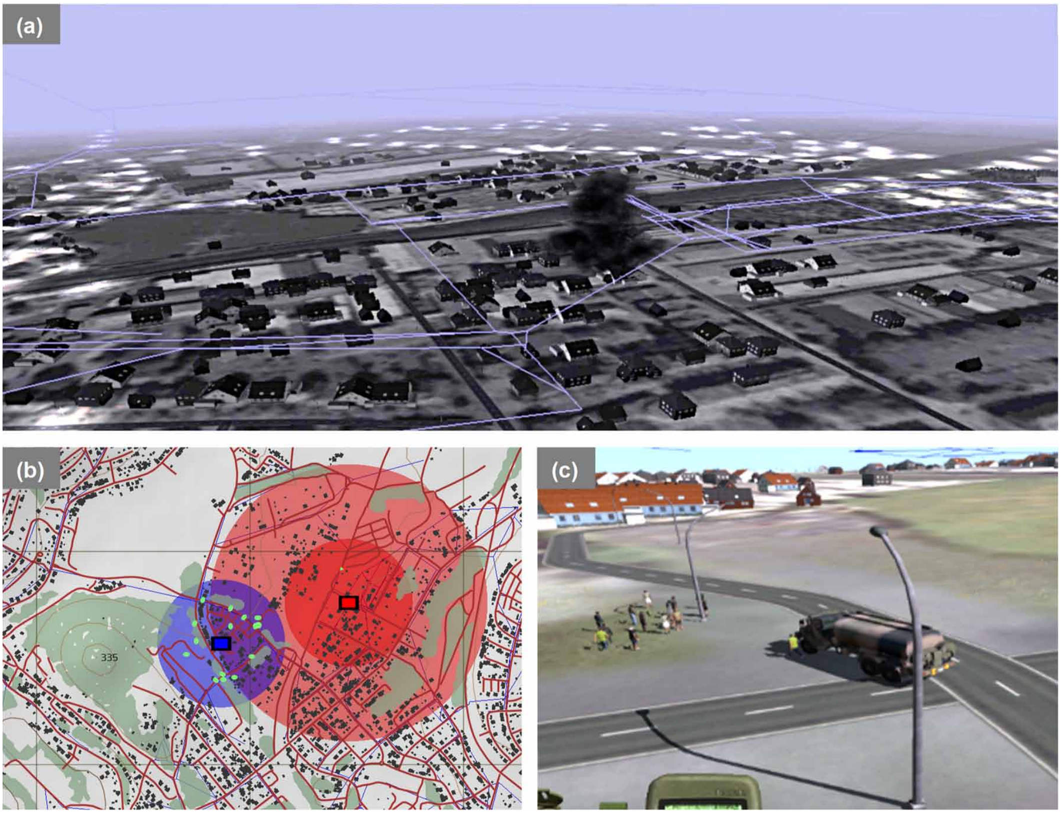
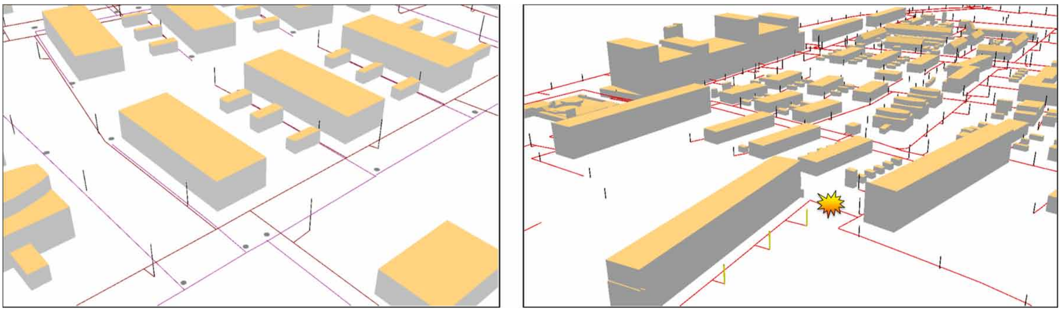
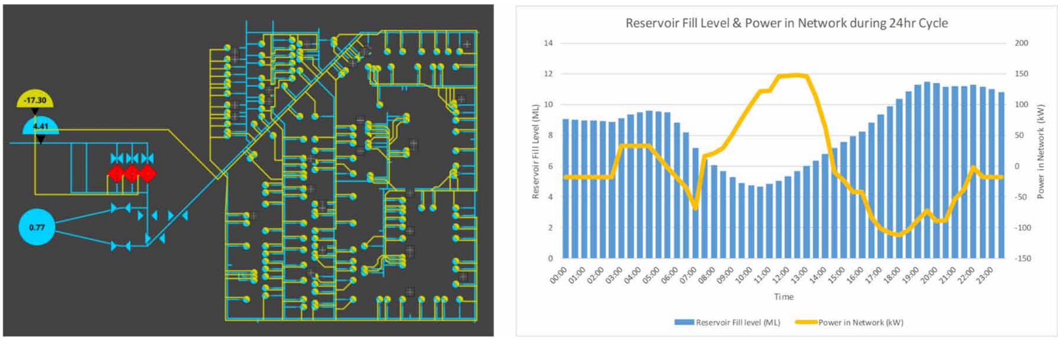


Figure 22. Representation of networks with related above-ground street lights and manhole covers (left). Visualization of street lights affected by a utility strike (right). (© 2018, Xander den Duijn. Used with permission.)



Establishing interoperability with these standards does, however, not mean that the Utility Network ADE is intended to replace the other standards; the ADE rather provides a common basis for the integration of diverse models in order to facilitate joint analyses and visualization tasks. Future work will focus on identifying methods to facilitate the exchange of data between the different data models and the ADE and on identifying common features supporting the integration. In addition, it will also be useful to evaluate the ADE against modeling and simulation tools, e.g. network design

Figure 23. Simulation of 24 hours of network operation at a hydroelectric power generation facility. (© 2018, Isaac Boates. Used with permission.)



and management tools or hydrological modeling tools, to learn about additional requirements from these tools and enhance the integration of the ADE with them.

Another advantage of the ADE is that it allows for linking utility networks with 3D city models; this is currently not supported by any other standard. Since the Utility Network ADE is defined as an extension of the CityGML standard, utility networks can easily be linked with CityGML-based 3D city models. This allows for performing comprehensive analyses that require an integrated modelling of cities and their utilities. It is planned to conduct further projects and studies to demonstrate the strength of this linkage, for instance in the context of combined district heating and electrical power generation and distribution.

The Utility Network ADE allows for a dual representation in different Levels of Detail (LoD), i.e. utility networks can be represented topographically and topologically either comprising only the most important components or including every single component to obtain a detailed representation of the network. However, the ADE is useful even when no detailed information on the structure of a network is available, as the ADE is able to represent the functional interaction between networks and city models through supply areas, functional roles, and the representation of the potential and current supply of commodities to city objects. In this way, the applicability of the ADE becomes even more versatile and applications do not necessarily have to rely on the availability of network information. Future work includes the definition of a more elaborate LoD concept. LoDs need to be considered separately for topographical, topological, and functional representations, and also separately for different forms of representations of utility networks with regard to single-line diagrams, block diagrams, or even more detailed schemas. This goes along with the question of how to represent networks geometrically, e.g. when to use 1D-point or 2D-line representations and when 3D-extrusions.

Prototypes are another interesting aspect which requires further research. Within a network, the same model of a network component, such as a T-fitting, pipe, or valve, is usually installed multiple times. It could be useful to define the individual models as prototypes and then to simply instantiate them at their specific locations.

The development of the Utility Network ADE up to now took place without synchronizing with other ADEs. From the comprehensive list of ADEs given in (Biljecki et al., 2018), the Energy ADE (Agugiaro et al., 2018) can be seen as the most relevant complementary development to the Utility Network ADE. The Energy ADE extends the CityGML standard, in particular buildings, by energy-relevant information required for doing energy simulations and energy assessment on the building and city level. Energy-related use cases will benefit from an integrated use of both ADEs, as Widl et al. (2018) demonstrate in a project that uses CityGML and both ADEs in energy-related simulations.

To support simulations, the ADE can be used to store simulation-specific data with the individual network components and derive complete simulation data sets from the integrated 3D city model.

A concept to be included in CityGML 3.0 is the so-called 'Dynamizer' concept which allows for modeling dynamic properties (Chaturvedi & Kolbe, 2016). This concept could be used for making the functional properties introduced in this paper dynamic, i.e., the actual supply of commodities to city objects (including current flow rates, voltages, etc.) and the actual roles of city objects and network features, and directly link these properties with sensors like smart meters.

The 3D City Database (3DCityDB) allows for storing, managing and visualizing CityGML-based 3D city models (Yao et al., 2018). The latest 3DCityDB release version 4.0 added support for CityGML ADEs, making it now possible to store and manage utility networks together with 3D city models which we be explored in more detail in future work.

It is planned in the medium term to include the CityGML Utility Network ADE in one of the next versions of the CityGML specification (version 3.x). In this way, the Utility Network ADE would become an integral part of the Core CityGML data model. If later on further extensions to the data model are required, they can be added through an ADE again.

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