NIBU: An Integrated Framework for Representing the Relation Among Building Structure and Interior Utilities in Micro-Scale Environment

Ihab HIJAZI[1],   Sisi ZLATANOVA[2],   Manfred EHLERS[1]

1. Institute for Geoinformatics and Remote Sensing (IGF), University of Osnabrueck, Barbarastraße 22 b, 49076 Osnabrueck, Germany

2. OTB, Research Institute for Housing, Urban and Mobility Studies Delft University of Technology, Postbus 5030, 2600 GA, Delft, the Netherlands

Abstract   This paper describes a framework for modeling interdependencies between different network systems and building structures. It provides an approach for the integrated analysis of interior building utilities by describing a framework to model and simulate infrastructure interdependencies and their complex behaviors. It is a graph-based spatial model that can support use cases such as providing the location and specifications of interior utilities to a technician who wants to perform a maintenance operation. This location could be needed for maintenance or replacement, or to investigate the result of damage to the building structure on another utility network, or to estimate the effect of different maintenance operations in different locations along utilities service systems. The model accounts for two important aspects: first, the relationship between interior utilities and building elements or spaces and second, the building hierarchy structure to which the utilities network is related. A proper hierarchy of the building is developed which supports the generation of human-oriented descriptions of interior utilities, where a method for partitions of large building element and spaces as well as a method to reference a network element to another building are developed. The connection of the different utilities network systems and buildings are generated using joints, which are based on a containment relation. An example is presented which shows the effectiveness of this approach for supporting maintenance operations, as well as the independences between the maintenance operation location and the other network systems. The paper presents the data model and explains the links with current 3D building model standards.

Keywords   Building Information Model (BIM); building service system; utility network; graph; city models

CLC number   P208

Introduction

Buildings rely greatly upon an array of complex infrastructure networks in providing their occupants with comfortable, safe, and healthy environments.[1] These networks are located in ceilings and walls, which creates difficulties for their management in existing 2D utility packages. Furthermore, their integrated maintenance is challenging. While there exists tools that focus on analysing and modeling individual networks, e.g., ArcGIS utility network extension and

Bentley Systems utility extensions, a far less investigated area is that of the interrelationships between multiple infrastructure networks and the building structure. Such interrelations are especially critical for potential cascading effects that may result due to these interdependencies.

Nowadays, researchers worldwide are investigating these interdependencies and simulating their failure and breakdown, and also the possible effects on exterior infrastructure at city, regional, and international levels.[2-8] Therefore, many concepts, algorithms, and tools for the mapping, assessment, and analysis of complete infrastructures, including the simulation of infrastructure failures, have been developed. However, modeling the interdependence of interior utilities networks or large buildings is a more complex exercise compared to exterior networks. The interior networks are three-dimensional structures nested in a building. They go through building elements (e.g., slabs, walls), part of it is contained within building storeys and spaces. The analysis of the interdependencies between building structures, or description of the location of interior utilities networks within buildings, is much more complicated than managing the interdependencies with external infrastructures, which mostly follow road and railroad networks. The geometric and topological structure of buildings is much more diverse than the geometric and topological structure of external networks, where exterior utilities can be easily referenced to the road one-dimensional structures. Furthermore, the interior utilities are more inter-related and connected.

Recently developed 3D city models (e.g., CityGML) or Building Information Models (BIM) models treat buildings as a divisible entity with internal partitions and subunits.[9-11] These models open the doors for new applications such as facility management and emergency response. Different methods for structuring the indoor space have been developed.[12-15] Their aim is to provide the knowledge about the connectivity structure within a building (e.g., corridors) which is essential for performing various network-based analyses that facilitate routing within buildings and allow connections to the urban transportation network outside the building. These models aim to support different situations for navigation such as rescue operation (shortest path analyses).[16,17] Therefore, the focus of these models is to represent the part of the building that is navigable for pedestrians and, by doing so, the other building elements such as walls and slabs are only used for visualisation. As a result, there are difficulties in managing and analyzing these network systems together with the building structure.

This paper presents a framework that deals with interdependences between utilities network and building structures. It examines the current building models and provides a cognitive model for indoor spaces. This caters for the representation of space from the perspective of humans. The paper provides a flexible way to couple 3D modeling aspects into one coherent framework, which fits the needs of utilities network application. The framework aims to provide an appropriate (verbal) description that will guide technical teams to the location of the defect in the network – after performing reachability analysis on individual networks.

1   Review of 3D building modeling approaches

The key element in the development of the presented framework is the Network Information model for Building Utilities (NIBU) model that interior utilities will be related to. Therefore, in this section we will provide a brief overview of the work that has been carried out on the development of building models, and their underlying information structure. These building data models can be subdivided into the following types: geometry, topology, and semantic models.

1) Models emphasizing on geometry. Many 3D city models are currently developed where buildings are represented as blocks applying simple reconstruction strategy in which 2D building footprints are extruded upward from the terrain. Such models are easy to produce and offer simple city visualization opportunities. They may be used for a limited set of applications, e.g., for visualization over the Internet through a customized web browser, e.g., Google Earth, ArcScene. Sometimes landmarks with a higher level of geometrical details inserted amongst the extruded blocks (external surfaces bounding internal volume,

especially if photographically textured mapped) can be used to increase the realism. Sometimes such simple models are used for basic analysis such as computing flood area, coverage areas for telecommunication receivers, etc. In CAD, full and detailed 3D models of individual buildings and small groups of buildings are widely used in architecture and construction, but their high spatial resolution and their variable geometry types often make them difficult for spatial analysis.[18,15]

2) 3D topological models. In the last decades, there have been many researches on various aspects of 3D topology, including different approaches to the creation, maintenance, and storage of these topologies (e.g., 3D FDS, SSS, 3D GIS data model by flick, De la Losa's 3D topological model).[19] Algorithms have been described for data validation, spatial analysis and detecting relationships using these models.[20,21]

3) Models comprising semantic along with structured geometry. Semantically-rich data exchange formats (e.g., IFC)[11] and object based building modellers (e.g., AutoDesk Revit) have been developed for architecture and construction, designed in part to facilitate the reuse of data for different stages of the design process and for different analysis tasks.[22,23] These models are commonly referred as to BIM. Similar approaches have been used for virtual cities, i.e., Quesy,[9] smart building and CityGML[10] are attempts to create a usable and formal standard for exchange of city models, using this approach. CityGML has also possibilities to represent the topology in the data sets.

Geometry models (first type) are not appropriate for the approach presented in this paper since they are developed mostly for visualization purposes, i.e., they do not provide any semantic or spatial relationships. The second two types (semantics and topology) have potential to serve our goals. They are already investigated for their applicability in developing navigation applications.[12,13,24] In the following section we will provide a detailed review and analysis of these works, which are related to the framework presented in this paper.

Various researches have concentrated on methods to simplify the complex spatial relationships between 3D objects and to build a 3D connectivity in built environment. Lee proposed the Node Relation Structure (NRS)[25], Ref. [26] described the Augmented Quad Edge (AQE), Refs. [24,27] presented the Dual Half Edge (DHE) structure. The work presented in these studies utilises the concept of duality in mathematics. A dual graph used to represent the connectivity between 3D entities, i.e., dual representation of the indoor environment can be understood as a room-to-room connectivity graph. 3D buildings are decomposed into volumes in primal space and they are represented as nodes in dual space. The dual of a node is a volume and the dual of a volume is a node. The dual of a face is an edge and the dual of an edge is a face (Fig. 1).
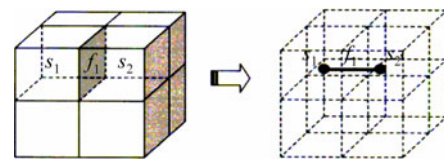

Fig.1   Duality in 3-cells[25]

The last two studies (ADE and DHE) are a direct modification of[28] 2D Quad Edge (QE) structure. They have the characteristics of storing simultaneously the primal and dual subdivision of a three-dimensional manifold in 3D. The DHE was a modification to AQE in order to facilitate construction operations, and enforcing a permanent link between the matching primal and dual half-edges. The NRS, AQE, and DHE data models were developed to support the implementations of indoor navigations system, e.g., in the context of the ease of use in managing and navigation 3D objects. The resulting graphs from these methods represent topological adjacency and connectivity relationships between spatial objects as well as metric information. Accordingly, methods for indoor routing can be efficiently applied.

The previous data models have benefits for the framework presented in this paper by providing a good mechanism to generate the relation between the spaces and its surrounding walls. The duality presented in these methods can be modified to support the purpose of our model. Refs. [14] and [29] have further proposed hierarchical models that decompose the graph resulted from the above dual-graph methods and organize it in hierarchical order. For example, a storey in a building may be represented as a graph

at a certain level and this entire graph being just a node in a graph at a higher level which stands for the whole building. The edges in the abstract graph connect the different storeys; Ref. [14] describes algorithms that can construct this hierarchical model based on floor plan entry and exit nodes. However, as argued by Hu and Lee if the relations are too abstract or coarse they are impractical—they cannot model reachability among regions. Ref. [31] provides an approach for automated partitioning of the building interior, not only to rooms but also into smaller parts, so-called cells. The described algorithm divides the internal spaces based on visibility criteria. It uses convex and concave concepts to divide large spaces into smaller parts. The algorithm can handle simple polygons as encountered in floor plans. The principal idea is to connect corners in a non-convex region in such a way that they partition the region into non-overlapping convex sub-regions. In another study Lorenz describes a method to reference building doors and provide an orientation to them, which is location within a space in a descriptive manner.

Our approach makes use of the hierarchical methods as well. The hierarchical models can be adapted and customized to further divide large building elements.

Another group of models relevant for our framework are the semantic models. Industry foundation classes (IFC)[11] and CityGML[10] are two standards independently developed, the former by the International Alliance for Interoperability (IAI), which is the standardization body for the AED/FM community, and the latter by the Open Geospatial Consortium (OGC), which is the standardization body for the geospatial community. The two standards are representing interiors of buildings: they offer rich 3D semantic models, they are object oriented and represent building objects based on their semantic role, e.g., slab, wall, space. The data models are associated with rich, detailed 3D geometry. Moreover, these building models provide a hierarchy to organize the building structure.

IFC organizes the spatial structure and space elements of a building in a hierarchy. The entire spatial structure is subsumed from the project which is the uppermost container of all building information.

There are two mandatory levels under the project. These are building and building storey. Other optional levels that can be subsumed from the project are sites, building sections, and spaces. Sites may contain zero or many buildings. A building model has at least one storey and may have multiple storey's; each building storey may have zero or more spaces related to it. All building elements are assigned to the building storey in which they are located. If building elements (or spaces) span through many storeys, then they are assigned to the storey in which they are based. This containment relationship is handled by the "Element in Space Containment". The relationship IfcRelContainsInSpatial-Structure should be used and the class IfcSpaceBoundary, which contains a relationship between a room-space and a building element. CityGML, Level of Detail 4 (LOD 4) also depict a hierarchy, where a building is composed of rooms and rooms are enclosed by surrounding surfaces. Stories can also be modelled using CityGML generic grouping mechanism (Fig. 2).
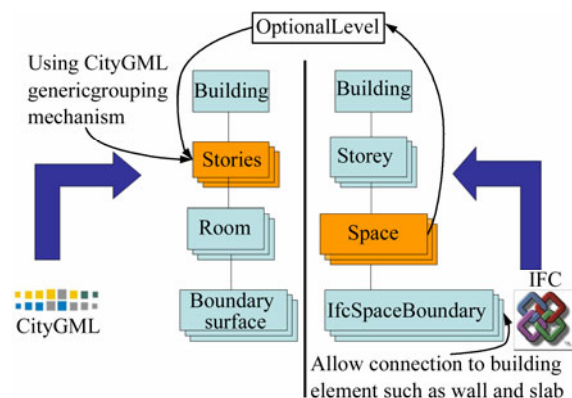

Fig.2   Deriving hierarchy for IFC and CityGML based on their data models

The hierarchy presented in these models, however, is not sufficient for the purpose discussed in this paper. The required hierarchy will be discussed in the following sections.

2   NIBU—modeling framework

Most of the analyses on utilities network require a graph model representing the connectivity between network elements. Analysing the relationship between network elements and the building structure requires a complementary model that supports referencing

these elements to the building elements. Complex analysis or simulations – such as collision detection (excavator vs pipes) and determination of damaged objects; predicating the result of closing a water controller on a specific network service and determining the spaces that would be out of service; or providing a description for the location of network components within building – requires a different approach, one that helps us to understand how utilities infrastructure interacts with building elements, either by a direct connection, or due to effects resulting from their spatial proximity.[7]

Our approach to modeling these interactions and interdependencies is based on extending the network graph of each network with explicit interdependency information. Fig. 3 illustrates our approach to representing interdependencies. A crucial aspect of this framework is the ability to link a network component to a building structure and to provide a description of the location of the interior building utilities within the building. Each network system (e.g., water, electricity) is represented as a homogeneous set of nodes, and each group of nodes is represented as an empty graph. An empty graph on n nodes consists of n isolated nodes with no edges, where each node represents a specific network element (e.g., pipe, fittings) in one system (e.g., gas, water) (see Figs. 3(a) and 3(c)).

Building elements are represented as another group of nodes. These are also represented by an empty graph (see Fig. 3(b)). Each building element, e.g., wall, slab or space, represents a specific node. Standards such as CityGML and IFC represent buildings as objects, where each building element represents a specific concept and has a 3D representation. Therefore, such elements can be extracted and modelled as homogeneous collections of objects represented as nodes.

The existence of a network element within a building element is realised using undirected edge; this links the nodes of the network element (represented as a node) and the building element. Fig. 3(d) illustrates this relation. The link is inserted between two such nodes if the intersection of the interior of the two corresponding object geometries is non-empty. Therefore, the edges represent the Egenhofer relations of "contains", "overlap" and "equals" between two objects from service systems and the
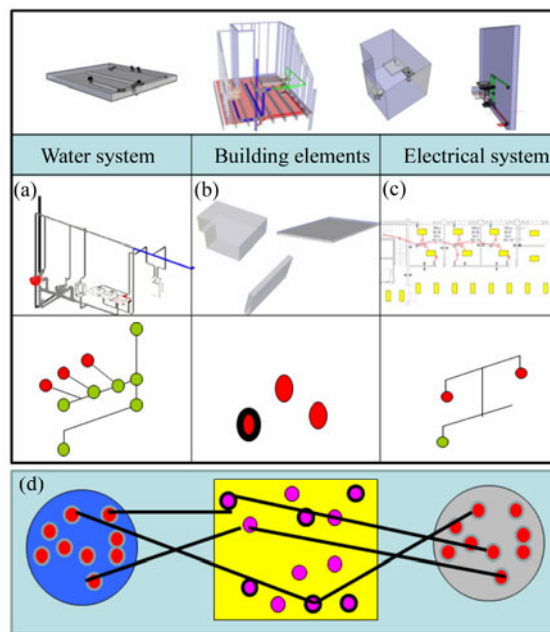
building elements.[30]

Fig.3 The NIBU modeling approach, nodes represents building and network object, edges represent the relationship between them

The generated graph between building elements and service system represents a collection of trees (forest). Each tree represents a star tree. One node has vertex degree n-1 (building element), and the other vertex degree 1. Fig. 4 below illustrates the generated graph.
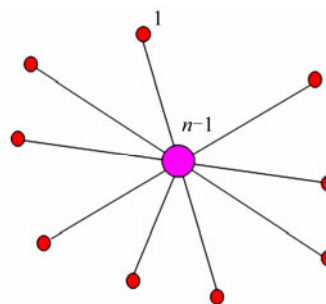

Fig. 4 The generated graph between building elements and service systems

In order to support the framework presented in the above section, we need cognitive models of building structure to link network components to it is building elements, e.g., space, walls and slabs. This is important in order to provide the result of complex analysis from the perspective of humans. For example, generating a humanly understandable direction for the location of utilities within buildings requires a useful explanation such as "Go to the first floor ...room no e12 ... in the ceiling". What is behind this statement a

one-level (or in general multi-level) hierarchical model of the building that network components is linked to? An example for this is depicted in Fig. 5. The ability to reference the water shut off valve will be defined by the containments relation as defined in the previous section, and then by having a cognitive manner that relates the wall where the shut off valve is to the space that it encloses, to the building storey it is within, and to the whole building.

Fig. 5   Shut off valve located in access panel inside wall

There is a relationship between spatial regions in the building within which they are nested. Premises are inherently organized into constituent floors, sections, rooms, and so forth. Current building models of indoor spaces, such IFC and CityGML are interesting in so far as they cater for the representation of spaces, which can be adapted for the perspective of humans. They are well suited for generating route descriptions. However, these models need more clarification regarding the ability to reference service systems in these buildings.

The problem of adapting any of these hierarchies is that none of them provides a direct way to connect a specific service to wall or slab and then a space, a story and a building. There is no single way to connect a specific IFC object with another. For example, *IfcFlowSegment* can be connected to the wall using the containment relation, which can be connected to space based on the information that spaces are enclosed by walls, which are connected to *IfcStorey* and building. This route for finding which wall is connected to which space, storey and building is a chosen route in a specific data file, but not a static defined one on the IFC schema level, i.e., space is an optional level. On the other hand, this kind of relationship is much more explicit in CityGML. A connection between a wall surface and a room and then a building is always the same. However, the wall class wherein the flow distribution element does not exist in

CityGML. Therefore, it is difficult to follow any of these hierarchies for the purpose of this data model; we define a hierarchy that can facilitate linking building elements to the hierarchical structure of the building.

Fig. 6 provides a UML diagram for the building data model. It considers two important issues: first, each building has at least one storey; and each storey must have at least one space. Second, the space is defined by the relationship between the space and the building element enclosing its volume and here is indicated in boundary class. The space has (1 to many) relationships to the building element that surrounds the space. Therefore, the building model sustains the relationship between the buildings-storey-space and building element enclosing it, e.g., wall, slabs. The structure of the building component consists of the different object classes.
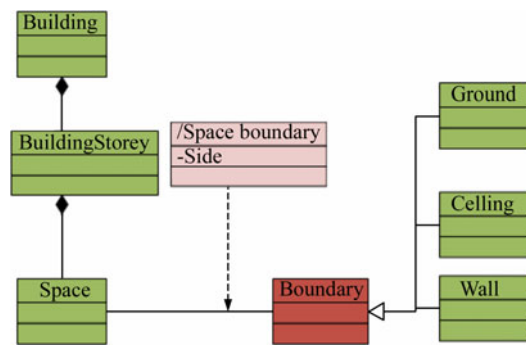

Fig. 6   UML diagram for the proposed building model

Space: The smallest building component is the space, which is enclosed by building elements represented in the model by the class boundary.

Boundary: The class boundary represents building elements which surround space; these building elements are further classified to the subtypes wall, ground and ceiling The boundary sides, i.e., the sides that create one boundary can be generated on the fly.

Building storey: Vertically structuring the building part, each building storey consists of at least one space.

Compared with CityGML and BIM/IFC, this model shows some similarities, but also a number of differences. The model has a direct way of linking building elements with the space it encloses; and the space is a primary class that should exist in every building storey. The building storey is aggregated by the spaces class. Space faces can be derived on the fly.

2.1 Extract space and boundary relations

The duality graph is utilized here to assign the walls and slabs to the space they enclose. Fig.7 illustrates the approach. The building element, i.e., slab in the figure would be defined as a node in the dual graph, which is represented as a 3D solid primal model. The adjacency between the building elements, e.g., slab and the spaces would be represented as an edge connecting the node of the building element with its adjacent spaces. Therefore, the relation that is required by the model could be extracted by this method. The relation between the spaces and the building element it encloses could be simplified in a graph as illustrated in Fig.7.
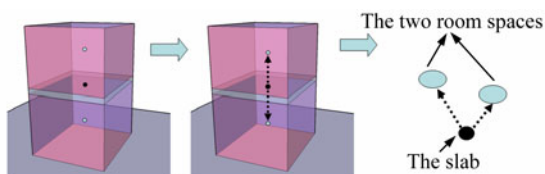

Fig. 7   Extracting the relation between space and it's surrounded elements

Moreover, organizing the spaces that are reachable by pedestrian and will allow for the people to access the network could be achieved using the existing entry algorithm. The algorithm facilitates the creation of the space hierarchy and organizes the building rooms that are within one floor.

2.2 Decomposition of large building elements and spaces

The above-mentioned approach works well for cases of simple plans like the one presented in Fig. 8. In this case, large building elements, such as floor slabs, can be easily divided into smaller parts based on the intersection between these spaces and floor slabs (Fig. 8(b)). However, strictly pursing this naive approach becomes difficult for larger buildings with large areas of open spaces, for instance in airports, main train stations or cinemas. Therefore, we need a suitable method to divide these large building elements into smaller ones, to which network components are linked. As mentioned above, Ref. [31] provides a method that allows a division of spaces. In this section, we will discuss how these methods can be utilized and test their suitability to support the framework presented in this paper.
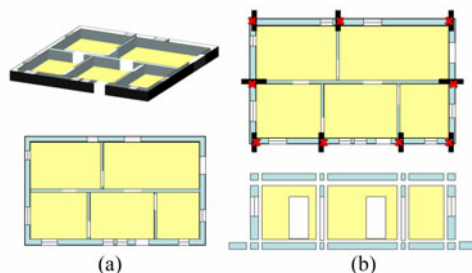

Fig. 8   (a) simple plan decomposition, (b) slab building element decomposed based on intersection between spaces and slabs

The described algorithm in Ref. [31] divides the internal spaces based on visibility criteria. The algorithm can handle simple polygons as encountered in floor plans. Fig. 9 provides an illustration of the algorithm. This approach can be used similarly to divide the large spaces into smaller ones creating smaller regions that can be used to have smaller parts of large building elements, e.g., slabs, and based on the intersect relationship between the sub-spaces resulted from this partitioning algorithm and the original slabs. Long walls could be partitioned in a similar way. See Fig. 9.
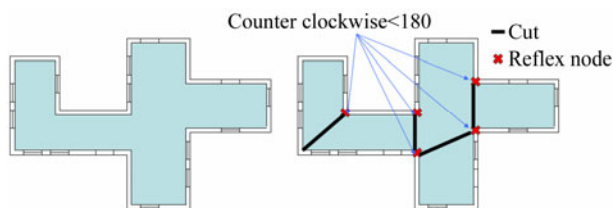

Fig. 9   Large space pertaining method based on concave-convex algorithm[31]

Furthermore, the network components within spaces or the decomposed spaces can be referenced to other building elements in order to generate a more accurate description of its location. For example generating instructions like: the pipe is between the two windows, or the shut-off is directly opposite the window to your right (location of the user is always from the access point to the space).

An example is depicted in Fig. 10. If a person is standing at door B, the location of the pipe can be described by the statement "between the two windows on your left", and this information can be computed by the trajectory from B to the centre, divide the room into the left and right. Windows C and D are to the left and window A to the right. This can be derived from the angular distribution of the door and windows. Thus,

D is "to your left". D is the second window in clockwise direction from B to D. This information can be stored as a list of angles between the door and a reference line which goes from the centre of gravity of the room to a fixed reference point on the wall.
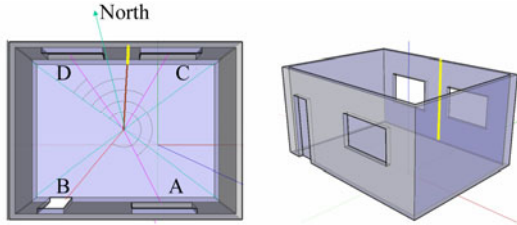

Fig. 10   Using angles to define location of network element relative to building elements

3   Example for modeling proposal

The following example illustrates a real-life example of the representation of a building utilities system. It demonstrates how the proposed framework NIBU allows for the integrated analysis of utilities, by enabling the referencing to other building elements and thereby providing a description of its exact location. Also, it allows an investigation of the location of maintenance operations that will affect utilities service system within the maintenance location. It further allows investigating of the cascading of failure or damage in building structures on other network systems.

Fig. 11 illustrates a plan and a section view for a building consisting of one storey with two rooms. The storey has a network of clean and waste water. This entire building structure is represented as a graph in Fig. 11, where the building elements are represented as nodes, as shown in the figure, and the graph has a hierarchy where each node is linked to

other building elements based on hierarchy. The first level represents the building, the second level represents the two rooms, and the third level represents the building elements enclosing space, surrounding the room's volume. The network elements are also represented as two separate homogenous sets of nodes, where each network component is represented as a node and the links represent the connectivity relation between these components. The round dashed edges represent the relationship between the network element and building element, based on containments relation.
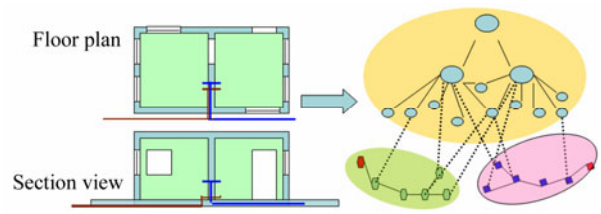

Fig. 11   Model building element

Let us assume that a maintenance operation will take place in the slab that is highlighted in Fig. 12(a). Now, if the maintenance team need to know if other building systems are within this element, they can figure it out by tracing the dashed link that connects building element to network element, based on containment relation(Fig. 12(b)). The dashed lines show that the two network systems have network components within this wall. The next step would be to perform trace analysis on each network system to define the shut-off location of each system. The description for the location of the shut-off would be defined first by using the dashed lines, and then the hierarchy provides a description for the location of the shut-off, which is in this case within a room and the building
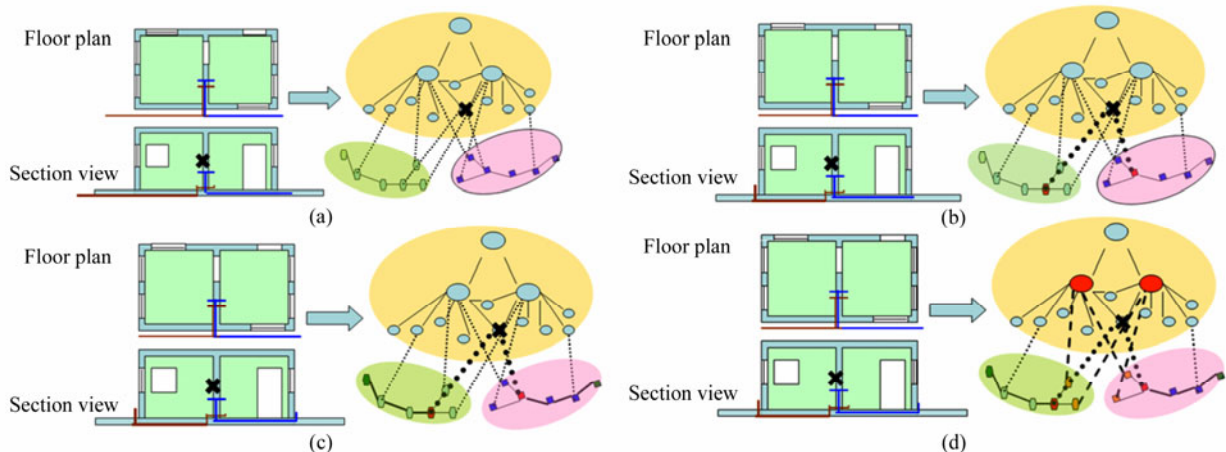

Fig. 12   Example for supporting maintenance operation using the proposed framework

(Fig. 12(c)). After the maintenance team has taken action and activated the shut off, the last operation that they will need to figure out is the location of the spaces that will be out of service. This is a two-step operation, the first step of which will be undertaken on each specific service system separately using the tracing operation on the local graph of the service systems to find the terminals in the network that would be affected. Then, their locations within the building will be defined based on the edge-joint relation (Fig. 12(d)).

4   The data model

The UML diagram shows the NIBU. The model defines the classes and relations needed to describe the geometric, thematic and topological representations of each utility network system, as well as their relation to other building elements. Furthermore, it contains classes representing the graph of network systems, as well as the resulting graph from the connection relations that are created between building elements and network components. The classes are arranged in two parts: the utility network systems, and the building structure.

The utilities network system is represented using the classes' *NetworkSystem* and *Dis_NetworkElement* classes. The class *NetworkSystem* represents a collocation of features that composes one utility system. The class *Dis_NetworkElement* represents a real-world network component, and provides a 3D representation of network objects as solid. These two classes are seen as interfaces which connect the NIBU model to existing semantic 3D models describing the 3D objects; e.g., the CityGML UtilityNetworkADE[32] has the classes *Network* and *NetworkFeature*, IFC has the class *IfcSystem* and the class *IfcDistribuationElement*. The two classes *Fittings* and *Segments* are specialisations of the class *Dis_NetworkElement* and inherit its attributes. *Fittings* represent fixtures that connect two *flowsegements* (e.g., pipes) and are intended to represent the nodes in the logical graph structure of the service system network. Therefore, a point representation is associated with this class to allow having a physical point represent this class. This class has several sub-types listed in the enumeration list. On the

other hand, the *Segment* class represents the flow segment, which is an edge in the logical graph structure; the class can have a curve representation that offers a physical simple representation of this class. Both classes comprise the class *Network_GRAPH* which links the *Dist_NetworkElement* sub-classes.

The building structure is represented using the classes on the left-hand side. The classes are structured in such a way to provide the hierarchy represented in Section 2. The *SubSpace* class represents the minimum space part that could be decomposed from a space that is represented by the 3D building models. Therefore, the *SubSpace* class has a relation with the *Space* class, which provides the interface to connect 3D building semantic models: e.g., IFC represents space as *IfcSpace* and CityGML represents space as *Room* surrounded by surfaces. Similarly, the *Boundary* class represents the smallest part of the building element that is enclosing the volume of the 3D space. Therefore, this class has a composite relationship with the class building element, which also provides the interface to building elements in the mentioned 3D semantic building models. The classes *Storey* and *Building* are represented by a grouping mechanism to assemble the spaces into specific storey's and the storey's into a specific building. Special aspects are considered to represent the building structure. This arrangement of building classes is to ensure that the smallest possible building elements that enclose a space can be referenced to as a space, a storey and then a building.

The relationship between the networks objects and the building structure is depicted in another graph, represented in the class *con_graph*. This graph is composed of two classes: Boundary, on the one hand, and the network components on the other hand, i.e., *Dist_NetworkElement*. The resulting graph can be used for tracking cascading damage result, planning maintenance operations and other causes related to managing interdependences of interior building utilities.

5   Conclusion

Building structures are a complex environment, and managing their service systems is a challenging

task compared to the exterior utilities. In this paper, we have presented a novel concept for modeling the interdependencies between building utilities and building structure. The approach is appropriate for different situations, such as support maintenance operations, simulating damage effects on other network systems and building structures, and supporting the generating of a description to locate and reference utilities network within building structure. The model extends several existing approaches and customizes it for the purpose of interior utilities applications; by explaining ideas and the requirements of the utilities network interdependences. The classes and their relationship are formally modeled using a UML class diagram. The data model is a graph-based spatial model that allows the analysis of 3D true geometry. Moreover, it provides classes that facilitate the interface between the data model and the current building standards, such as CityGML and BIM/IFC, and therefore it is possible to construct the model from 3D geometric data and current 3D building data model standards. The model is structured hierarchically, and therefore it is possible to relate and reference network elements to building elements. Each of its elements corresponds to a certain domain concept – wall, door, room – which can guide technical staff to network element locations inside the building.

Interdependencies between building structure and utilities services system are modeled using a logical link that is created based on the Egenhofer relations ("contains", "overlap" or "equal"). The building model presented in this paper is customized for the purpose of utilities network. The building structure is complemented and plays a crucial role in providing a cognitive and meaningful model that supports the managing of the interdependencies between network components and building structures. The presented framework is illustrated with several examples. The representation of the building structure as well as the network element and the linkage between them is introduced using the logical link. The derived graph is expected to successfully support the queries of the use case and to provide the required information.

This conceptual framework is the first step towards integrated modeling of interior utility networks and the building structure. Future work will concentrate on testing of this approach with real data sets. Special attention will be given to the structuring methods and the possibility of creating the model in a totally automated way from the IFC (for the utility network and building representations) or CityGML (the building structure).

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