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Integrated 3D modeling of multi-utility networks and their interdependencies for critical infrastructure analysis

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Abstract

In today's technologically advanced society the dependency of every citizen and company on working infrastructures is extremely high. Failures of critical infrastructures, such as the Italian blackout in 2003 or the failure of power supply in wide parts of Europe in 2006, demonstrate the strong linkage of networks across borders. However, also infrastructures within the same geographic region but of different types have strong interdependencies and failures in one type of network can have cascading effects onto the other networks. In order to support risk analysis and planning of emergency response actions the modeling of critical infrastructures and their mutual dependencies in 3D space is required. Decision makers need a comprehensive view of the disaster situation to be able to estimate the consequences of their action. For this purpose, a comprehensive understanding and simulation of cascading or looping effects as well as the propagation of the disaster extend is needed. But neither the existing utility networks models nor the international standards for modeling cities or buildings map the mutual interrelationships between different infrastructures or between the city and its infrastructures.

In this paper the requirements and a novel framework for the integrated 3D modeling of critical infrastructures within cities is presented. By giving a *dual re-*

presentation utility network components are modeled both according to their 3D topography and by a complementary graph structure embedded into 3D space.

Keywords: 3D Data Models, 3D City Models, 3D Utility Networks, Interdependent Critical Infrastructures, Cascading Effects, Disaster Management, Emergency Response, CityGML

1. Introduction

The field of critical infrastructures, the simulation of their failure and breakdown, and possible occurrences of cascading or looping effects are examined by researchers worldwide.

The European Union, Germany, United Kingdom, and the USA have critical-infrastructure programmes which mostly define electricity generation, transmission, and distribution as well as gas production, transport and distribution, telecommunication, water supply, transportation and heating, and many more as critical infrastructures (see [18]). These programmes address the identification of important objects, risk analysis based on threat scenarios [4, 5] and the vulnerability of each object as well as the identification, selection, and priorisation of counter-measures and procedures. As it is shown by Johnson [4], a small fault can trigger a blackout of a whole power supply network across the borders of different countries, leading to a domino effect that has separated, in the discussed case Italy from the whole European grid. It is easily conceivable that many other infrastructures are critically depending on electrical energy. A wide failure of energy supply would have for example the consequence that telecommunications, water supply, sewage disposal and many other infrastructures would also fail, assuming that they do not dispose of a backup system. However, it is completely unknown whether, e.g., by the failure of water supply (which may include uncontrolled leakage of water) failures in other infrastructures can be induced (cascade effect) or even are amplified and reflected (loop effect), or which effects or damages will be caused on the city structures. In order to be able to estimate the consequences of their action, decision makers have to get a comprehensive view of the disaster situation. A very detailed understanding and simulation of cascading or looping effects as well as the propagation of the disaster extend is needed. The base for such a common simulation and an all comprehensive common operational picture (COP) of the actual situation of a disaster is an integrated 3D topographic model of critical infrastructures and their inherent spatial relations to the city.

In section 2 the requirements on modeling 3D multi-utility networks as well as modeling of interdependencies between critical infrastructures are discussed in detail. Hence, in section 3, an overview of related models like the Industry Foundation Classes (IFC) [23], ArcGIS and INSPIRE is given, whereas in section 4 our conceptual approach of modeling utilities with respect to the identified requirements is presented. In section 5 it is shown how the UtilityNetworkADE is implemented as an extension of the international standard CityGML [10]. In section 6 we draw conclusions and give an outlook to future work.

2. Requirements on modeling 3D multi-utility networks

Pederson et al. [18] and Tolone et al. [24] present some scenarios and approaches to model and simulate critical infrastructures and their complex interdependencies. Tolone et al. further demonstrate that the behavior of critical infrastructures can be better understood through multi-infrastructure simulations. In order to understand the dynamics and dependencies of utility networks and to allow the propagation and visualization of effects (see [4]) a first identified requirement on multi- utility networks is that a geometrical, topological, and functional embedding of critical infrastructures into the urban space must be done. This will also allow the joint visualization of virtual 3D city models and 3D utility networks, which would be very helpful to understand the locations and spatial relations of infrastructures in the context of city objects. A better understanding facilitated by a joint 3D visualization would result in a better decision making process and coordination between decision makers and actors such as fire fighters. Moreover, an integrated modeling of utilities and city topography facilitates the visualization and analysis of dependencies between city objects and network components, such as which city object depends on which infrastructure.

Complex analyses or simulations such as collision detection (e.g. excavator vs. pipe), determination of explosion impact (determination of damaged objects), and simulations predicting, for example, the spread of water in a flood scenario above and below the ground require the 3D topographic representation and description of the components of the utility network of a city.

The structural description of the entire network by graph structures with a 3D embedding is suitable to calculate the relative position between network objects of different commodities, their spatial relation to each other as well as their spatial relation to other objects of the city, such as buildings, city furniture, or roads. Due to the fact that the different types of infrastructure of the city lie above and in between each other the embedding into the 3D space plays an important role. Furthermore, 3D visual inspection helps in getting a better understanding of the spatial relations of the networks relative to each other. Network analyses such as the calculation of slope or slope change becomes possible. Thus, it is conceivable that a 3-dimensional description of the city (see [10]) as well as a suitable 3D description of the underlying utility network has to be realized. The 3D objects of the network must be integrated into the 3D space of the city and thus they can be queried in the context of a disaster management.

An investigation of existing utility network models [8, 9, 13, 14, 17, 23, 25] shows that different types of hierarchies are used to decompose networks into sub networks or single features into their components. On the one hand hierarchies are suitable to express different kind of pressure levels, flow rates as well as voltage levels. On the other hand hierarchies are suitable for realizing different kinds of feature aggregation within the same sub network. While for the evaluation of the connectivity of network objects a very general view of the network connectivity is sufficient, simulating the failure of network components and resulting cascading effects may require a more detailed description of the interior of a network component. For example, a switch gear cabinet may consist of different switches, transformers, and fuses. Each of these components of the switch gear cabinet may trigger a network failure and may lead to a cascading effect across different networks. Thus, it is mandatory for an integrated network model that both the whole network can be expressed as an aggregation of different sub networks with homogeneous commodity and those individual network components, such as a pump or switch gear cabinet can be represented as an aggregation of a set of network components.

In the context of disaster management and the analysis of critical infrastructures it is important to understand that critical infrastructures interact with each other, either by direct connection, or due to effects resulting from their spatial proximity. These interactions are called interdependencies and can be classified in different types. Some type definitions for interdependencies are given by Dudenhoefer et al [5]. They categorize interdependencies as physical – direct linkage, geospatial – infrastructure components at the same location (only 2D!), policy – binding of infrastructure components due to policy or high level decisions as well as, informational – a binding of information flow between infrastructures. The interactions between infrastructures are often very complex and may cause cascading effects which can lead to disasters. Therefore the modeling and development of models that accurately simulate critical infrastructure behavior and their interdependencies and vulnerabilities is important (see [16, 19, 20, 21, 23]).

Other research groups have developed various modeling approaches including agent based modeling [1, 19, 20], effects-based operations modeling [4, 5], mathematical models and models based on risk [18, 21]. But as mentioned before, in chaotic situations like disasters or emergencies, decision makers should understand the dynamics and dependencies of infrastructures. Failure to understand those dynamics will result in ineffective response, domino effects (see [4]) and poor coordination between decision makers and emergency actors. Thus, Dudenhoefer et al. [5] present in their paper the issues of interdependency modeling, simulation, and analysis. They examine the infrastructure interdependency and provide additionally some formalism for these dependencies. Even though it is the most comprehensive work concerning interdependencies and critical infrastructures (to the best of our knowledge), the linkage to objects and topography of the city and its resulting effects to the city are neglected.

As a result of the previous discussion an integrated 3D model of heterogeneous utility networks has to meet the following requirements:

1. Utility networks must be embedded into 3D space and need to be integrated with 3D representations of urban entities, i.e. 3D city models.
2. Network components must be represented both by 3D topographic descriptions and by a topological and structural description of all network components with an embedding in 3D space.
3. In general, the model must support both types of hierarchical modeling: the modeling of feature hierarchies (as an aggregation of many features) and the modeling of network hierarchies (as an aggregation of sub networks of the same type of commodity)
4. An integrated model for multi-utility networks must support the simultaneous representation of heterogeneous networks.
5. Special attention has to be paid to the modeling of interdependencies, which establish explicit relations between the network entities of different utility types and can be of spatial, non-spatial, logical, informal, and policy kind (c.f. [5]).

These requirements form the basis for the examination of existing concepts, systems, and the development of a new comprehensive framework in the following sections.

3. Related Models

Several models for utility networks on the urban and building scale have been developed in the past. In the following, we will examine the utility models of the Industry Foundation Classes (IFC), the commercial GIS ArcGIS, and the recently presented network core model of the European INSPIRE initiative.

3.1 Modeling Utilities in IFC

The most important standard for data exchange of buildings in the field of architecture and civil engineering are the Industry Foundation Classes (IFC) [22]. The IFC represent logical building structures, accompanying properties, optional 2D and 3D geometry as well as utilities. The module 'Shared building service elements' is defined in the interoperability layer and defines the basic concepts for interoperability between building service domain extensions, such as electrical and control domains or heating, ventilation, air conditioning etc. This module includes basic type definitions as subtype of *IfcTypeProduct*, for instance sanitary types, boiler types etc. and occurrence definitions for flow and distribution systems which specify the placement (position) data, instance specific data, references the type and finally the connectivity with other elements and systems.

In order to build up a network the IFC offer two different ways of connectivity. A connection between building service elements may be physical or logical. In general, a logical connection realizes the connection of two components via *Ports*, whereas a physical connection realizes the connection via a realizing element such as *IfcFlowFitting*. The connectivity concept of IFC comprises both the physical connection between elements (*IfcRelConnectsElements*) and the logical connection of building service items on the level of their ports (*IfcRelConnectsPorts*). An *IfcPort* can have a placement and a representation and occurs at each connection point between *IfcElements*. The connectivity is realized through the use *of IfcRelConnectsPorts* and only compatible elements are allowed to connect to each other. If the optional attribute *RealizingElement* of *IfcRelConnectsPorts* is used the connectivity is switched from a logical connectivity to a physical connectivity (see fig. 1). In order to define the flow direction it is possible to use the *IfcFlowDirectionEnum*, which defines a connection point as a 'source of flow', a 'flow sink', as a 'source and sink', or as 'undefined'.

Element hierarchies can be expressed by using the *IfcRelDecomposes* relationship which supports the concept of elements being composed or decomposed. This realizes a whole/part hierarchy which allows traversing from the whole to the parts and vice-versa. Thus, a pump may be the aggregation of IfcFlowFitting, IfcFlowController, and IfcFlowMovingDevice.

While it is possible to express feature hierarchies, network hierarchies cannot be represented. This may be due to the fact that IFC is focused on the representation of single buildings (or building complexes). However, it is possible to model the interdependencies between different networks by using the logical connection of *IfcRelConnectsPorts* (see [23], page 88).

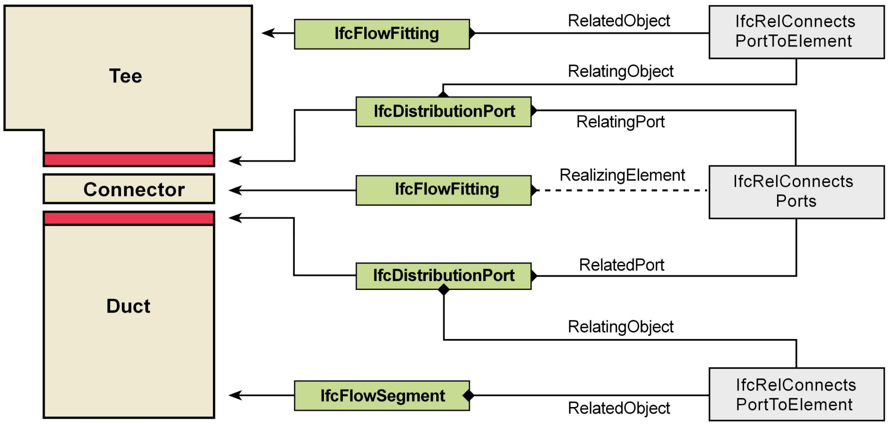

Fig.1: Connectivity example between two building service elements [23].

In summary, IFC supports the representation of the 3D topography of network elements and the logical connectivity on the level of ports within a graph structure. However, there is no explicit embedding of the graph in 3D space; the location is only given implicitly, if network components have a 3D geometry. The utility network model focuses on structures within sites and does not address networks on the city level interconnecting sites/buildings.

3.2. Modeling Utilities in ArcGIS

In ArcGIS the different types of utility networks are mapped to a core model which is based on geometric networks, being labeled graphs with a spatial embedding. This core model represents the basic structure for all kinds of utilities. A network is constructed from edges and junctions as line and point features. Each real world utility object can be represented as one feature in the network whereas same kinds of features can be represented by a feature class [3, 8, 9, 22]. The geometric part of a utility network (see fig. 2) is a single graph structure consisting of Edge and Junction elements and can have any number of participating feature classes. The graph is composed of features from one or more feature class in a feature data set [8]. It binds together feature classes which form a network and contains all attributes, relationships, and validation rules. The logical network (see fig. 2) is a special data structure to store the connectivity between features of the network and is implemented by a set of tables. This network is automatically set up and maintained when the geometric network is created or edited.

In contrast to ESRI's street network model all feature classes can take part in the networks as one of the four network types: simple edge, simple junction, complex edge, and complex junction. A simple edge has a one-to-one relation between the feature and the edge element and connects always two junctions. However, a complex edge may connect more than two junctions in order to represent a sequence of edge elements divided by junctions. While they realize a logically connected sequence of edges, they geometrically represent a single feature – and in this respect it is a kind of feature hierarchy. Simple junctions have a one-to-one correspondence between the feature and the junction element and are represented only by one point in the network. In order to enhance the feature hierarchy approach a complex junction can be represented as an object in the geometric network and as multiple objects including junctions and edges in the logical network. A pump for example may be represented as a box in the geometric network with one input line and two output lines. However in the logical network this box is represented as a set of valves, tees, pumps (represented by nodes), and pipes (represented by edges); see lower part of fig. 2.

In order to support the flow of commodity a junction feature can have the attribute *AncillaryRole*, representing its role as source, sink, or neither. To prevent that non-suitable network components are linked to each other, connectivity rules can be specified. The modeling of network hierarchies as well as the modeling of interdependent utility networks within the framework (as it is possible in the transportation network model of ArcGIS which supports multi-modal networks) is not supported yet.

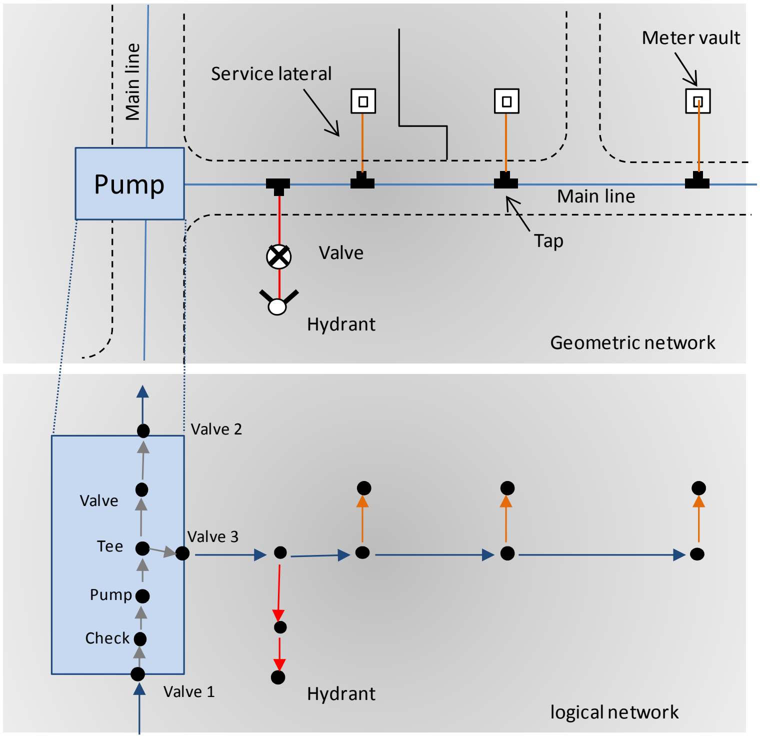

Fig.2: Example of a feature dataset consisting of a geometric and a logical network.

3.3. The Generic Network Model of INSPIRE

The “Network” package of the INSPIRE application schemas [13] defines the basic application schema for networks which is extended by additional, domain specific spatial data schemas [14]. The central class is *NetworkElement* which may be any entity that is relevant for a network. The network package consists of further classes, which are required for modeling networks, such as *Network*, *Link*, and *Node*.

A *Network* is a collection of *NetworkElements* which is the superclass for elements like *Area*, *Node*, and some special classes such as *GeneralisedLink*, *LinkSet* and *GradeSeparatedCrossing* (see fig. 3). Thus, a simple network may only consist of *Nodes* and *Links*, where a Link must be bounded by exactly two nodes.

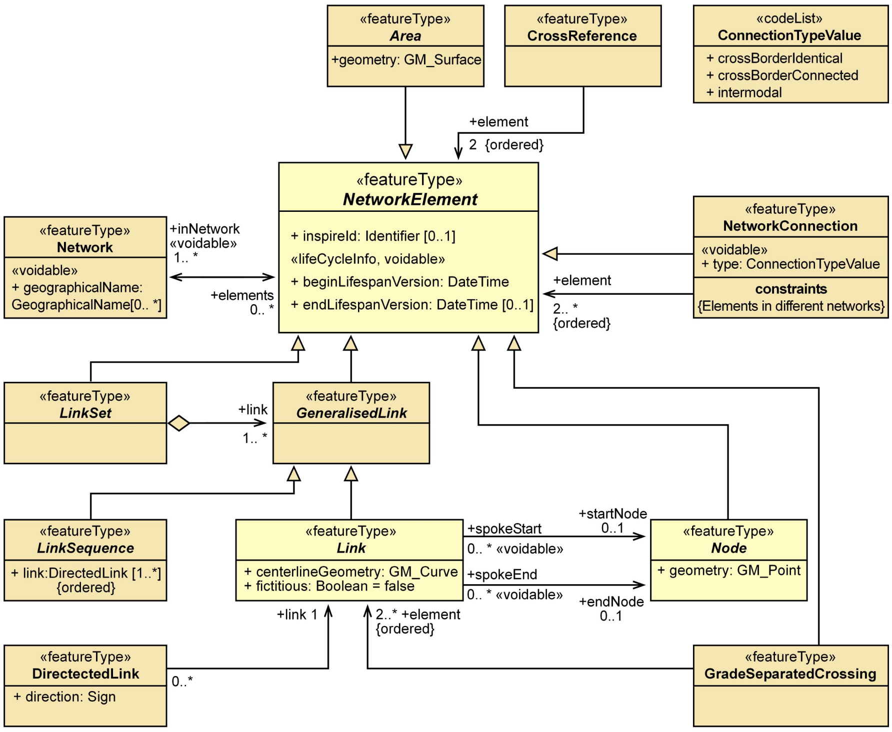

Fig. 3: Network Application schema of INSPIRE (adapted from [13]).

The clear distinction of NetworkElements into point like (Node) and line like (Link) objects and the lack of a feature aggregation schema does not allow for hierarchical decompositions of network components. For example, a point like object cannot consist of other point like or line like objects. The hierarchical modeling of a line like object is supported by the class *LinkSet*. A hierarchical modeling of a network and the modeling of interdependencies is possible by using the class *NetworkConnection*. NetworkConnections are also NetworkElements relating two or more arbitrary NetworkElements facilitating the modeling also of hierarchical networks (see [14], page 93). Since the INSPIRE data model specifications do not make use of 3D geometries, the graph can only be embedded in 2D. Also the INSPIRE core network model does not consider a dual representation of network entities by a 3D topographic and 3D network model.

4. 3D multi-utility network model

In this chapter we propose a novel framework for the representation of 3D multi-utility networks which overcomes the limitations of existing modeling approaches discussed in the previous chapter and addresses the requirements for critical infrastructure models as identified in chapter 2. The entire data model will be given in UML in chapter 5.

4.1 Conceptual modeling

We define a utility network as abstraction of the collection of all topographic real-world objects being relevant network components such as pipes, pumps, or switchgear cabinets. The conceptual modeling of a utility network and its components employs the ISO 19100 series of geographic information standards for the modeling of geographic features issued by ISO/TC 211. According to the General Feature Model (GFM) specified in ISO 19109 [15], geographic features are defined as abstractions of real world objects. The GFM is a metamodel that introduces general concepts for the classification of geographic features and their relations as well as the modeling of spatial and non-spatial attributes and operations. Object oriented modeling principles can be applied in order to create specialization and aggregation hierarchies.

4.1.1 NetworkFeature and FeatureGraph

The basic unit for modeling utility networks within the proposed framework is *NetworkFeature*. *NetworkFeature* is an abstract concept which maps topographic network components onto respective GFM feature types. It allows for the modeling of thematic properties as well as the definition of taxonomies and partonomies of network components. Hence, it forms the base for the semantic modeling of concrete network features in various infrastructures such as gas, power, or water supply networks.

A main concept of our modeling approach is the *dual representation* of a *NetworkFeature* according to which each network component can be represented both by its 3D topography and by means of a complementary graph structure called *FeatureGraph*. The *dual representation* addresses the need for both types of representation as discussed in chapter 2. The modeling of 3D topography is realized in compliance with ISO 19109 as spatial aspect of a *NetworkFeature*. The value domain for spatial attributes is defined by the Spatial Schema specified in ISO 19107 [15] which allows for describing the geometry of a *NetworkFeature* in up to three dimensions.

In addition to its 3D geospatial representation, each network component is mapped by *FeatureGraph* onto a separate graph structure representing its functional, structural, and topological aspects. This concept differs substantially from previous modeling approaches which usually map the entire utility network onto a single topological network graph derived from a classification of network components into point-like and line-like objects. For example, pipes within a water supply infrastructure are usually given as line-like features and thus mapped onto edges. A T-fitting element is consequently to be mapped onto a node at the intersection of its connected pipes. Functional or structural aspects of the T-fitting are not taken into account. For example, its pipe-connecting ends could also be represented as individual edges, especially if they have a considerable geometric extent or in order to model structural changes such as differing pipe diameters. However, existing approaches lack the possibility to map a single network component onto a set of nodes and edges.

In contrast, the proposed *FeatureGraph* explicitly allows for a graph-based representation of each *NetworkFeature*. The resulting graph structure follows the general principles of graph theory [6] and has clear semantics. We distinguish two types of nodes: exterior and interior nodes. An exterior node represents a topological connection point where other network components may be attached. Interior nodes are used to model internal structural, physical, or logical aspects of the network component. For example, an interior node may represent the narrowing of a water pipe which results in changes of flow speed and pressure. In contrast to exterior nodes, no other network component may be topologically connected to an interior node. In order to link a pair of nodes within the graph structure of a *NetworkFeature*, a special type of edge called *InteriorFeatureLink* is introduced which is only allowed to relate two nodes belonging to the same *FeatureGraph* instance.

Figure 4 exemplifies two valid FeatureGraph representations for a T-fitting element.

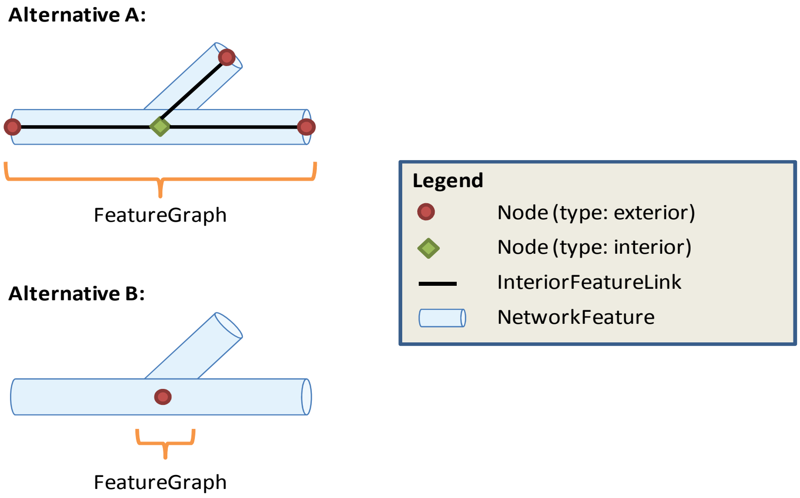

Fig. 4: Two alternative FeatureGraph representations for the same object.

The first alternative results from a functional description of the T-fitting and represents its pipe-connecting ends as individual edges. Each connection point is explicitly marked by an exterior node. An interior node is added where the two axis of the T-fitting meet. The second alternative maps the entire T-fitting to a single exterior node which is the minimum possible *FeatureGraph* representation. Modeling a single *InteriorFeatureLink* is not allowed because an edge has always to be bounded by exactly two nodes.

In order to support sophisticated graph-based analyses and simulations, both nodes and edges may carry additional attributes, e.g. to model weights or the *FlowControl* of a *NetworkFeature*. Examples for *FlowControl* are the on/off state of a switch within an electrical circuit or the gradual impact of a valve on the flow of water. Furthermore, the exterior nodes of the *FeatureGraph* may denote a *ConnectionSignature*. Only those network components having an identical or compatible *ConnectionSignature* are allowed to connect. A *ConnectionSignature* is to be seen as set of connectivity constraints addressing arbitrary aspects of a *NetworkFeature* such as functional, physical, logical, or even geometric properties. For example, the exterior nodes of a T-fitting could define a certain pipe diameter as required connection signature for connecting elements. Both *FlowControl* and *ConnectionSignature* are abstract concepts which have to be specified within the context of a concrete utility network model. Additionally, each *FeatureGraph* can have a geometric embedding in 3D space which allows for 3D analyses of the *FeatureGraph* instances and introduces metric information such as edge lengths into the graph.

Due to the semantic differentiation of nodes and edges and the possibility to model attributes, the resulting graph can be classified as both typed and attributed. This requires the conceptual modeling of nodes and edges as semantic objects. Consequently, the topological primitives *TP_Node* and *TP_Edge* specified by ISO 19107 are infeasible for their representation. Nodes and edges are rather mapped onto two corresponding GFM feature types called *Node* and *Edge*. By this means, nodes and edges can be semantically classified and augmented by spatial and non-spatial attributes. The geometric embedding of both *Node* and *Edge* is realized as spatial *realization* association to a *GM_Point* respectively a *GM_Curve* primitive. A *FeatureGraph* is modeled as feature collection of *Node* and *Edge* instances.

4.1.2 Network and NetworkGraph

The aggregation of *NetworkFeature* instances to an entire utility network is called *Network*. A *Network* is characterized by a homogeneous type of commodity such as water, electricity, or gas. Analogously to *NetworkFeature*, a *Network* employs the concept of *dual representation*. Whereas its 3D topography is implicitly given by the 3D topography of its components, the graph-based mapping is explicitly modeled as *NetworkGraph*.

A *NetworkGraph* represents the graph structure of the entire utility network. For this purpose, it links the *FeatureGraph* instances of the aggregated network features. Thus, a *NetworkGraph* conceptually is to be seen as graph of graphs. It results from the pair-wise linking of exterior nodes in different *FeatureGraph* instances being parts of the same *Network*. For this purpose, a special subtype of *Edge* is introduced called *InterFeatureLink*. The following figure depicts two valid excerpts of *NetworkGraph* representations. For illustration purposes, the connected pipe elements are shown in a detached way.

The main purpose of *InterFeatureLink* is to establish a topological connection between two network features. Since it is derived from *Edge*, it can additionally be embedded into 3D space. However, a further spatial representation of an *InterFeatureLink* is not required if both exterior nodes linked by the *InterFeatureLink* geometrically collapse (see the first alternative of figure 5).

Network and *NetworkGraph* are the central concepts within our framework allowing for analyses and simulations of an entire utility network based on its 3D topography and graph-based representation. Both are realized as GFM feature collections.

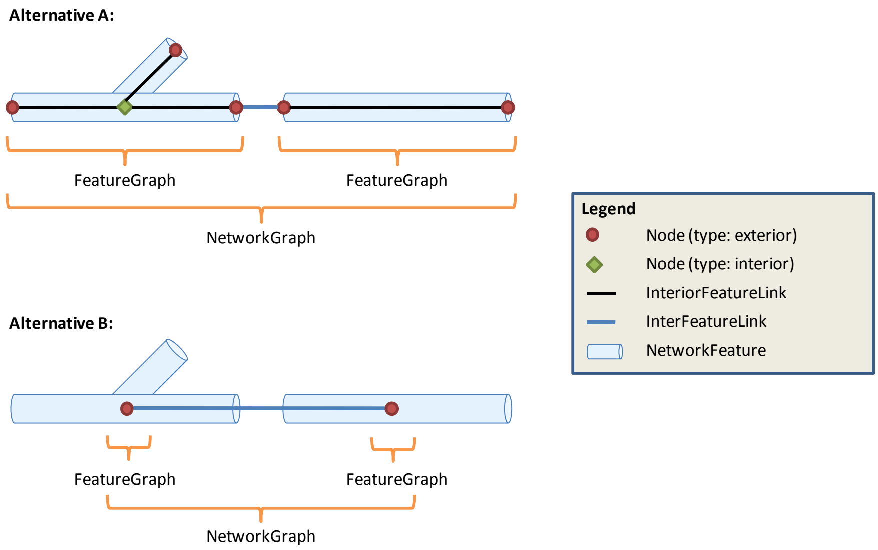

Fig. 5: Two different modeling alternatives for a NetworkGraph connecting two FeatureGraphs using an InterFeatureLink.

4.1.3 Modeling hierarchies

Our framework supports hierarchical modeling for both network components and entire utility networks. A component hierarchy allows for the decomposition of a *NetworkFeature* into its parts which again are components of the utility network. Thus, it represents a *consists-of*-relation between two or more *NetworkFeature* instances of the same *Network* and is conceptually realized through an aggregation association of *NetworkFeature* with itself. This recursive modeling approach enables hierarchies of arbitrary depth.

For example, a switchgear cabinet is a *NetworkFeature* of a power supply network which provides connectors to attach other network components. At the same time, it is internally built from further devices such as switches controlling the flow of electricity. These internal components are both connected to the switchgear cabinet and to each other, and may themselves consist of further internal devices. Figure 6 sketches this example.

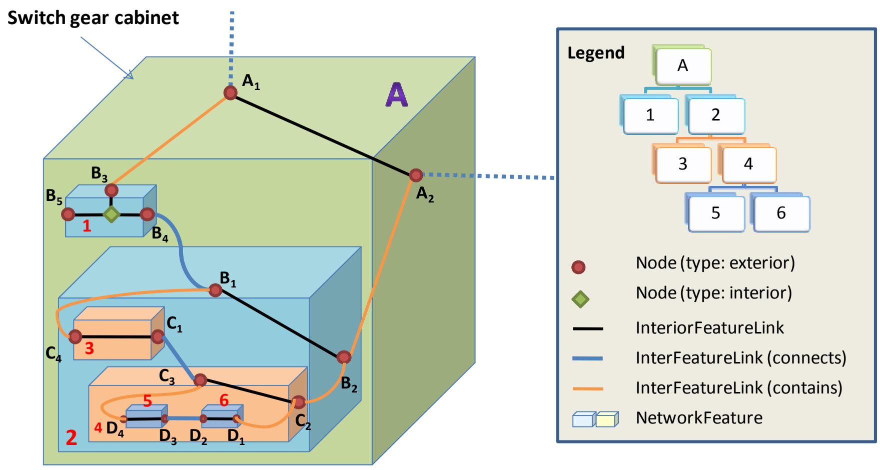

Fig. 6: Feature aggregation and use of InterFeatureLinks.

For its graph-based representation, a feature hierarchy is simply a set of *FeatureGraph* instances which have to be topologically connected at their exterior nodes. Again, this is to be seen as a graph of graphs. For linking *FeatureGraph* instances, the *InterFeatureLink* has been introduced in the previous section. However, the concept of the *InterFeatureLink* has to be augmented such that it additionally provides information about whether the network components are connected on the same level or over different levels of the hierarchy. Graph traversal algorithms can evaluate this information in order to decide whether or not to traverse down a hierarchy.

The modeling of hierarchies of utility networks follows the same concepts. A network hierarchy is used to semantically and topologically decompose a *Network* into sub networks all of which share a homogeneous type of commodity. For example, a gas supply network can be separated into three sub networks for high pressure, medium pressure, and low pressure. However, in order to establish a link between two *FeatureGraph* representations within different parts of the hierarchy, an *InterFeatureLink* is infeasible since it may only connect network features within the same *Network* (cf. previous section). For this reason, a third subtype of *Edge* called *NetworkLink* is defined which has to be used to connect the exterior nodes of two *FeatureGraph* instances when crossing *Network* borders.

4.1.4 Multi-utility networks and interdependencies

In contrast to the existing modeling approaches introduced in chapter 3, the proposed model explicitly facilitates the integration of multiple utility networks with heterogeneous type of commodity. Each utility network is modeled as separate instance of *Network* following the general concepts introduced in the previous sections..

As shown in chapter 2, interdependencies between infrastructures may result from various reasons such as physical linkage, geospatial adjacency or closeness, or policy. The different types of interdependencies can be introduced into our model through the concept of *dual representation* and, thus, are available for cross-network simulations and analyses. First, geospatial effects can be implicitly evaluated based on the 3D topography representations of both network features and networks. Second, interdependencies can be made explicit within the graph-based representation of the multi-utility network as additional link between *FeatureGraph* instances belonging to different utility networks. Conceptually, this link is modeled as *NetworkLink*. Since *NetworkLink* is realized as GFM feature type, it may carry arbitrary further spatial and non-spatial properties. By this means, a *NetworkLink* can be augmented by additional information in order to model a specific type of interdependency such as a physical, informational, or policy-based interdependency.

5. Mapping to a CityGML Application Domain Extension

The integration of utility network models into their 3D urban context in order to capture their mutual impact on urban objects has been identified a crucial requirement for simulations and emergency studies in the field of disaster management (cf. chapter 2). Semantic 3D city models provide the corresponding integration platform.

CityGML [10] is an international standard for the representation and exchange of virtual 3D city and landscape models issued by the Open Geospatial Consortium (OGC). CityGML defines an Urban Information Model which represents the semantics and ontological structure of the most relevant topographic objects in cities and regional models in addition to their 3D geometry, topology and appearance information. The conceptual model of CityGML is based on the ISO 19100 standards family and is implemented as an application schema for OGC's Geography Markup Language (GML 3.1.1) [2].

CityGML has been designed as a universal topographic information model that defines the feature classes and attributes which are useful for a broad range of applications. It provides thematic models for the representation of buildings, digital terrain models, city furniture, land use, water body, and transportation etc. For extra information to be modeled and exchanged which is not covered by the thematic models CityGML offers an extension mechanism called Application Domain Extensions (ADE). An ADE specifies a systematic extension of the CityGML data model comprising the introduction of new properties to existing CityGML classes as well as the definition of new feature types or entire conceptual models based on the general concepts of CityGML.

In order to embed the 3D multi-utility network model into the context of a 3D city model and to enrich CityGML by the possibility to represent utility networks, we have mapped our conceptual model onto a CityGML ADE called UtilityNetworkADE. Figure 7 illustrates the structure of the ADE by means of a UML package diagram.

The proposed conceptual model for 3D multi-utility networks is contained in the core package *NetworkCore*. It has a dependency relation to CityGML and to the the GML3 geometry model which implements the ISO 19107 standard and is used for modeling the 3D topography of network features. Based on the abstract concepts of the *NetworkCore* package, further concrete packages for different types of utility networks can be implemented such as *GasNetwork* or *FreshWaterNetwork*. Common types of network features which can be reused within these packages are grouped into *NetworkComponents*. Future steps will include the specification of these packages.

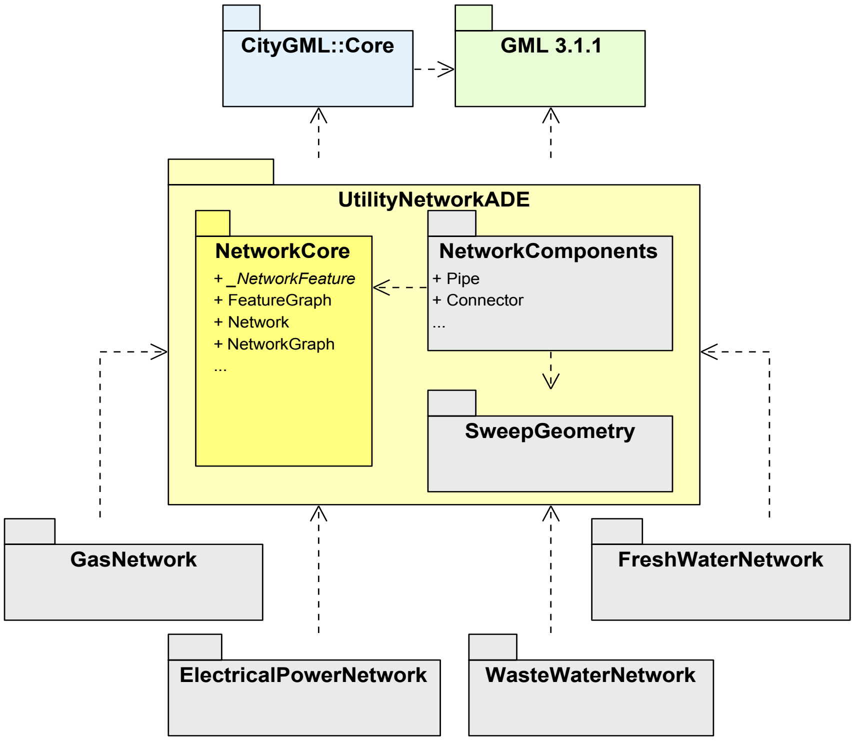

Fig. 7: Package diagram of UtilityNetworkADE.

Finally, figure 8 shows the 3D multi-utility network model as UML class diagram.

The class names follow the names of the respective concept they implement as introduced in chapter 4. Prefixes are used to denote both CityGML and GML classes whereas the stereotypes <<*Feature*>> and <<*Geometry*>> indicate the corresponding general concepts from ISO 19109 and 19107.

The abstract base class *_NetworkFeature* for modeling network components is derived from the thematic CityGML root class *core::_CityObject*. First, by these means the UtilityNetworkADE is embedded into the CityGML data model. Second, the general modeling concepts of CityGML for the representation of topographic objects also apply to *_NetworkFeature*. An entire utility network is represented by the class *Network* as an aggregation of *_NetworkFeature* objects and is realized as *gml::_FeatureCollection*.

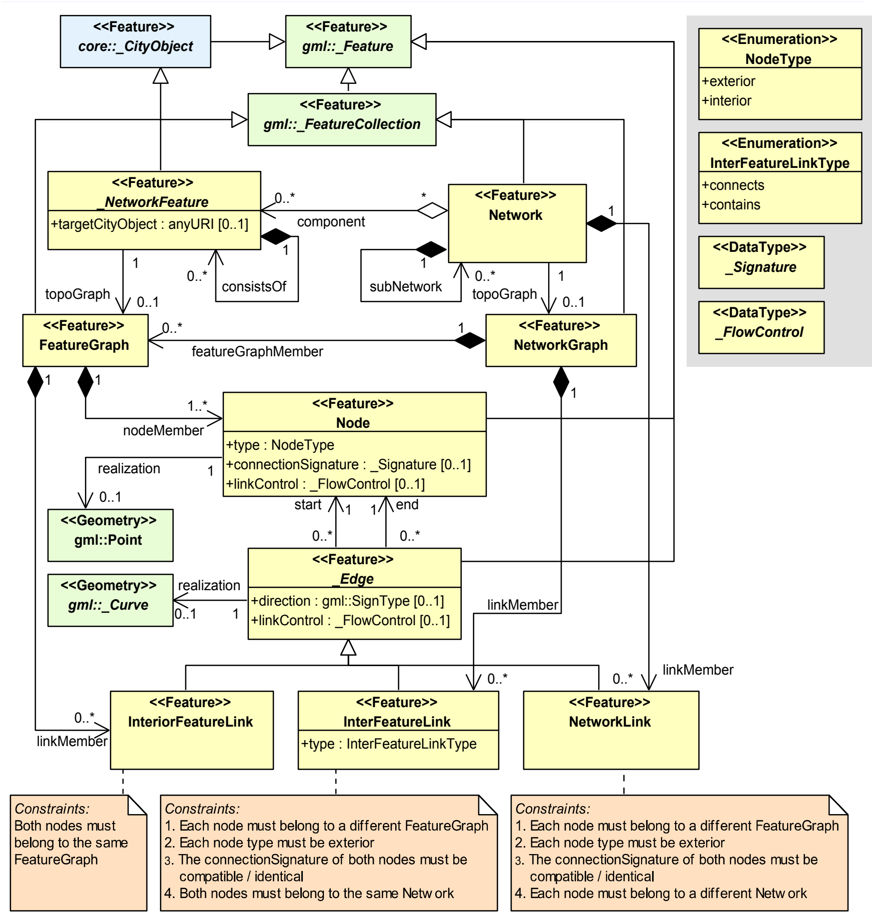

Fig. 8: UML class diagram of the UtilityNeworkADE core model.

The proposed UtilityNetworkADE has already been successfully employed by Hijazi et. al [26] for mapping interior utility structures modeled in IFC to our conceptual framework without information loss. For this purpose concrete network feature classes based on the *NetworkCore* package have been defined.

6. Conclusions and Outlook

Comprehensive analyses of critical infrastructure require the integrated and simultaneous consideration of multiple heterogeneous utility networks within a common framework. Only by these means mutual dependencies between infrastructures can be evaluated that may cause cascading effects across different networks. A key prerequisite for corresponding network models is the possibility to link critical infrastructures in order to denote interdependencies explicitly. Furthermore, the model must support geospatial analyses in order to determine the implicit interdependencies based on spatial relations like proximity between network components within the same or different infrastructures. For example, the burst of a water pipe may cause damage to nearby or underlying components of a power supply network. Such geospatial analyses require the embedding of network structures into 3D space as well as the 3D topographic representation of network components in addition to a graph-based model. Moreover, the topographic representation allows for the integration of network components into their 3D urban context in order to capture the mutual influence of urban objects.

None of the existing models for utility networks examined in chapter 3 supports all of these aspects. For this reason, in chapter 4 of this paper we have presented a novel framework for the integrated 3D modeling of critical infrastructures which meets the requirements. Its fundamental concept of *dual representation* facilities the representation of a utility network component both by its 3D topography and by a complementary graph structure which can be embedded into 3D space. In contrast to other approaches, this graph structure is not derived from a classification of network components into either point-like or line-like objects. We rather employ a stronger concept which allows the mapping of each component onto its own separate graph structure in order to be able to model further structural, physical, or logical aspects. The graph representation of the entire utility network results from topologically connecting these component-based graphs. The modeling of hierarchies of arbitrary depth is supported on the level of both single network objects and entire utility networks. Mutual dependencies between infrastructures can be introduced as further edges between the graph representations of heterogeneous networks. Finally, we have mapped the proposed conceptual model onto a CityGML Application Domain Extension called UtilityNetworkADE in order to integrate the utility networks with 3D city models (cf. chapter 5).

The proposed framework forms a common core for multi-utility simulations and analysis of interdependent critical infrastructures. As it is a superset of the utility network models examined in chapter 3, datasets represented according to these models can be converted into the new framework without information loss. As for future work, we will show how existing datasets modeled according to these approaches can be mapped onto our framework. For this purpose, we will augment the developed core model of the UtilityNetworkADE with packages for concrete network objects of the different types of utilities such as water and gas pipes, cables, valves, pumps, and switchgear cabinets. Moreover, we will further investigate different types of network interdependencies, e.g. policy-based or informational, as well as their modeling requirements in order to map them onto the abstract concepts of our framework. It is planned to bring the UtilityNetworkADE into the future revision process of CityGML in order to make it an official module of this international standard.

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