Integrated management of indoor and outdoor utilities by utilizing BIM and 3DGIS

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ADE Application Domain Extension. 21

AEC Architecural Engineering and Construction. 3

AQE Augmented Quade Edge. 24

$B-Rep$ Boundary Representation. 19

$BIM4GeoA$ BIM for Geo-Analysis. 7

BIM Building Information Model.. xviii

CAD Computer Aided Design.. xvii

CGI Common Gateway Interface. 101

CSG Constructive Solid Geometry. 19

$CityGML$ City Geography Markup Language.. xviii

$DBMS$ Database Management System. xviii

DHE Dual Half Edge. 24

DTM Digital Terrain Model. 19

$Digraph$ Directed graph. 14

FM Facility Management. 3

GIS Geographic Information System. xvii

$GML3$ Geography Markup language. 19

GUI Graphical User Interface. 94

Glossary

HVAC Heating Ventilation Air Conditioning. 18

IAI International Alliance for Interoperability. 3

IFC Industrial Foundation Class. xviii

IFG Industrial Foundation Class for GIS. 28

IP Information Product. 8, 31

KML Keyhole Markup Language. xviii

LOD Level of Detail. 19

NIBU Network for Interior Building Utilities. xvii, 17

NRS Node Relation Structure. 24

OGC Open Geospatial Consortium. xviii

OSS Open Source Software. xviii

OS Open Specification. xviii

PIECES Performance, Information, Economy, Control, Efficiency, Services. 32

QE Quade Edge. 24

QUASY Quartierdaten-Managementsystem. 28

SIG Spatial Interest Group. 19

SQL Structured Query Language. 16

UML Unified Modeling Language. 8

UtilityNetworkADE Utility Network Application Domain Extension. 7

XML Extensible Markup Language. 17

Abstract

Computer Aided Design (*CAD*) and Geographic Information System (*GIS*) are two technologies/systems that are used in tandem in different phases of a civil infrastructure project. CAD systems provide tools to design and manage the interior space of buildings, while GIS is used to provide information about the geo-context. These two technologies encroach upon each other's territory. In fact, the business processes related to them do not even have these boundaries. Utilities infrastructure is an area wherein integrated information management, facilitated by input from both systems, is crucial.

This research provides a framework and a data model, "Network for Interior Building Utilities" (*NIBU*), for integrated analysis and management of interior building utilities in a micro-scale environment. The framework considers managing individual network systems by providing semantic categorization of utilities, as well as a graph structure based on a "Modern" adjacency list data structure. The framework also considers managing the interdependencies between different network systems and the building structure. NIBU is a graph-based spatial data model can be used, in providing the location and specifications of interior utilities to a technician, to perform a maintenance operation, or to estimate the effect of different maintenance operations in different locations along utility service systems. The model focuses on two important aspects: 1) the relationship between interior utilities and building elements (or spaces) and 2) the building hierarchy structure to which the utilities network is related. A proper hierarchy of the building that supports the generation of human-oriented descriptions of interior utilities is also developed during the research. In addition, a method for partitioning of large building elements (and spaces) was utilized. The connection of the different utilities network systems and buildings were established using joints, based on a containment relationship. A user requirement study consisting of three use

case scenarios ("maintenance operation", "emergency response" and "inspection operation") was conducted during the research, and these use cases were used to develop the required functionalities and to test the proposed framework.

The framework relies on standards data models related to Building Information Model *BIM*/CAD and GIS, and these standard models were used as data sources for obtaining information about the utilities. BIMs support the semantic and geometric representation of interior building utilities, and, more recently, City Geographic Markup Language (*CityGML*) has been extended to model utilities infrastructure. Semantic harmonization was employed to achieve the integration and provide a formal mapping between the BIM i.e. Industry Foundation Class (*IFC*), CityGML and NIBU. The semantic and connectivity information from these (BIM/ GIS) standards were mapped onto NIBU. Furthermore, the building structure and the required hierarchy were obtained from these models. The research proves that BIMs provide the required amount of information that is needed for the framework and model (i.e. NIBU). By contrast, CityGML does not provide the amount of detail required by NIBU.

The research also provides an information system that facilitates the use of BIM for geo-analysis purposes, by populating/implementing the NIBU and its functions. BIM4GeoA is a concept for combining existing Open Source Software (*OSS*) and Open Specification (*OS*) for efficient data management and analysis of building information within its broader context. The core components of the system are the Spatial Database (i.e. PostgreSQL/PostGIS), the Building Information Model Server, a Virtual Globe application (i.e. Google Earth 3D viewer), and the models of existing BIM/3D Open Geospatial Consortium (*OGC*) standards (IFC, Keyhole Markup Language (*KML*), CityGML). Following the system development, a thorough analysis of the strengths and weaknesses of these different components were completed to reinforce their strengths and eliminate their weaknesses. The system is used in implementing the NIBU model and its functions; i.e. NIBU is mapped to PostgreSQL/-PostGIS spatial Data Base Management System (*DBMS*). The model is populated directly from a BIM Server with the help of an IFC parser developed during the research. Five analysis functions are implemented in the system to support spatial operations. These were: trace upstream, trace downstream, find ancestors, find source, and find disconnected. The investigation proves that NIBU provides the semantics and attributes, the connectivity information and the required relationship necessary to facilitating analysis of interior utility networks and manage its relations with building structures.

Glossary

Dedication

To my beloved parents, Hamzi and Fatima.

Despite the difficulties that they are suffering while striving to live in their homeland, Palestine, they continue to set an example of patience and human dignity, showing to me and my sisters thereby the way that leads to more hopeful and peaceful destiny.

Also, to my wonderful wife Hanan, my son Hamzi, and my daughter Nada who entered life during this journey of mine, I give my thanks for standing near me and donating part of the time that I should have spent with them for working on this thesis. The future is ours.

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Special thanks go to those who kindly assisted me in completing this thesis. I am extremely grateful to ESRI in Redlands, California for offering me the internship. Many thanks go in particular to Annie L'Heureux, Eric Wittner, Khalid Duri, Hamid Younis and Phil Sanchez for their help during the internship. I have also benefited from the advice and guidance of Dr Andrew Baldwin, who kindly devoted himself to proofreading this thesis. I also sincerely thank Dr Umit Isikdag for providing me with valuable help in understanding the IFC standard. My deepest gratitude is due to Ahmad Abu Jeberah, Dr Sufyan Samerah, Dr Nadia Abu Zahera, Dr Firas Al-Douri, Mohammad El-Mekawy, Dr Bernhard Höfel,and Florian Albrecht.

I am deeply indebted to my parents. Where I am today is no small part due to their encouragement and support, I thank my mother Fatima for her constant prayers and good wishes. I also thank my father Hamzi - the great educator, who always had high expectations for his son. The love and distinct support of my wife, Eng. Hanan Khaldi, have sustained me throughout my entire PhD studies. Special thanks to my son Hamzi and my daughter Nada, my gratefulness and appreciation for their presence in my life is beyond words. My sisters have always stood by me and provided me with all the required help and support. I would also like to acknowledge my uncle Dr Yahya Ismail and my cousin Khalid Hijazi for their advice and inspiration. I express my deepest gratitude to all these family members.

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CHAPTER 1

Introduction

In today's society, people spend the vast majority of their lives and activities, whether awake or asleep, inside buildings (Rich and Davis, 2010). For the first time in modern history, statistics show that there are more people living in urban than in rural environments. Therefore, the complications of urban infrastructure are intensifying (www.unfpa.org, 2011). Additionally, buildings are coming to be considered the preeminent consumers of energy, since their gas emissions far exceed the emissions that come from transportation or industry (http://ec.europa.eu, 2011). Moreover, a huge amount of the world's resources is being consumed by construction materials; and, consequently, there is a great need of looking for new ways of managing facilities.

1.1 3D GIS

As regards, first of all, the importance of facilities and their place in modern society, bringing GIS to interior space has the potential to generate a revolution in facilities management. GIS were originally designed for the management and analysis of spatial relationships. Typically, they have been used to solve geo-spatial problems, from global-level analysis down to regional, city, local and even campus level, where buildings are represented as block models. Over the years, the GIS community has built marvellous spatial data fabrics that include for example, utility infrastructures, transportation and demographics. However, when it comes to buildings, these are not mapped, and are in fact treated as holes (Rich and Davis, 2010). In order to get the benefits of GIS for buildings, there is a need to extend the geographical scale of GIS to this level of granularity, i.e. to the interior of buildings.

For a long time, CAD represented the primary media available for understanding the interactions of buildings and their contents and associated workflows. On the other hand, GIS focused on what is referred to as landscape and exterior environment. While there is some CAD companies provide GIS solutions e.g. AutoCAD Map, CAD and GIS technology still not crosses the boundaries of the other. Yet business processes do not have such artificial boundaries; there are many examples of how facility management can process across these (Rich and Davis, 2010). Examples of these business processes can be shown as follows:

- Power and water utilities would not be of much use if they stopped at the outside of the building. They have to be integrated and traced from the exterior to the interior of buildings.
- Pedestrian movement does not stop at the entrances of buildings; people move in and out of buildings. In a big shopping center or an airport, finding the needed destination in a timely manner is a crucial issue.
- Maintenance management workflows in a building require both inside and outside work, which is done across the entire supply chain.

3D city models, in their current status, are developed to include interior spaces, where they treat buildings as divisible entities with internal partitions and subunits (Benner et al., 2005; Gröger et al., 2008). The capability of these 3D city models goes beyond visualization in terms of the applications that they can support. Visualization is seen as the tip of the iceberg for these 3D models (El-Mekawy, 2010). The models are semantically rich and focus on providing representation of the earth surface and its spatial objects within a city. Regarding buildings, these models adopt architectural floor plans as the common denominator for visualizing the built environment, and, consequently, open the door for an increasing number of applications. Examples of these applications are: real estate management, crisis and disaster management, facility management, and indoor navigation. BIM is seen as an essential data source for these 3D city models, as it creates more navigable, interactive and visually realistic information for built environments (Peachavanish et al., 2006). It provides these applications with information about the interior space usage and the connectivity between spaces.

Integrating BIM into GIS has associated problems, arising from different geometric representation methods, and coordinating real-world versus local coordinate systems; therefore, there is a need to re-use the BIM data. Standardization of data models has been suggested and practiced as a major stride towards achieving the goal of interoperability (Akinci et al., 2008; Peachavanish et al., 2006; Weiming et al., 2010). IFCs (Liebich, 2010b) and CityGML (Gröger et al., 2008) are officially recognized as two standards, and have been independently developed; the former by the International Alliance for Interoperability (IAI), which is the standardization body for the Architecture Engineering and Construction (AEC)/Facility Management (FM) community, and the latter by the OGC, which is the standardization body for the geospatial community. There have been efforts to integrate BIM and GIS using these two standards; this allows for a certain amount of integration of BIM into GIS (www.iai.no, 2011; Peachavanish et al., 2006; I-Chen and Shang-Hsien, 2007; Akinci et al., 2008; Isikdag and Zlatanova, 2009). The focus of the transformation methods presented in the above studies considers only the building's architectural elements, such as walls, spaces, doors, while also concentrating on the geometry transformation issues. At the same time, there have been efforts in developing 3D primitives, 3D analysis functionalities, and data structure (Arens et al., 2005; Pu and Zlatanova, 2005; Musliman et al., 2007; Borrmann and Rank, 2009a; Borrmann and Rank, 2009b). The focus is mostly on validation functions for 3D objects, neighborhood relations (e.g. within, touch and intersect) and metric calculation in 3D (e.g. volume, distance and area), with the purpose of investigating the connectivity relations that represent the areas that are navigable by pedestrians.

However, 3D city models still need enriching with further information about other interior building elements such as interior building utilities. It is an important component of built environments, and plays a crucial role in providing building residents with healthy and comfortable environments, and is another application where the integration between the interior and exterior is essential. BIM standards provide a representation of these building service systems. The 3D city model (CityGML) has also been developed recently to represent the 3D utility infrastructure in cities. Therefore, interior building utilities and their integration into the 3D geospatial context, in addition to the integrated analysis with other building elements, comprise the subject-matter of this thesis.

1.2 Interior building utilities

Utility networks inside buildings consist of pipes and cables. Examples include air-conditioning (heating/cooling, power), plumbing (water and waste water), gas, sewage and electricity. These forms of infrastructure play a crucial role in providing building occupants with comfortable, safe and healthy environments. They are defined as a ”group of electro-mechanical components connected by suitable pathways for transmission of energy, materials or information and directed to a specific purpose” (Reffat, 2002). In large complexes, such as commercial buildings, offices, universities, hospitals or factories, building service systems can be extremely intricate, taking up large amounts of space spread across separate areas or double floors/false ceilings, and will therefore account for a sizeable proportion of the regular maintenance required. Enhancing the efficiency of the services and expediting the process of response to occupants in the case of emergencies, repairs or maintenance operations requires integration of both interior and exterior network infrastructure in a 3D environment, and the provision of a suitable approach for integrated analysis of these systems with building structures (Hijazi and Ehlers, 2009a; Hijazi et al., 2009). Most facility management offices still have paper maps. The digital systems widely employed by utility operators are usually expensive packages with elaborated functionality (e.g. ArcGIS, Bentley Water), making them less attractive for facility managers of building complexes. Furthermore, professional software for management of network systems generally provides 2D solutions, which need considerable development in order to be integrated into 3D models of buildings.

In addition, research on integration of outdoor 3D utility networks with other 3D objects has been discussed intensively in the literature (Du et al., 2006; Du and Zlatanova, 2006; Beck and Stickler, 2009; Döner et al., 2010). Unlike outdoor utility networks, building service systems are mostly located inside building elements, e.g. ceilings and walls. 3D measurements using traditional 3D data collection methods, such as magnetometers, radio-detection or surveying, are usually not applicable to interior networks (Döner et al., 2010). Moreover, managing the interior utilities within building structures is a crucial issue, the interdependence of interior utilities networks of large buildings is a more complex exercise compared to outdoor networks. The interior networks are three-dimensional structures nested inside a building. They go through building elements (e.g. slabs, walls); part thereof is contained within each building's 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 is managing the interdependencies with outdoor infrastructure, which mostly follows road and railroad networks. The geometric and topological structure of buildings is much more diverse than is 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.

There is, therefore, a lack of studies considering interior utilities. In addition, the complexity of interior utilities, as compared to exterior ones, provides the motivation to conduct this study. The thesis will investigate the requirements of utilities in a built environment, and offer a solation that can be customized to support the interior utilities problem.

1.3 Research Objective

The research has the following key objectives:

1. Explore the functional requirement, spatial relationships and visualization requirements that GIS should provide in order to facilitate utilities analysis in and between buildings within a 3D environment.
2. Design a conceptual model capable of accommodating the object needed to support the integrated analysis of interior building utilities both within geospatial context and considering the complex building structure, and which also responds to user-and technology-driven requirements.
3. Explains the links between the conceptual model and the current 3D building model standards; and, by doing so, provide a framework for achieving interoperability between BIM/GIS.
4. Develop a low-cost, open-source, web-based 3D GIS solution that allows integration of the 3D building designs within 3D city models.

To achieve the objectives defined above, the research proceeds from two principal understandings: The prime focus of the research work is ensuring 3D GIS functionality. Offering a fast 3D GIS system is confined to the requirements of the model. Performance optimization is beyond the scope of the thesis.

The second understanding refers to the concept regarding remote access of data. Therefore, the system has to provide access to a wide spectrum of users; and hence the system architecture must rely on standard.

1.4 Contributions of the Research

The research contributes to micro-scale 3D GIS research and, more specifically, demonstrates how a GIS can be used to conduct different types of spatial analysis and visualization of facilities, both between and within buildings.

First, the user requirement study conducted in this research has considered planning a 3D GIS, investigating the 3D requirements, including the defining of 3D analysis functionalities, spatial relationships and other aspects that should be considered while planning a GIS. Current methods and literature available have so far considered only 2D aspects.

Second, the NIBU framework presented in this study represents a complex 3D spatial building structure and the relationships between this structure and interior utilities. The framework can support different scenarios, such as maintenance operations and providing the location of the network objects within building structure. It studies the cascading effects of damage at one location on other utilities systems.

Third, the study provides a framework for integrating interior-exterior utilities into one data model by means of semantics mapping. The approach involves harmonizing the semantics and thus allows formal mapping between NIBU, BIM and real-world networks in CityGML - Utility Network Application Domain Extension (*UtilityNetworkADE*). The information provided in the thesis can contribute to the efforts of enriching 3D city models with urban knowledge, so as to extend their functionality and usability.

Finally, the proposed system architecture BIM for Geo-Analysis (*BIM4GeoA*) allows for the combining of existing OSS and OS for efficient data management and analysis of building information within its boarder context. This is in contrast with the traditional tools being developed that enable the transformation of building models to be represented using 3D city data model standards, and which thus enable the visualization within 3D geospatial context using GIS software; i.e. they are limited for visualization purposes and neglect spatial analysis, the very core of a GIS. The proposed system BIM4GeoA focuses more on analysis.

1.5 Organization of the thesis

Although organized in eight chapters, the work presented by this thesis can be subdivided into five parts, i.e. introduction (see chapter 1 and 2), clarification of requirements (see chapter 3), conceptual design (see chapter 4 and 5), implementation (see chapters 6 and 7) and conclusion (see chapter 8)

Chapter 1 (this chapter) presents an overview for the research; its scope, objective and contribution.

Chapter 2 aims at clarifying some basic terms and concepts that are applied later in the thesis. It provides an introduction to the methods used for graph representation and utilities network and an overview of implementation within current spatial DBMS, 3D city models and building representation within these models. We provide an overview of building models and prototypes related to the framework presented in the thesis, also utilities network models within standards both in GIS and BIM. It further discusses related work in terms of interoperability and standards for the BIM and GIS domains (specifically IFC and CityGML)

Chapter 3 presents a study on user requirements. The chapter starts with an introduction on common methods to explore user requirements. The review of methods clarifies techniques to approach users (i.e. investigations into current activities, data and customers and exploring desired activities, data and potential users). The chapter presents the results of the investigation for the use of GIS for interior space, based on case studies in existing literature, and our study in the University of Osnabrueck. A group of Information Products (IP) is described. The chapter clarifies and elaborates on the requirement of utility network IP. The 3D Geovisualization is clarified, and the required 3D functionalities and spatial relationships are discussed and summarized.

Chapter 4 summarizes the user requirements and establishes the database requirements with reference to integrated analysis within a geo-context. An extended framework is introduced, i.e. the required classes to model interior utilities and integrate them within building structures are described. We formally define the basic element of the modeling framework; first, its logical graph structure to represent the connectivity relation between network objects. Next, the framework for representing the relationship between building structures and utilities network are introduced. We also discuss existing methods for space partition, and we evaluate their applicability to the presented framework. The chapter continues with formal definitions of the model using a Unified Modeling Language (UML) diagram. An example for the modeling proposal completes the chapter.

Chapter 5 discusses the possibilities for the generation of the new model NIBU based on the current building standards. The chapter presents the mapping of BIM and CityGML/UtilityNetworkADE into NIBU. The study discusses the integration approach, i.e. utilize semantic harmonization as an approach for BIM/GIS integration, and then it presents the investigation's result and describes how NIBU classes can be derived using equivalent concepts in IFC and CityGML. In this chapter, the NIBU is utilized as a unified model to integrate interior and exterior utilities

Chapter 6 deals with implementation. It introduces the development of a system architecture that enables the integration, query, retrieval, analysis and visualization of data on the web. It presents the system architecture and investigates some OSS modules and its capabilities to build a 3D geo-information system. The chapter presents a prototype with its three components: IFC parser, analysis functionalities and GUI for query and visualization. The system presented is the basis for all further development, because it offers easy access to the BIM data and allows its integration in a geo-context.

Chapter 7 uses the system architecture and the prototype presented in chapter 6. It presents the mapping of NIBU into a relational spatial DBMS. It also includes the algorithm and conversion method from IFC into the proposed network data model and the derivation of graphs and semantic information using the IFC entities. The developed functions are presented and demonstrated for the use cases. Tests of the systems are discussed as well

Chapter 8 first summarizes the work done in the thesis, the results and major findings of our research. The chapter concludes with possible direction for future work.

1.6 List of publications

Work presented in chapter 3 was first published in the ISDE6 summit in Beijing, China.

Hijazi, I. & Ehlers, M. (2009): 3D web requirement: A case study for the University of Osnabrueck, Proceedings of the 6th International Summit of Digital Earth, 9-12 September, Beijing, China.

Work presented in chapter 4 was published in two journal paper.

Hijazi, I., M. Ehlers & S. Zlatanova (2010): NIBU: A New Approach to Representing and Analysing Interior Utility Networks within 3D Geo-Information Systems (Published in International Journal of Digital Earth).

Hijazi, I., S. Zlatanova & M. Ehlers (2010): NIBU: An integrated framework for representing the relation among building structure and interior utilities in micro-scale environment (Published in Geo-Spatial Information Science)

Work presented in chapter 5 was first published in the 5th 3D Geoinfo conference in Berlin and was given the best paper award in the conference and selected to be published as book chapter in the Springer series Advances in Geoinformatics.

I. Hijazi, M. Ehlers, S. Zlatanova, T. Becker, L. van Berlo (2010): Initial investigations for modeling interior utilities within 3D geo context: Transforming IFC interior utility to CityGML UtilityNetworkADE. In: Kolbe T., König G., Nagel C. (Eds.): Advances in 3D GeoInformation Science, LNG&C Series, Springer, Berlin - Best paper award.

Work presented in chapter 6 was first published in the international conference of 3D GeoInfo in Berlin 2010.

Hijazi, I., M. Ehlers & S. Zlatanova (2010): BIM For Geo-Analysis (BIM4GeoA): Setup of 3D Information System with Open Source Software and Open Specification (OS).In: Kolbe, T. et.al. (2010) International Archieves of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Conference on 3D Geoinformation, Vol XXXVIII-4, Part W 15, Berlin, p. 45-49. - Best paper award.

Also the following publication was related to the work presented in this thesis.

Manfred Ehlers and Ihab Hijazi (2009): Prototype application for web 3D routing in building, Proc. SPIE 7840, 784016; doi:10.1117/12.872838.

Hijazi, I., Ehlers, M., Zlatanova, S. & Isikdag, U. 2009. IFC-CityGML transformation framework for geo-analysis: A water utility network case, Proceedings of the 4th 3D GeoInfo Workshop, 3-4 November, Ghent, Belgium.

CHAPTER 2

Background

This chapter presents of an overview of the key element in the development of this thesis: the graph theory, the management in spatial DBMS, utilities network representation in 3D models both in GIS and BIM, the 3D city models, a review of building models, and a literature review on BIM - GIS integration. The aim is to familiarize the reader with the fundamental concepts and principles used in the thesis and which are now widely agreed upon GIS and AEC society.

The chapter can be divided into three sections. First, the chapter clarifies the term graph, refines its types, and discusses its different data structures, leading up to a recommendation of the model proposed in this thesis. The chapter also discusses graph representation in current spatial DBMS; the issues discussed here are closely related to the model presented in chapter 4. Second, the utilities network in CityGML standard and BIM is presented; this section describes the major characteristics of these models and provides an overview about it, creating a basis for the discussion in chapter 5. The last part discusses the different city modeling types and their characteristics. Some specific modeling approaches relevant to the thesis are highlighted and further explained, which also provides the basis for the second part of chapter 4.

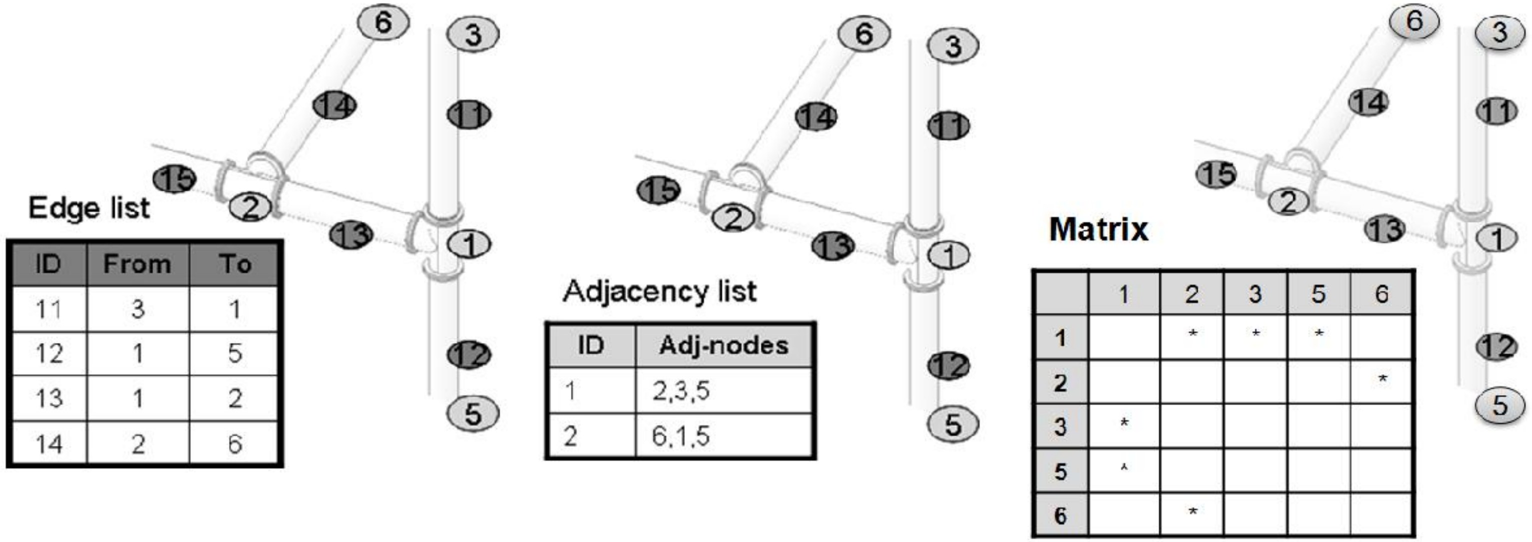
2.1 Graph data structure

Distribution systems are typically modelled (in CAD and GIS) as networks (M.Curtin, 2007; M.Curtin, 2008) . Such networks form a directed graph, where each connector, fixture or outlet is viewed as a vertex. Each uninterrupted stretch of wire or pipe is viewed as an edge. Flow networks are represented by a special kind of graph, called a tree, where the nodes are reachable from one starting node and where are no cycles. When creating a graph for a flow network, a question that deals with reach-ability in a (directed graph) *Digraph* G could be answered like this (Goodrich and Tamassia, 1998):

- Given vertices u and v, determine whether u reaches v (i.e. there exist a chain between u and v)?
- Find all the vertices of G that are reachable from a given vertex s?
- Determine the ancestor vertices for a given list of vertices?

While the graph's theoretic definition of a network remains constant, the ways in which the networks are structured in computer systems vary. The network in GIS is a geometrical and topological representation of utility networks (M.Curtin, 2008; M.Curtin, 2009). The three most popular approaches are referred to as the edge list structure, the adjacency list structure, and the adjacency matrix (V.Aho et al., 1985; Goodrich and Tamassia, 1998; Cormen et al., 2001). Figure (2.1) provides an illustration of graph data structure for water utility network.

The adjacency list data structure "Modern" combines both the adjacency list structure and the edge list data structure (Goodrich and Tamassia, 1998). This unified data structure has been implemented for flight networks, where the flight network is a directed network. A schematic illustration of the basic structure of the adjacency list data structure "Modern" for a directed graph G is shown in Figure (2.2). The adjacency list data structure "Modern" has an adjacency list to each vertex, which provides both the incoming edges list and the outgoing edge list. At the same time, the edge object holds a reference to the position of the edge (Goodrich and Tamassia, 1998).



Edge list

ID	From	To
11	3	1
12	1	5
13	1	2
14	2	6

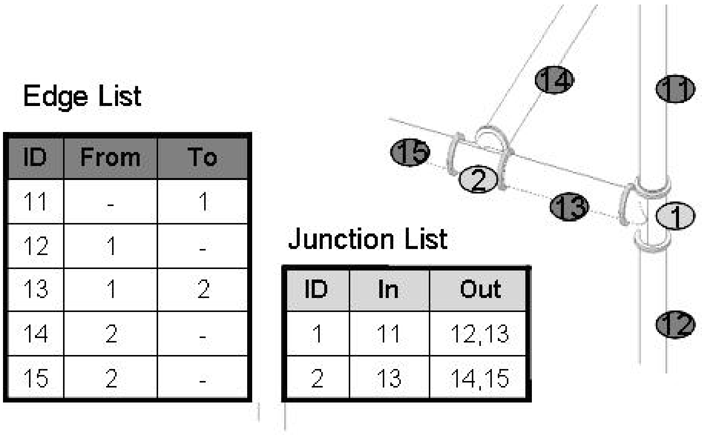
Adjacency list

ID	Adj-nodes
1	2,3,5
2	6,1,5

Matrix

	1	2	3	5	6
1		*	*	*	
2					*
3	*				
5	*				
6		*			

Figure 2.1: Different representations of a graph: a) Adjacency list, b) Edge list and c) Adjacency matrix



Edge List

ID	From	To
11	-	1
12	1	-
13	1	2
14	2	-
15	2	-

Junction List

ID	In	Out
1	11	12,13
2	13	14,15

Figure 2.2: Adjacency list data structure "Modern", for each vertex the incoming and outgoing edges is stored, and for each edge a pointer to the start and end node are stored.

2.1.1 Network data model in spatial DBMS

Another important component in our development is the use of a spatial DBMS. DBMS are especially useful for management of large complex datasets that are to be accessed by various users. Mainstream DBMS have provided spatial extensions to support spatial data types for management and analysis on them (Rigaux et al., 2002; Khuan and Abdul-Rahman, 2005; Pu and Zlatanova, 2006; Shashi and Sanjay, 2003). They can store points, lines and polygons using x, y and z coordinates; and most of the extensions are compliant with the simple feature specifications for Structured Query Language (*SQL*) specification of the OGC (www.opengeospatial.org, 2011). There is increasing interest in developing 3D primitives, as well as in developing 3D analysis functionalities (Arens et al., 2005; Borrmann and Rank, 2009a; Borrmann and Rank, 2009b; Musliman et al., 2006; Pu and Zlatanova, 2005; Musliman et al., 2007). The focus is mostly on validation functions for 3D objects, neighbourhood relations (e.g. within, touch, intersect), and metric calculations in 3D (e.g. volume, distance, area). Oracle Spatial 11g offers support for a volumetric data type. Some spatial DBMS (e.g. Oracle Spatial 11g and PostGIS) offer network models that are capable of performing some routing analysis within the confines of 2D geometry (www.oracle.com, 2010). In our developments, we have used the open-source DBMS PostGIS (www.postgis.org, 2011). Spatial DBMS offer us the means to organise information for utilities (Du and Zlatanova, 2006).

The spatial DBMS are useful for storing and managing building information in the geoinformation domain, when a large facility is managed by a GIS. It provides spatial data types and spatial indexing techniques, and thus allows for easy and efficient access to spatial data (Borrmann and Rank, 2009a). Utility networks can be stored either in geometry models, or in network models of mainstream DBMS (Du et al., 2006). 3D spatial analysis, however, can only be found in research environments (Gröger et al., 2004). In our prototype, we have used PostgreSQL / PostGIS (www.postgis.org, 2011). The PgRouting project follows the edge list data structure; it adds a set of libraries that allows the construction of a network model and routing functionality, such as the Dijkstra algorithm and the shortest path shooting star algorithm. Its main objective is to provide tools for 2D location-based services (PgRouting, 2011). Since the data structure is only 2D (nodes are represented with x,y), and the developed functions are limited to routing only, we have developed a new data structure to store a developed 3D network such as $NIBU$.

2.2 3D utilities network data models

IFC and CityGML are the most two prominently 3D standards in both AEC and GIS industry, the following will provide an overview of these standards and detailed analysis of the representation of utilities within these models.

2.2.1 Interior building utility in BIM/IFC

An international standard for data exchange of BIM data is the IFC. It was developed by the IAI to facilitate interoperability in the building industry (Liebich, 2010a). The goal of the IFC is to enable interoperability between building information systems. The latest release is IFC 2x3 TC1. Version 2x3 has introduced the IfcXML specification by using Extensible Markup Language (XML) schema to define the IFC models in parallel with EXPRESS [1] (I-Chen and Shang-Hsien, 2007). By contrast with the traditional de facto standards of CAD exchange, such as drawing files dxf or dgn, the IFC is strictly model-based. A wall is not a set of lines (polygons), but rather an object with specified attributes and relations (Clemen and

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[1] EXPRESS is a standard data modeling language for product data (Liebich, 2010b)

Gründig, 2006). The key contents of the current IFC 2x3 include (Liebich, 2010a; Isikdag et al., 2008; Schevers et al., 2007; Weiming et al., 2010):

- IFC enables re-use of building information through the whole building lifecycle.
- IFC is an object-oriented and semantic model.
- IFC provides the representation of building models in 3D.
- IFC is a spatially related data model, wherein spatial relationship between building elements are maintained in a hierarchical manner.
- IFC provide a schema for electrical wiring and plumbing details.

IFC supports utility networks inside buildings (building service systems); it has a shared building service element layer that defines the basic concepts required for interoperability between building service domain extensions: i.e. the plumbing, Heating Ventilation Air Conditioning (*HVAC*), electrical and control domains. IFC methodology for specializing building service components follows a general approach for a component within a distribution system, no matter what the systems is. Therefore, the same IFC component can be shared and used to represent the different networks (e.g. gas, water and electricity) (see Figure (2.3)). The IFC concept for utility support has the following major characteristics (Liebich, 2010a):

- All building service elements are exchanged by a subtype of *IfcDistributionElement*. The various subtypes inherit attributes and relationships from *IfcDistributionElement* and do not add any further attributes. These subtypes are introduced for the purpose of semantics and logical structuring of the model. Examples of these subtypes include *IfcFlowSegement*, which defines the occurrence of a segment of a flow distribution system that is typically straight, contiguous and has two ports (e.g. a section of pipe or duct). *IfcFlowController* defines the occurrence of elements of a distribution system that are used to regulate flow through a distribution system (e.g. damper, valve, switch, relay). Its type is defined by *IfcFlowControllerType* or its subtypes.
- IFC handles connectivity using two methods, logical and physical connectivity. Logical connectivity can be achieved without having a physical element to realize the connectivity. Physical connectivity, on the other hand is achieved by enhancing the logical connectivity with entity.

- IFC represents building objects by considering the real 3D shape; such as Constructive Solid Geometry (CSG) or SweptSolid. One object can have several representations. Building service components implement solid model representation using specific types, which are: Boundary Representation ($B-Rep$), SurfaceModel and SweptSolid, more information about these representation methods are given at appendix B. Each of these types can be replaced by Mapped representations, which allow the reuse of the shape of a particular object. The object can be inserted once or several times by using a block reference, including a transformation matrix.

- IFC provides the concept of system; a system is defined as an "organized combination of related parts within an AEC product, composed for a common purpose or function or to provide a service".

2.2.2 Utilities within CityGML - UtilityNetworkADE

CityGML is an OGC standard, which provides a specification for the representation of 3D urban objects (Gröger et al., 2008). It is the only 3D information model for the exchange of 3D city models. One of the reasons for creating such a model was to enrich 3D city models with thematic and semantic information. The information model of CityGML is an XML-based format implemented as an application schema of Geography Markup Language ($GML3$). Today, CityGML seems to provide the best framework for semantic-geometric relations of 3D objects above the earth surface (Emgaard and Zlatanova, 2008; Groneman and Zlatanova, 2009). It maintains a good taxonomy and aggregations of Digital Terrain Models (DTM), sites (including buildings), vegetation, water bodies, transportation facilities, and city furniture. The underlying model differentiates between five consecutive Levels Of Detail (LOD), where objects become more detailed with increasing LOD regarding both geometry and thematic differentiation. In LODs 2-4 of CityGML the building facade is defined in the form of boundary surfaces, i.e. wall surface, roof surface, ground surface or closing surface. The LOD4 allows the representation of interior building elements, e.g. rooms, furniture, interior wall surfaces. Nevertheless, the current version of CityGML still lacks the integration of subsurface features, such as geology, utility networks and underground constructions (e.g. tunnels). Recently the Special Interest Group 3D (SIG) has been working on some extensions of CityGML; these include extensions to represent bridges (www.citygmlwiki.org, 2011) and utility networks. The latter is the extension to model utility networks in cities (Becker et al., 2010b). The

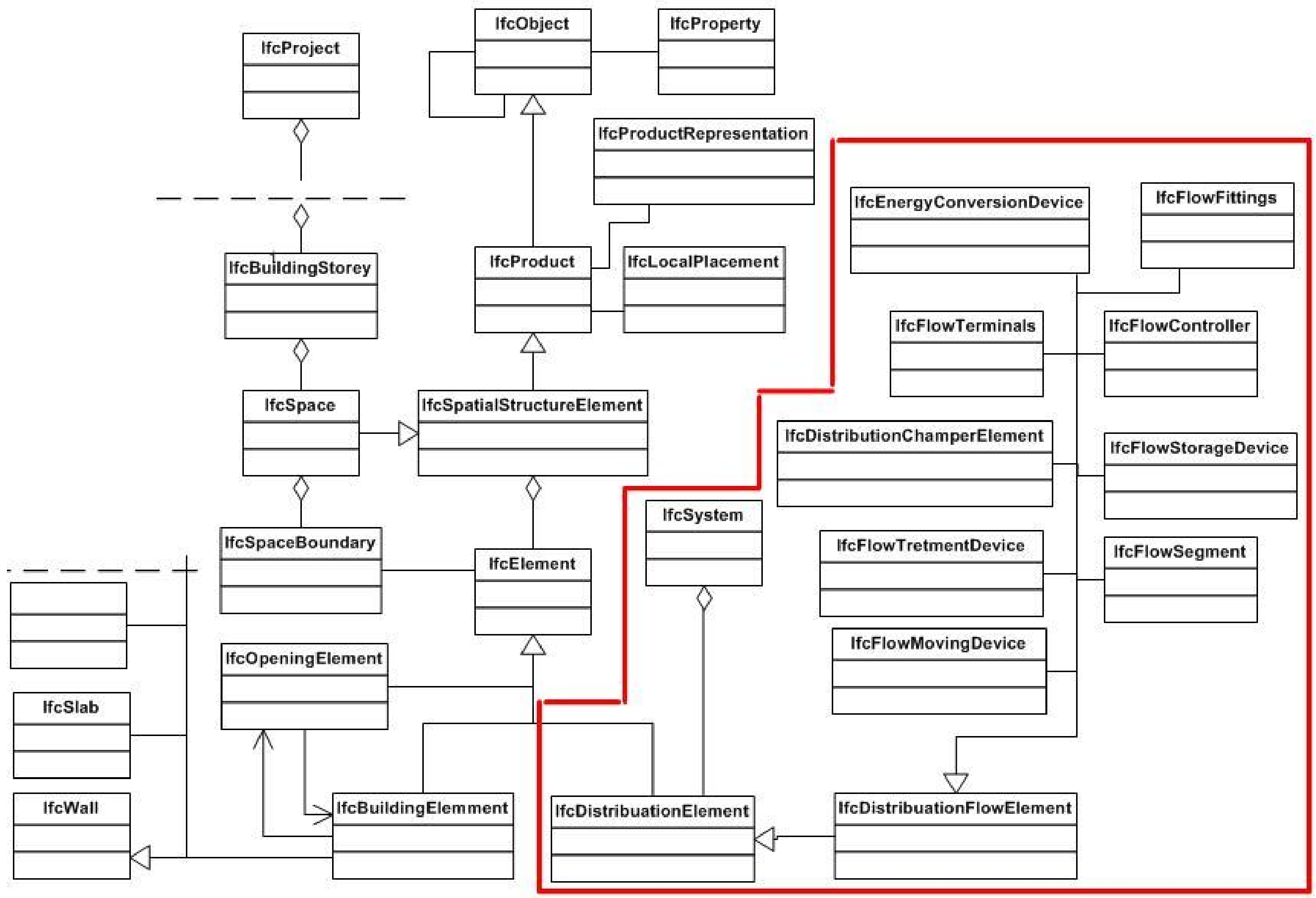


Figure 2.3: Informal IFC schema, the highlighted part represents the hierarchy chart of interior utility - building service elements

intuitive efforts have resulted in the publishing of the first draft version for utilizing the CityGML concept of Application Domain Extension (*ADE*) to provide an abstract level data model that provides the main concepts to model utility networks regardless of its type. The ADE forms a new package, providing the possibility to integrate one or more utility networks into a city (Figure. 2.4) takem from (Becker et al., 2010b). The data model has the following features (Becker et al., 2010b).

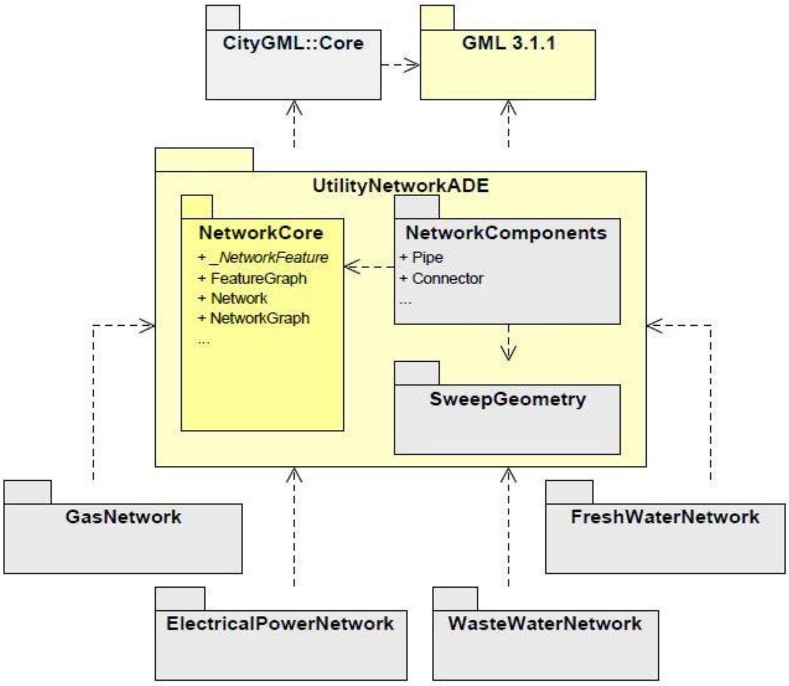


Figure 2.4: UtilityNetworkADE and its relation to CityGML and GML

- It provides a graph data structure with simple geometry representations, as well as true geometry representation of utility network objects.

- The network features, which represent any topographic object in the network (e.g. pipe, tunnel), are inherited from the *CityObject* class, just as are other classes such as streets or buildings.

- All the utility network elements are generalized (core model), with no classification of elements based on their specialized functions in the network.

- The data model allows the aggregation of a utility network element to represent a specific network as well as the aggregation of many features to represent a superior feature.

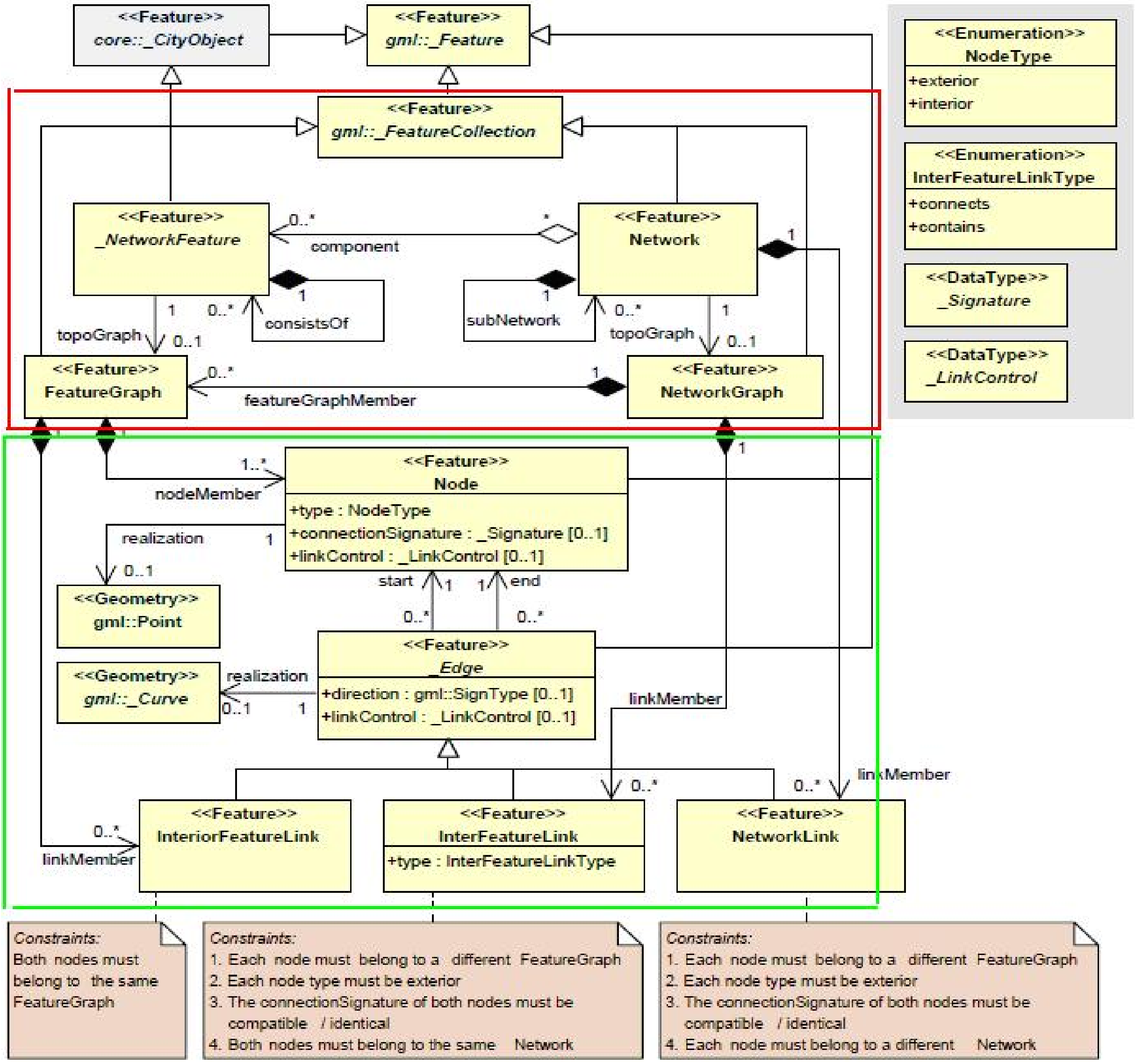
Figure 2.5 provide a UML diagram of the UtilityNetworkADE data model, detailed description of the UtilityNetworkADE classes are provided in appendix C.

2.3 Review of 3D building modeling approaches

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. 3D geometrical models; 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 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 texture image draped over) can be used to increase realism. Sometimes such simple models are used for basic analysis such as computing flood area, coverage areas for telecommunication receivers. In CAD, full and detailed 3D models of individual buildings and small group of buildings are widely used in architecture and construction, but their high spatial resolution and their geometry types often make them difficult for spatial analysis(Kolbe et al., 2009).

2. 3D topological models; In the last decades, there has been a lot of research 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, or De la Losa's 3D topological model) (Zlatanova et al., 2004). Algorithms have been described for data validation, spatial analysis and detecting relationships using these models (Ellul and Haklay, 2006; Ledoux and Meijers, 2010).



Constraints:
Both nodes must belong to the same FeatureGraph

Constraints:
1. Each node must belong to a different FeatureGraph
2. Each node type must be exterior
3. The connectionSignature of both nodes must be compatible / identical
4. Both nodes must belong to the same Network

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2. Each node type must be exterior
3. The connectionSignature of both nodes must be compatible / identical
4. Each node must belong to a different Network

Figure 2.5: UML class diagram for the UtilityNetworkADE the red part represent the topographic classes and the green part represent the graph representation

3. 3D semantic models along with structured geometry; semantic data exchange formats (e.g. IFC) (Liebich, 2010b) 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 (Eastman, 1999; Papamichael et al., 1999). These models are commonly referred to as building information models (BIM). Similar approaches have been used for virtual cities i.e. QUESY (Benner et al., 2005) and CityGML (Gröger et al., 2008) are attempts to create usable and formal standards for exchange of city models. 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 thesis since they are developed mostly for visualization purposes i.e. they don't 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 (Becker et al., 2010a; Becker et al., 2009; Boguslawski and Gold, 2009; Boguslawski and Gold, 2010). In the following section we will provide a detailed review and analysis of these works, which are related to the framework presentenced in this thesis.

2.3.1 Detailed analysis of specific approaches

Various research projects have concentrated on methods to simplify the complex spatial relationships between 3D objects and to build a 3D connectivity in built environment. Lee and Kwan proposed the Node Relation Structure (NRS) (Lee and Kwan, 2005), Ledoux and Gold (Ledoux and Gold, 2007) describe the Augmented Quad Edge (AQE), Boguslawski and Gold (Boguslawski and Gold, 2009; Boguslawski and Gold, 2010) present the Dual Half Edge structure (DHE). The work presented in these studies utilizes the concept of duality in mathematics. A dual graph represents 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, see Figure (2.6) from (Lee and Kwan, 2005).

The last two studies (ADE and DHE) are a direct modification of Guibas and Stolfi's (Guibas and Stolfi, 1985) 2D Quad Edge structure (QE). The NRS, AQE, and DHE data models were developed to support the implemen-

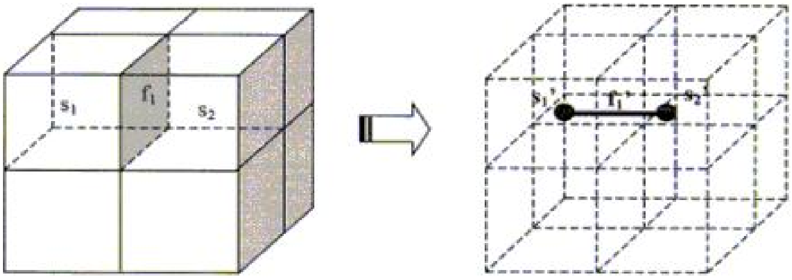

Figure 2.6: Duality in 3D

tations of indoor navigations system e.g. in the context of the ease of use in managing and navigating 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 thesis by providing a good mechanism to generate the relation between indoor spaces and its surrounding walls. The duality presented in these methods can be modified to support the purpose of our model as will be presented in chapter 4.

Hu and Lee (Hu and Lee, 2004) and Lorenz and Ohlbach (Lorenz and Ohlbach, 2006) 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; Hu and Lee (Hu and Lee, 2004) describe 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 reach-ability among regions. Stoffel et al. (Stoffel et al., 2007) provide an approach to automated partitioning of the building interior, not only to rooms but also to 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.

Our approach makes use of the hierarchical methods as well. The hierarchical models can be adapted and customized to further divide large building elements. A detailed description for the use of these methods in our model is presented in chapter 4.

Another group of models that have important relevance for our framework are semantic models. IFC (Liebich, 2010b) and CityGML (Gröger et al., 2008) are two standards represent interiors of buildings: they offers 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 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, one or more 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. CityGML, LOD 4 is also provides a hierarchy, where a building is composed of rooms and rooms are enclosed by surrounding surfaces (appendix D presents a CityGML building class) . Storeys can also be modelled using CityGML generic grouping mechanism - see Figure. (2.7)

2.4 BIM/CAD - GIS integration

Since the advent of CAD and GIS tools, participants have been increasingly leveraging these tools throughout the different phases of civil infrastructure projects (Akinci et al., 2008). However, data conversion between these CAD/BIM and GIS results in an enormous mismatch, that requires manual work to be undertaken, due to the limitations associated with exchange of data and knowledge. In 3D, bridging the gap between CAD and GIS is even more challenging (van. Oosterom et al., 2005; Isikdag and Zlatanova, 2009; Emgaard and Zlatanova, 2008; Tegtmeier et al., 2009; I-Chen and Shang-Hsien, 2007). This is due to the several different factors. For example, existing CAD and GIS platforms have been developed independently for different purposes and this results in significant differences in terms of;

- Data formats they support.

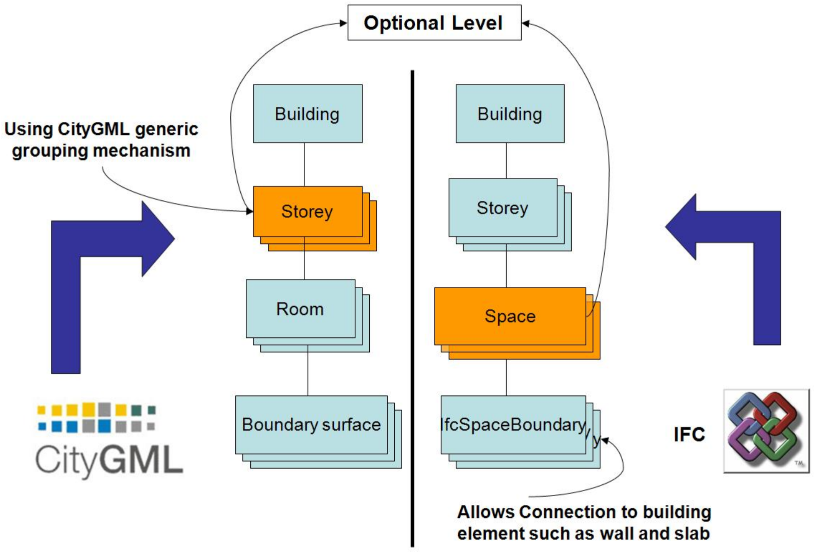

Figure 2.7: Deriving hierarchy for IFC and CityGML based on their data models, the orange boxes represent optional levels

- Terminology they used.
- Semantics concepts they represent.
- Reasoning techniques on which they are based.
- Different scale representations.
- Differences in coordinate system.
- Differences in geometric representations in both systems.

CAD software provides all kinds of primitives to create geometric (and their visual attributes), and represents the objects with different representations such as CSG and SweptSolid, however, these primitives are not supported in GIS (e.g. parametric primitives) while geospatial models mainly use B-Rep as the main geometrical representation method. Furthermore, CAD models usually do not store topologic information, which is in fact an important characteristic of geospatial models (i.e. geospatial models use topology to store geometric information in a more efficient manner). For these reasons current CAD and GIS platforms are not interoperable.

As a result of the developed building standard such as IFC, the integration between geospatial information and BIM/CAD could have been achieved at the semantic level (Isikdag et al., 2007). Efforts dealing with bridging the gap between BIM/CAD and geospatial information models provide harmonisation of semantics that allows the interoperability at the data level such as IFC explorer (http://www.iai.fzk.de, 2011).

2.4.1 Related work

To date, a certain amount of work has been carried out on the integration of IFC, GIS and CityGML. Two approaches have been followed: (1) to transfer geo-data from GIS to BIM; and (2) to transform BIM data into GIS. The Industrial Foundation Class for GIS (*IFG*) (www.iai.no, 2011) was one of the first efforts for the integration of IFC models with GIS (and geospatial models). Benner et al. (Benner et al., 2005) proposed the Quartierdaten-Managementsystem (*QUASY*) object data model, which is a 3D semantic building model for urban development. The authors also developed a tool for automatic generation of semantic building models based on IFC-models. Nagel and Kolbe. (Nagel et al., 2009) demonstrate converting IFC to CityGML, and focus mainly on the CityGML-Building class. Their two-step transformation strategy incorporates CityGML as an intermediate layer between 3D graphic models and IFC/BIM models. I-Chen and Shang (I-Chen and Shang-Hsien, 2007) present an algorithm for automatic conversion of IFC to GML. The algorithm works only on the transformation from SweptSolid to B-Rep. Isikdag and Zlatanova (Isikdag and Zlatanova, 2009) provide preliminary ideas for defining semantic mapping between the IFC data model and CityGML. The purpose of their work is the automatic transformation between the two models. In another study, Isikdag et al. (Isikdag et al., 2008) have investigated the possibilities of automatic conversion from IFC to GIS based on two case studies: fire response and site selection. Their research includes a description of a developed tool for automatic conversion from IFC to ESRI shapefile and GeoDatabase. Another effort for integrating BIM into CityGML is GeoBIM ADE. Its purpose is to extend CityGML with the semantics of IFC (Berlo and de Laat, 2011). In parallel, commercial software for conversion from IFC to CityGML and vice versa is in development (i.e. IFCExplorer (http://www.iai.fzk.de, 2011), BIMserver (www.bimserver.org, 2011), and FME from Safe Software (www.safe.com, 2011)). However, the focus of the transformation methods presented in the above studies lies on the building's architectural elements, such as walls, spaces, doors. It concentrates on the geometry transformation issues. To our knowledge, there is no systematical study on enabling interoperability between IFC and GIS for utility networks.

2.5 Summary

The chapter provides the basis of the work presented in the thesis; graph data structure, utilities in spatial DBMS, 3D utilities network models within GIS and BIM, building models, and BIM-GIS integration.

The utilities network is an application of the directed graph, and has the capabilities to support reach-ability analysis. The chapter distinguishes four types of graph data structure; edge list data structure, adjacency list data structure, adjacency matrix, and the ”Modern” adjacency list. The ”Modern” adjacency list data structure has advantages, since it combines both the edge list data structure and adjacency list data structure. Current DBMS provide extensions for managing spatial data, as well as extensions for analyzing the utilities network. It is mostly 2D and based on edge list data structure and is therefore not capable of managing 3D network requirements.

The study provides a revision for the utilities models in both the BIM and GIS fields. IFC (Liebich, 2010a) and CityGML (Gröger et al., 2008) are officially recognized as two standards, which have been independently developed: The former by the IAI, and the latter by the OGC. These studies show that both standards can hold 3D geometry representation of network objects and connectivity information. Network objects in these standards are also classified based on their semantics.

Finally, the chapter distinguish three types of city models: the geometry, topology and semantic models. The last two types play an important role in the work presented in this thesis. The chapter further elaborates on some of these modelling approaches and highlights their benefits to the framework presented in this thesis. Among these are duality and hierarchy in the semantic models.

The next chapter will present the results of a user requirement study for possible implementation of GIS for interior building, and will elaborate on interior building utilities.

CHAPTER 3

Investigation for 3D GIS requirements for built environment: utilities network use cases

Advances in computer hardware and software are making GIS increasingly affordable and easy to use (Longley et al., 2005). These developments are also extending the capabilities of GIS as a tool in analysis and visualization - most recently, in 3D visualization (Batty et al., 2001).

Current research on 3D GIS concentrates mostly on data modeling, visualization and data collection (Abdul-Rahman and Pilouk, 2007), and, by doing so, neglects spatial analysis, the very core of a GIS. Professionals in urban planning, engineers, utility managers are especially keen on talking about the advantages of 3D GIS capabilities for representing the 3D structure of urban environments and for conducting 3D spatial analysis (Lee, 2004).

This chapter, in accordance with the first objective of the research, explores the readiness and requirements of users of a 3D GIS for built environment. It was conducted at the University of Osnabrueck. User problems and routine operations have been studied, in order to produce contemporary and advanced solutions. The study describes a group of IPs[1] that will be able to support the university community (building mangers, engineers, students and staff) in their daily work. In this chapter we give detailed information about utility network IP, as it was discussed in the previous chapters certain amount of research was undertaken to develop methods to manage

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[1] "Information product" is a term used in Roger Tomlinson's framework to describe the data that goes through GIS to produce information; a group of information products creates an application.

and analyze interior spaces but not utilities network. Different aspects of 3D IPs have been investigated and determined, such as 3D visualization, 3D analysis task and functionalities, and 3D spatial relationships.

Since the focus of this chapter is on the identification of user requirements, the means of information-gathering is important. A very particular strategy for determining user requirement has been followed. First, elicitations of requirement are based on ascertaining, through conversations with staff, both their personal responsibilities and similar project experience. Second, the study selects the most appropriate framework for identifying the current business custom and workflow, and for envisioning the 3D aspects and characteristics of the required IPs.

This chapter is organized into two parts as follows. Part 1 provides an overview of the whole implementation methodology and of its outputs. Section 3.1 summarizes the method used to define the requirements. Section 3.2 presents the results of the investigation for the use of GIS for interior space, based on case studies in existing literature and our study at the University of Osnabrueck. A group of IPs is listed. Section 3.3 provide a formal description of the 3D aspects of IP based on literature review. Part 2 provide a detailed description of utility network IP which is the subject of this thesis. The IP is explained in three use cases which are presented and analysed: analyses functionalities, 3D spatial relationships, and 3D geo-visualization are determined and descried.

3.1 Methods to define user requirements

In GIS different approaches are proposed to define requirements; most of them are business-oriented. They all begin by defining the strategic purpose and end with the final product (Huxhold and Levinsohn, 1995; Tomlinson, 2003). These approaches study the user needs for the four GIS components (hardware, software, data, and training). Roger Tomlinson's approach is well known and widely accepted; it follows mostly the *PIECES* [1] framework. The approach helps us to understand the production process, which includes data and procedures that this study is trying to determine. It defines 10 steps required to implement GIS; these steps are tools that provide ways to prepare for GIS planning, assets requirement, and directions for how to implement the system. Figure 3.1 gives an overview of the whole methodology.

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[1] The PIECES framework is used for identifying operational problems to be solved. It consists of the following: Performance, Information, Economy, Control, Efficiency, Services)see (Norman, 1996).

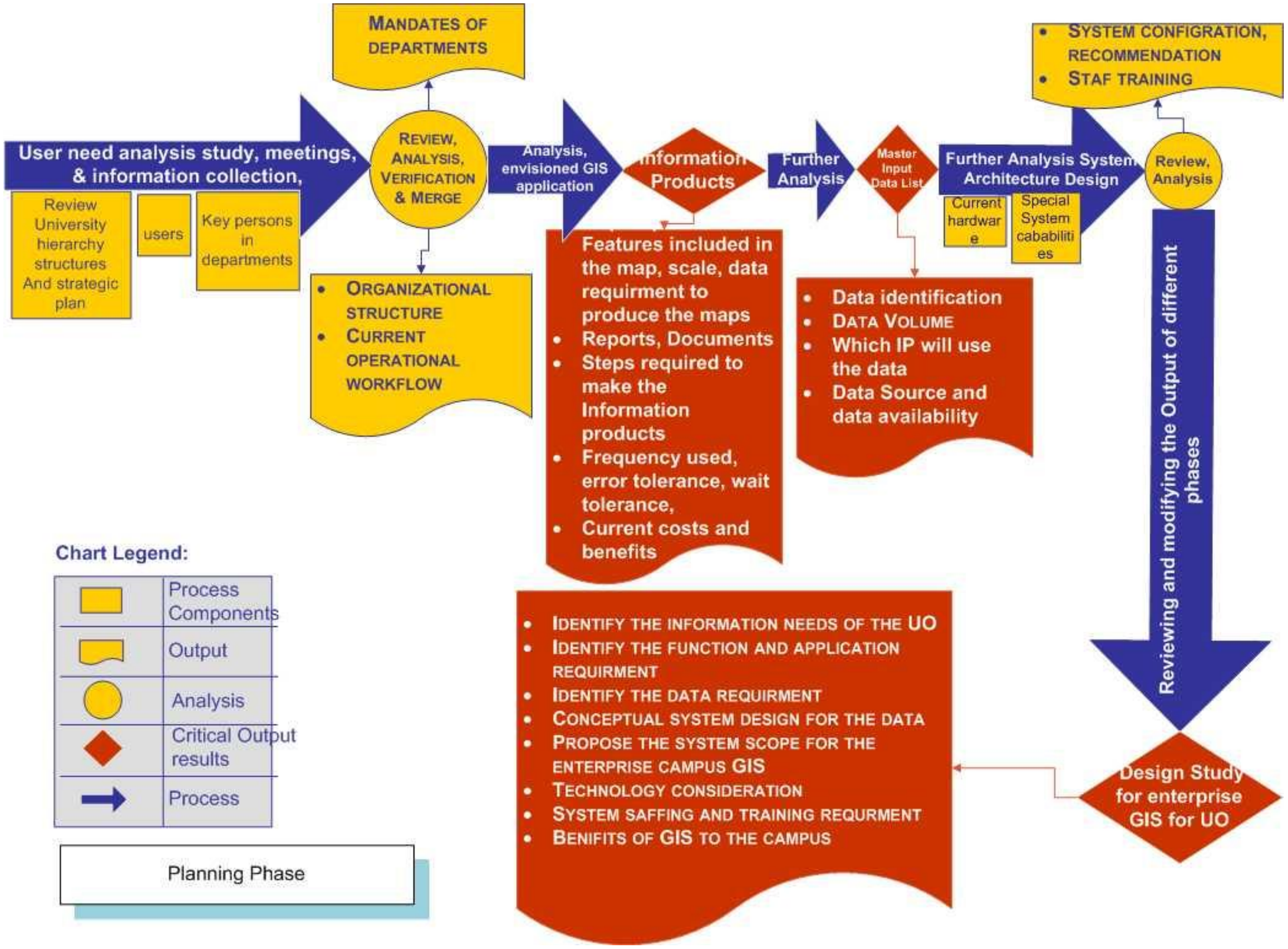


Figure 3.1: Tomlinson framework for planning GIS implementation

The component of the methodology can be set up to suit the size and nature of a particular situation. For the purpose of this research, those parts of the methodology dealing with the elicitation of functional and data requirements are considered (Tomlinson, 2003).

The definition of user requirement, involved interviewing individuals and obtaining answers to the following questions.

- What is your responsibility in your job?
- What do you have to achieve?
- What do you have to produce?
- What do you need to know to carry out your tasks?
- What information could GIS produce and put on your desk that will provide you with what you need to know or help you monitor or keep track of your responsibilities?

The information collected from the aforementioned interviews was then compiled to address the following questions.

- How do individuals currently make decisions?
- What do they need to know to perform their tasks?
- What information products are appropriate for these tasks?

Through asking the same questions in different departments, we were able to generate a picture of the mandates and responsibilities and the current workflow within departments, and how these interact with other workflows. Analysing the answers to these questions provides us with information about the data that are available and required for making the IP. We can then determine what functions are needed, and what data these functions must handle to turn the data into the required IP. Knowing what functions are necessary and what data these functions must handle will provide sufficient information to define the entire technological requirements, including hardware and software. Regardless of the framework adopted to gather requirements, there are three generally accepted ways to answer the question needed to ascertain the requirements (Norman, 1996):

1. Global research, such as reviewing reports, forms, and files.
2. Individual interviews, research, and site visits.
3. Group sessions in the form of workshops, e-mails lists, etc.

In this research, the first two methods are mostly used for defining requirements. Since the studied area is rather new, experience regarding similar solutions can hardly be investigated.

Finally, the determination of user requirement in this study is organized according to Tomlinson's approach for determination of the process, function and data on the basis of global and individual methods. The study revised and evaluated 20 case studies that have used GIS for managing their campuses and interior spaces. The 2D applications in these case studies provide a valuable indication for the possible development of the 2D GIS functions to 3D. A number of interviews to define the mandates and responsibilities and the data to be used have been conducted within the University of Osnabrueck.

3.1.1 Identification of users

Since this study discusses user requirements, an important step is to clarify these users. User here means, in particular, a GIS user in a large complex (a built-up area such as a university campus, hospital, etc). Suitable categorizations of these users are technical, public, and administrative staff: the last two groups are considered potential users (http://geology.er.usgs.gov, 2011), who cannot use the present system because of lack of expertise, but could become a user of the system if it were converted to a GIS.

Technical users are a group of users dominated by a professional staff with architectural or engineering backgrounds, and who are reliant on CAD or hard-copy maps to plan campus extension or maintenance operations. Presenting GIS to this group of people will allow them to integrate their designs and work operations into the broader context thereof. GIS will provide these people with creative thinking and decision-making processes via spatial analyses. The GIS that is presented for this group of people should provide them with other values than illustration or drafting. GIS will not be effective here, because it is a relatively poor competitor against software that is specifically designed for drafting or illustrations.

The second group of users are administrative staff, decision-makers and planning staff; this group depends on the information provided by the first group; for example, the department may be looking for a suitable space for a specific event or determine evacuation route after a building extension.

Public users can be considered the third group of users; these are campus community or visitors, members of the public who need to find their way to a specific space within the campus, or disabled persons who need to know suitable routes to specific buildings (McCormick, 2003).

It's very clear that the need for accuracy of these different groups of users is varied. For example, accuracy to 0.3 m is good for engineers, but is overkill for many users, who simply want an illustration of where something is in the campus reference maps (Valcik and Huesca-Dorantes, 2003). These are all valid needs that must be accommodated in a system that serves a large institution, but at the same time the requirement to integrate such heterogeneous data presents significant complexities. Yet complexities in the process and incompatibility of data can be used as rationale for these groups of users to work alone, doing their own thing in isolation from each other.

In this context, the requirements of users for developing 3D GIS for the campus will be explored.

3.2 Part1: Inventory of 3D GIS requirements

3.2.1 Global perspective

The first part of the user's requirement determination goes through revision of reports, papers, and projects. We investigate how the early adopters used 2D GIS to organize and manage an urban environment. 20 case studies were revised and evaluated, including 15 university campuses, 1 hospital, 2 companies and 2 airports The objectives of this investigation are: 1) define early adaptors of GIS as an administrative tool, and its uses in complexes such as campus areas like universities, companies, or hospital 2) define the most frequent 2D analysis functionalities used and which might be important for 3D GIS 3) provide comments on these uses of GIS on a detailed scale.

Evaluating these case studies shows that the main purposes of implementation may be categorized into three main groups: administrative (planning, management), technical and public reference information system (see table 3.1).

Analyzing the 2D functions that are used to produce the output for these applications shows that all these functions are based on semantic queries, which are referred to a thematic feature data. There are limited uses of spatial queries that are based on geometric queries, which describe the spatial reference and the concrete spatial extent of a feature, or topological queries

Purpose	Operation	Functions
Public	Interactive campus map shows campus building, streets, walkways, trees, parking plots, etc. Helps public and disabled person determine how to access a particular building prior to coming to campus	Zoom in, Zoom out, pan, identify and zoom to select.
	Find specific space, staff office, etc	Query and display of feature as a result of semantic queries.
Administrative (planning, management)	Interior space usage	Classification, grouping of features of one theme according to one attribute, or limited set by user
	Which space is vacant	Query and display of feature as a result of semantic queries
	Nurse finds the patient's bed location	Query and display of feature as a result of semantic queries
	Doctors group patient by their medical functions	Query and classification, grouping of feature of one theme according to one attribute
	Spaces area, specific departments owned	Query and display of feature as a result of semantic queries, metric analysis to calculate areas
	Relocation management	Query and display of rooms, furniture, equipment as a result of thematic queries
Technical	Energy consumption analysis	Metric analysis, calculation
	Managing utilities network in campus identifying infrastructure project on building occupants	Utility network analysis

Table 3.1: Current use of GIS for interior space categorized into public, administrative, and technical

that are referred directly to the topological relation, such as inclusion, or neighborhood of two or more features (Volker, 2003). These limitations are caused by different factors, including:

- The current GIS functions are suitable for GIS applications, which typically occur within geographies that are relatively large when compared to a university campus, hospital or company (McCormick, 2003). They are usually not suited for an urban context. Physical planning or management applications within GIS tend less toward natural or generalized land characteristics and more toward urban facility characteristics and space allocation. Utilities and related infrastructure tend to be more condensed and complex.

- 2D representation is not enough; buildings are composed of floors, and floors are composed of rooms. Pipes and cables are located between ceilings and walls and cannot all be overlaid to the same level. Topological and geometrical analysis is not possible in a 2D representation and modelling.

- Implementing the 2D GIS analysis tools does not have the same analytical impact when one has the option of directly examining the real environment (McCormick, 2003). Experience suggests that the ability to directly inspect the campus reduces the need for map maintenance. If 3D is prepared, however, the expectation of spatial accuracy appears to increase in the context of a more detailed campus environment.

In conclusion, the exploration of the 2D GIS spatial analysis has supplied information about the set of operations that has to be preserved in 3D, such as thematic queries. Current GIS analysis functionalities have limitations when we try to use them in the urban environment. The requirements of the user in an urban environment will be investigated in the next section.

3.2.2 Individual perspective (investigation of 3D GIS requirement)

The investigations of 3D GIS requirement in the University of Osnabrueck were performed using the framework defined in section 3.1. After analysing the university's hierarchical structure, interviews were undertaken to analyse mandates and responsibilities of all the major divisions that will be involved - see Figure 3.2 taken from (Tomlinson, 2003). A number of interviews with key persons in building management (technical office, planning

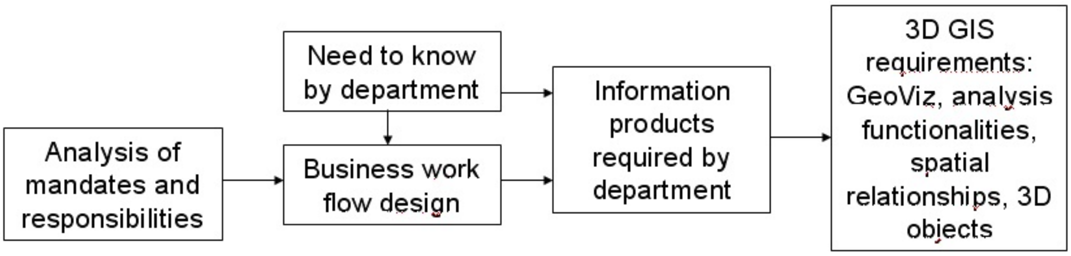


Figure 3.2: Informtion product determintation process

office, and management office), libraries, academic affairs and communication departments, as well as several administrative personal, have been conducted to determine the IPs needed by various departments in the university.

The purpose of this investigation is to identify a group of GIS IPs for a built environment. This section provides a list of these IPs. A thorough description of the 3D requirements - specifications that will allow the actual products to become a working reality will be presented in the next section.

3.2.3 IPs for the University of Osnabrueck

The requirement selection process was established 11 IPs. Below is a list of the IPs that are required by different offices.

1. **Technical office:** The office's main responsibilities are to provide maintenance and repair to the university's buildings, utilities infrastructure and furniture.

    - Utility network IP (water, electricity and sewer): the IP will be used to obtain data about the utilities network in maintenance and repair situations. It should represent the network elements in and between buildings, and provide 2D semantics for the network element in the campus. The IP should be able to calculate the 3D length of the network elements, and provide 3D tracing capability from any specific point in the network. There is also a need for inspection reports and a service outage notification report.

    - Carpenter IP (room inventory): The Tischlerei office in the university requires an IP that provides information about campus rooms furniture, doors and windows. The office will use the IP to repair and maintain the furniture in the university. The department needs to know what furniture is inside a specific room, and what its specification and conditions are. They also need to be able to have a drawing in 2D and 3D for a specific space in the university where they need to design furniture elements.

- Building maintenance IP: The office requires IP products that provide information for the renovation of the different buildings, as well as campus elements like walls paintings, etc. The department needs to know the building materials of the different elements, their last maintenance date, space usage and occupants.

2. **Building management office:** the office's responsibilities are the daily businesses activities related to the campus environment, such as cleaning, maintaining the green areas and resource reservation.

   - Green area IP: The office needs this IP to document the tree inspections, and to plan trimming operations in case of dangerous trees. The application must provide the ability to update and document the status of the trees that are inspected. In addition, the application must be able to show which buildings, roadways, walkways, cables, landscape furniture, etc. (things in the 3D space of trees) will be affected.

   - Cleaning IP: The property management department requires a cleaning IP. The department will use this IP to plan the cleaning operation and to provide the field crew with the required information to undertake their work.

   - Campus community IP: The IP will be used by the general public and the campus community. There is a need to provide the campus community and campus visitors with the ability to find a specific space, person, or institute within the campus. The IP will aid a disabled person to find a suitable route within the campus. The IP should provide the direction and the routing capabilities inside and between buildings (3D routing). The IP will provide this information in a web-based user interface. The IP should provide tools for updating of the network features like different door types, elevators, stairs, etc.

3. **Building planning office:** the main responsibilities of the building department are to plan the use of spaces within the university building, to provide the different departments with the required spaces, to plan any future extensions, and to provide a pleasant and safe environment.

- Movement IP: The building planning office requires movement IPs during the allocation and moving of departments, persons or facilities. The department needs to know how much space and equipment and how many facilities belong to one department, person or facility and where all these elements are located.
- Planning site selection IP: The office needs this product to support the site selection process. In most site selection operations, the planning department requires a tool that allows the comparison of different locations suitable for a specific project. One of the criteria that they consider is the ability of the people to see the site from different locations, as well as the view from a proposed location. This IP will provide a quantitative comparison of the different locations.
- Space usage IP: the office needs this product to create statistics and summaries about the space usage; the product should provide reports on the space usage by department, as well as the intensity of space usage.

4. **Campus safety office:** the office responsibilities are to ensure the campus emergency preparedness.
    - Fire response IP: The safety office needs this IP to maintain information about the fire-fighting system in the university, and responses to reported fires. In response to fire, the IP product should allow the user to find the nearest fire extinguisher to a specific room or facility on any one floor, and should give reports about the usage of the space where the fire is. Furthermore, the IP should provide the ability to select the nearest hydrant outside the building.
    - Hazardous materials IP: The safety office need to know the location of hazardous materials in the campus. The location of underground tanks that contain hazard materials, and the location of emergency shut-off systems (natural gas supply system and electrical supply system) are required by the department for fast response to emergencies and will help them to evacuate people from such areas immediately.

3.3 IPs description - 3D aspects

In this section we specify an output product that the GIS must be able to generate, such as maps, reports, etc. Since this study is about 3D GIS requirement, detailed descriptions of the 3D aspects of these IPs are provided:

3D analysis functions, spatial data relationships and geovisualization. These 3D aspects are developed based on literature review because current GIS user requirement determination methods do not consider these 3D aspects.

3.3.1 3D analysis functionalities

From our experience, a systematized study of 3D GIS functionalities is not yet available, and the current GIS software is mostly 2D GIS with a 3D extension for visualization (Zlatanova et al., 2002a). Some taxonomies for 3D analysis are presented in the literature; all were created for a particular area of application and fulfill their intended purpose (see (Kim et al., 2010; Raper, 2000; Göbel and Zipf, 2008; Zlatanova, 2000)). Zlatanova's taxonomy is the most comprehensive. It distinguishes seven classes of spatial operations. Her taxonomy encapsulated all functions and other processes into the following specialization operations:

1. Metric operations: distance, volume, area and length.
2. Position operations: selection of objects based on location.
3. Proximity operations: based on geometric characteristics and the creation on new objects.
4. Relationship operations: are selection based on spatial relationships.
5. Visibility operations: selection based on geometric characteristics and further processing.
6. Semantic operations: semantic characteristics.
7. Mixed operations: selection on the basis of geometric and semantic characteristics.

3.3.2 Spatial relationships

Some theoretical frameworks are available to describe spatial relationships, see 9-intersection model Egenhofer and Herrring 1990 in (Egenhofer and Herring, 1990) and the dimensional model (DM) in (Zlatanova et al., 2002b). The 9-intersection model has been developed to provide sufficient topological possible relations between 3D objects that are disjoint, meet, contain, cover, are inside, are covered by, are equal, or overlap (Hoop et al., 1993; Zlatanova, 2000). It was used to define the relationship that should exist between the different objects. Also, graph data structure as descriped in the previous chapter is used traditionally in GIS to present the connectivity relation.

3.3.3 Visualization requirement

Geovisualization: Geovisualization is defined as "a set of tools and techniques of graphic visualization that supports geospatial data analysis through the use of interactive visualization" (Maceachren and Kraak, 1997). In 3D, visualization is one of the most important components of the system. Realism and interaction are necessary for information to be understood quickly (Abdul-Rahman and Pilouk, 2007). In this part of the study, we describe the 3D representation, 3D resolution and interaction functionalities.

3D representation: the presentation of the 3D data plays a crucial role in 3D GIS (Zlatanova, 2000). It is necessary to look into the different components of the 3D scene for each IP. This part of the IP identifies how visual materials are represented in virtual environments from different theoretical and application perspectives. Different methods are defined in the literature for the representations of 3D objects: reality axis, level of details, dimensionality, graphical and model classification, etc. see (McCloud, 1993; Gröger et al., 2008; Kirschenbauer, 2005; Verbree et al., 1999; Kibria, 2008). Several parameters have been elicited, and the suitable representation method for each dataset in the 3D scene has been examined and determined. The selected parameters are: iconic, indexed, verisimilar, rendering method.

Iconic, indexed and verisimilar define the degree to which displays are realistic or abstract. Iconic means representation in a very basic form. Indexed means related to the representation of object values from some phenomenon in a new form where they can be easily understood (Sherman and Craig, 2003). Verisimilar is another form of representation, which shows the ultimate possible realistic representation (Kibria, 2008).

Another parameter affecting the readability of the scene is the method used to render the objects. Three basic techniques are presented in the literature (Abdul-Rahman and Pilouk, 2007). These are: (1) wire frame, (2) shading and (3) textures. Wire frames (transparent mesh) present only the frames of the model in the scene; no sides of the 3D object are visible, while master polygonal walls of the 3D objects are semi-transparent. The shaded method more advanced than the wireframe method (Abdul-Rahman and Pilouk, 2007). In this method, the frame is visible in lines and the polygonal sides are visible with varying opacity and with shade and shadow; color can be assigned to each triangle and then displayed by a filling operation during the hidden line and surface operation. The last method is texture; a technique to wrap an image (scanned real photos or synthetic images) onto the "geometry". Figure 3.6 present the results of the 3D representation requirements for the utility network IP.

3D resolutions: resolution is defined as the smallest feature that can be mapped and sampled on a given scale (Tomlinson, 2003). For a 3D GIS, this issue becomes more crucial with respect to the complexity of geometry. For this part of the IP, we investigated the resolution requirement of each object. The result show that the requirements are varied; for example, a building with exterior walls is considered enough for orientation applications, but not for technical staff dealing with water utility maintenance operations. Results show that technical applications such as utilities networks tend to be more intensive than public applications (see figure. 3.7).

3D GIS interaction functionalities:

the IPs described in this research are for the management and analysis of building objects, for the purpose of administrative planning, maintenance activities, and general public information. So the required interaction functionalities are to facilitate exploration of the 3D world scene. These tools are "click on" and "select" data in the scene, interactive navigation tools that facilitate the exploration of virtual worlds such as "zoom in", "zoom out", "fly through", "walk through", "pan". Other interaction tools for editing the geometry are not required by the IPs described, and are beyond the scope of this research (Kibria, 2008).

3.4 Part 2: Utility network IP description

The rest of this chapter tracks the creation of an actual information product description. Most of the IPs described above are require information about the interior space. As explained in the previous chapter, certain amount of work exists to integrate the BIM interior space in GIS and to analyze it. Therefore, emphasis is placed here on the utility network application since the literature shows a gap in the work conducted in this specific area.

3.4.1 Use cases

Use Case 1: Maintenance operation

The first case focuses on warning residents about a scheduled or unscheduled maintenance. Facility managers need to perform maintenance operations, which can be either 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 (see Figure 3.3). Therefore, buildings occupants need to be warned. The operational workflow starts by announcing the maintenance operation prior to its date; a notification to the building's occupants is printed and hung at the building entrance, 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 (although this is not easy to define in the current system).

The facility management teams we have interviewed do not have yet a tool that allows them to search the network and quickly access the information that enables them to contact the persons in the part of the building that will be affected; or, at best, retrieval of the relevant information takes a sizable amount of time, and since not all the information can be retrieved, the team has to make an assumption and generalize the announcement. They need to be able to input the location of the maintenance and have the GIS return an information product that include 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 and the building elements (e.g. wall or slab) also the network segment under suspicion, the segments connected to them both upstream and downstream, any other building elements that immediately surrounds the shut-off location. Finally, the team needs to define the network elements and its contained rooms that would be out of service when there will be a shut-off. Also needed is a textual description providing a reference to the location of the rooms within the building would be useful.

Use Case 2: Inspection operation

The second use case refers to the inspection of waste water. 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. The inspection team needs to find the location of these elements inside these buildings to test whether they are working probably. The team need an IP that allows to them to select a point in the network. The system should identify the buildings that contain the devices that are connected to the defined point and need inspection, and also show the exact location of these devices in the buildings and how they connect to the external network. Therefore, the proposed system should provide a suitable description for the location of

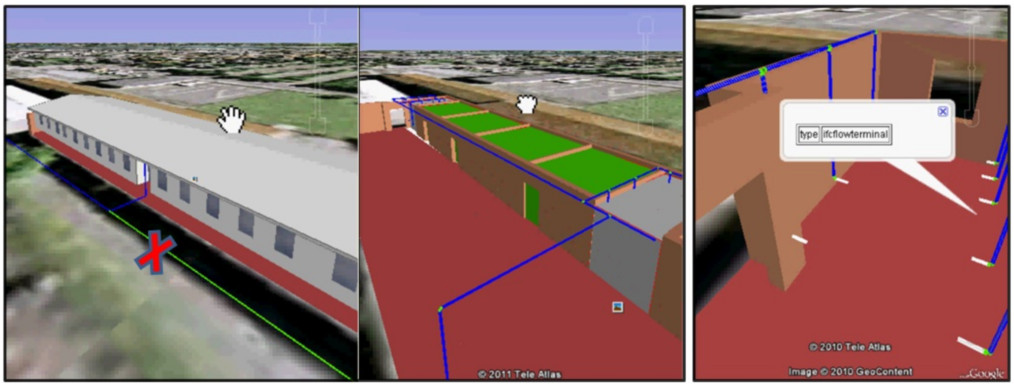


Figure 3.3: The left-hand diagram shows the rooms inside the building (highlighted in gray color) that will be out of service when a shut-off is activated from outside the building (highlighted in red); while the diagram on the right shows the elements of the network that are out of service in case of maintenance. The white colour represents the part of the network that is out of services

these devices inside the building, e.g. the building element, space, storey, and the building they are within (Figure 3.4).

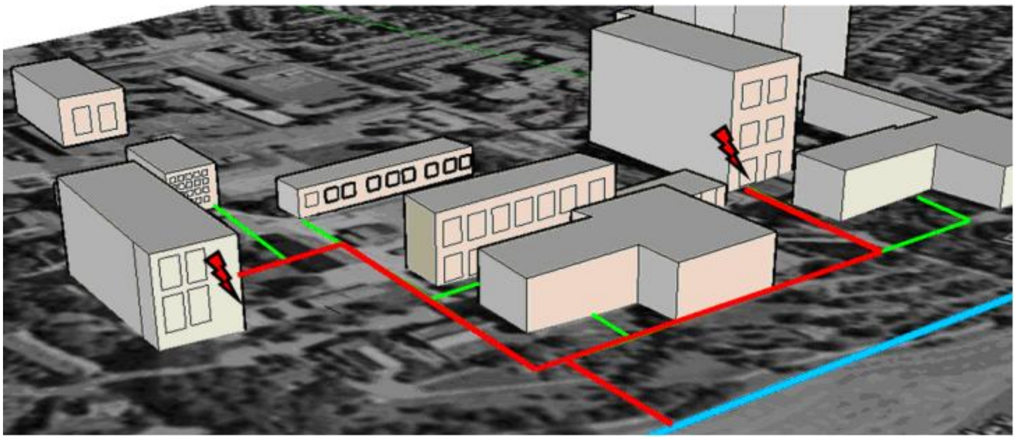


Figure 3.4: Trace operation performed by the city to select part of the network, to assure that the network does not waste the natural resources. The red colour represents the highlighted part of the network that connects the inspection equipment to external network outside the campus.

Use Case 3: Emergency response

The last use case refers to emergency situations, when the precise location of a shut-off valve, and the response in a timely manner are key issues.

During emergency responses (e.g. fire incidents), the crew team should be able to disconnect any part(s) of the service system.

The operational workflow starts with a notification of the facility management to help. The facility management needs an IP that can be used to define the location of the building where the accident has occurred. They must identify which device (switch or transformer) should be turned off, so as to disconnect the relevant part(s) of the service system in the building. Moreover, the system should also generate a notification report; lists all the buildings that will be affected by shutting off, and communicate this list to all the occupants of these buildings. The list should include detailed information describes the location of the shut-off referenced to the building structure, starting from the building element to the room, storey, and then the building. Decisions based on unreliable information about the location of a shut-off can result in a delayed response to a critical situation and additional costs will result from the extra damage.

On the basis of the use cases presented, we define queries that are relevant to the prototype we are developing. These queries will be used for the validation of the proposed network model in this thesis:

1. Find the location of facilities inside the building that will be out of service as a result of an operation taking place at a specific location outside of this building.
2. Find the location of a shut-off when there is a problem at a specific location on the network, and inform people about the shortage of service.
3. Find the part of the network that is expected to cause the failure in some specific locations.
4. Describe the exact location of the treatment device inside the building.
5. Provide information as to how disconnect part of the network in case of emergency.

3.4.2 Use cases analysis

Functional requirements

The use cases provide us with the required information to envision the step by step process of building the utility network IP, from the workflow description we identify the dataset, and system functions required to facilitate the workflow.

Figure 3.5(a-e) gives details of the step by step for the use cases, with the first case subdivided into two parts: ”regular maintenance”, and ”repair”.

Spatial relationships

The investigation of the operation that would be performed provides us with the relationships that should be preserved in utility network IP. The 9-intersection model has been used to define these relations as described in section 3.3. Below is a list of these 3D objects and their spatial relationships.

- The facility management team needs a link in the data level between the network fixtures (e.g. lamps, sinks), and the building space in order to select the spaces - or part of building that would be out of service.
- There is a need for a link between building elements (e.g. slabs, walls) and network elements so that the maintenance team can easily locate elements of the network in a building. The description of the location of a network component should include attribute links to the space which is enclosed, the storey and the building where it is located.
- There is some network-to-network linkage that must be made between the network systems; i.e. the logical relationship between the hot water in the tap and the electricity network that needs to be maintained in the network.
- Finally, the relation between the exterior and interior networks need to be maintained.

Visualization requirement

The Geovisualization methods defined in section 3.3 provide a basis for determinining the proper method for visualizing each object of the utility network IP. (Figure 3.6) presents the results of the 3D representation requirements. In addition, the resolution requirment for each object is determined using the table presented in Figure 3.7.

3.5 Summary

The chapter presents the process of determining the user requirements for 3D GIS in a university campus. An important fact that has been realized is that bringing GIS into interior space requires the taking into consideration

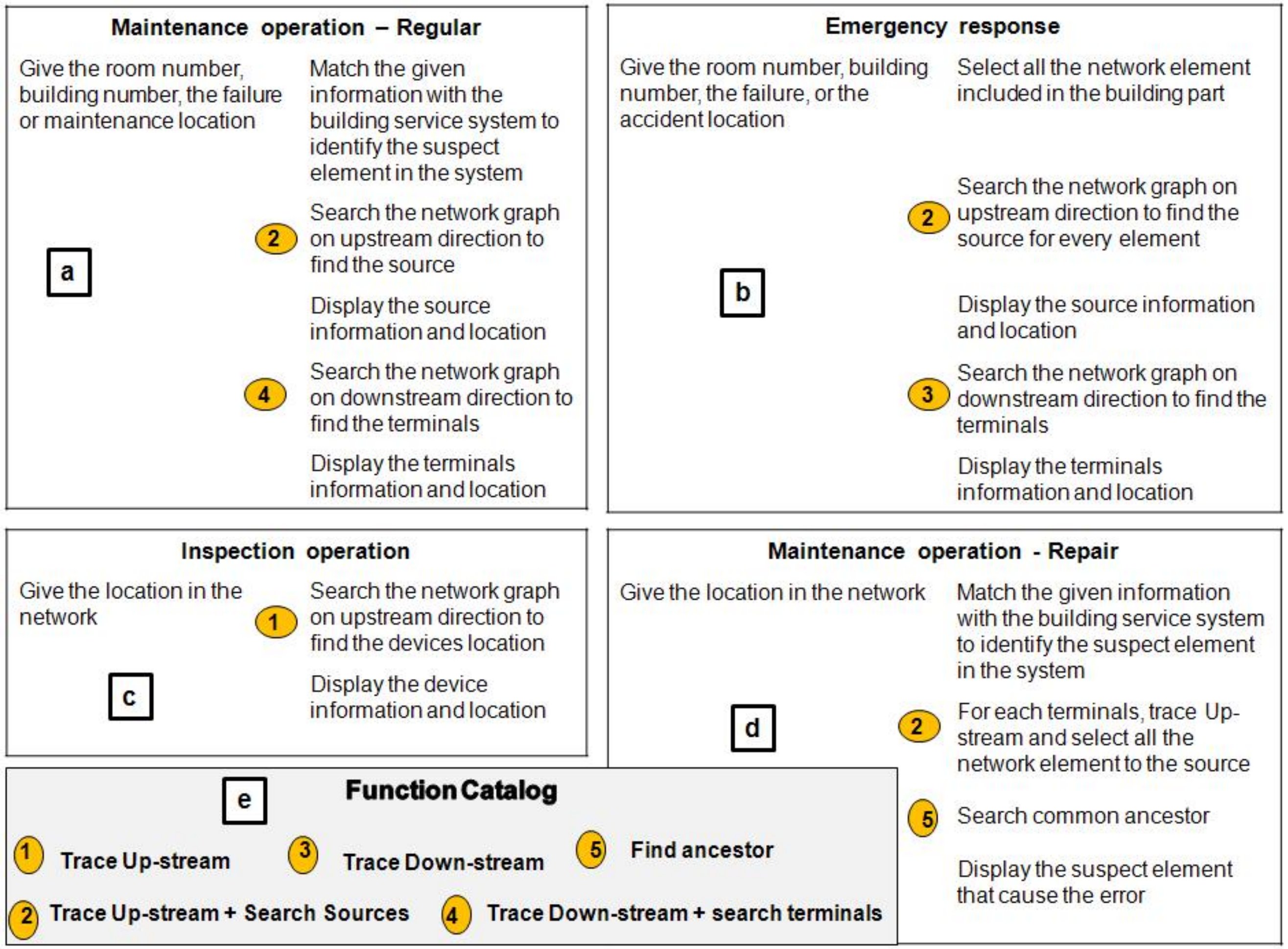
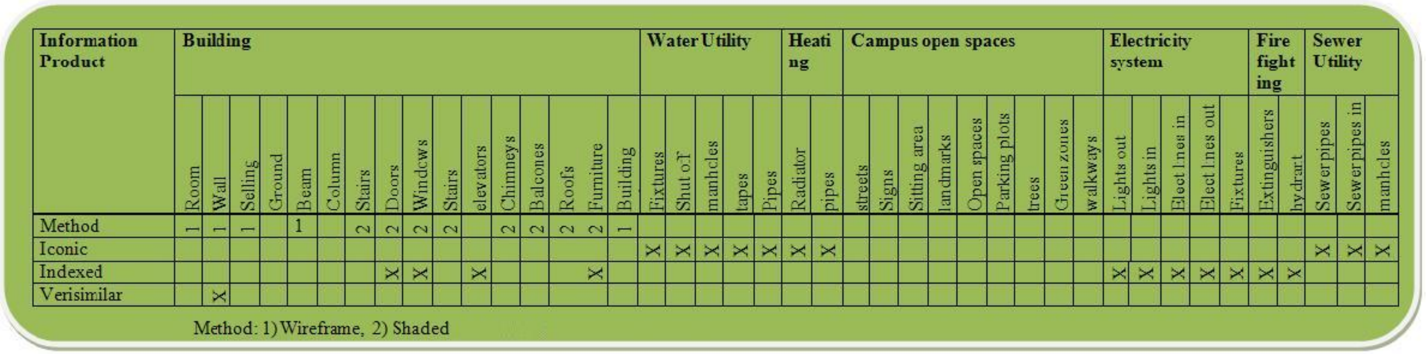


Figure 3.5: Use cases analysis, a sequence of operation that should be undertaken to achieve the goal of the use case: a and d maintenance operations, both regular and repair, b) emergency response, c) inspection operation, and e) function catalogue to list the functions that are required by all use cases.



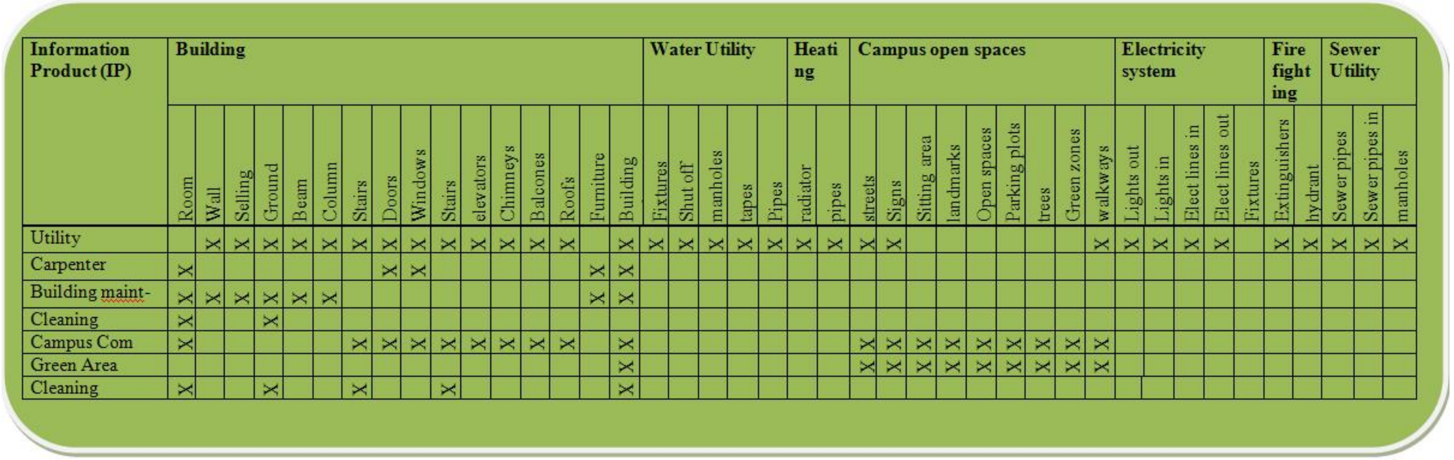
Information Product	Building																
	Room	Wall	Selling	Ground	Beam	Column	Stairs	Doors	Windows	Stairs	elevators	Chimneys	Balcones	Roofs	Furniture	Building
Method	1	1	1		1		2	2	2	2		2	2	2	2	1
Iconic																
Indexed								X	X		X				X	
Verisimilar		X														

Information Product	Water Utility					Heating		Campus open spaces								
	Fixtures	Shut off	manhcles	tapes	Pipes	Radiator	pipes	streets	Signs	Sitting area	landmarks	Open spaces	Parking plots	trees	Green zones	walkways
Method																
Iconic	X	X	X	X	X	X	X									
Indexed																
Verisimilar																

Information Product	Electricity system					Fire fighting		Sewer Utility		
	Lights out	Lights in	Elect lnes in	Elect lnes out	Fixtures	Extinguishers	hydrart	Sewerpipes	Sewerpipes in	manhcles
Method										
Iconic								X	X	X
Indexed	X	X	X	X	X	X	X			
Verisimilar										

Method: 1) Wireframe, 2) Shaded

Figure 3.6: Determination of the suitable 3D representation method for the different objects required by utility network IP



Information Product (IP)	Building																Water Utility					Heating		Campus open spaces									Electricity system					Fire fighting		Sewer Utility		
	Room	Wall	Selling	Ground	Beam	Column	Stairs	Doors	Windows	Stairs	elevators	Chimneys	Balcones	Roofs	Furniture	Building	Fixtures	Shut off	manholes	tapes	Pipes	radiator	pipes	streets	Signs	Sitting area	landmarks	Open spaces	Parking plots	trees	Green zones	walkways	Lights out	Lights in	Elect lines in	Elect lines out	Fixtures	Extinguishers	hydrant	Sewer pipes	Sewer pipes in	manholes
Utility		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X							X	X	X	X	X		X	X	X	X	X
Carpenter	X							X	X						X	X																										
Building maint-	X	X	X	X	X	X									X	X																										
Cleaning	X			X																																						
Campus Com	X						X	X	X	X	X	X	X	X		X								X	X	X	X	X	X	X	X	X										
Green Area																X								X	X	X	X	X	X	X	X	X										
Cleaning	X			X			X			X						X																										

Figure 3.7: Resolution requirement for each IP

of different settings compared to those being used in more natural contexts. The 3D campus GIS presents tremendous untapped potential for GIS applications. The study has presented a group of IPs that can be viewed as potential implementations for the use of 3D GIS in a built environment. A detailed description is provided for the utility network IP. One realization that results from this research is that there are numerous common issues and applications to be found among campus settings.

Current methods available for planning GIS consider 2D settings, and provide techniques to describe the GIS solution using traditional 2D products such as 2D maps and 2D analysis functionalities. Therefore, the chapter develops a description for 3D products based on a literature review description for the things that need to be considered during the planning of 3D GIS i.e. 3D virtual reality, 3D analysis functionalities and 3D spatial relationships.

The university campus proves to be an ideal area for conducting this research. The university community consists of many overlapping bodies (student, faculty, staff, alumni, visitors, consultants, local government). The physical scale of the environment provides a suitable area within which to examine the current GIS tools and databases and envisions others that are suitable for these dense urban areas.

The chapter focuses on the utility network IP. Three use case scenarios, "maintenance operation", "emergency response" and "inspection operation", are developed. The use cases are used to define the 3D requirements to develop GIS to manage interior building utilities. These requirements can be summarized as follows:

1. There is a need for a holistic modeling framework that supports the management of interior networks and links it to the exterior network, and which is able also to manage the interdependency of the network and the building structure. Such a model will help us to determine the effects of maintenance operations undertaken on external utilities on interior networks, as well as to work out the cause of waste materials discharged from interior networks into the exterior network. It will also allow us to investigate both the result of damage to the building structure on another utilities network, and also the effect of different maintenance operations in different locations within buildings on utilities service systems. The model will help us to see the whole picture of the network and use it for planning future maintenance and enhance management.

2. Operational level: An application is required for managing large amount of data. This application should help the staff in dealing with their

daily operational duties, and assist them in handling emergency situations in a more effective way. These tools will include the following: First, development of reach-ability analysis functions to support the spatial operations as defined in the use cases. These functions are: trace upstream, trace downstream, find ancestors, find source, and find disconnected terminals. The functions are developed to support the analysis on 3D network including both interior and exterior network. Second, development of tools that allow the integration of interior building utilities with exterior utilities.

The next steps are to develop the modeling framework. The goal is to develop part of the IPs described in this study as a prototype for GIS applications in built environments, combining both 3D spatial analysis and 3D visualization.

CHAPTER 4

Network for Interior Building Utilities (NIBU)

Chapter 3 clarified user requirements for 3D GIS for built environments, and delineated the scope of the thesis regarding those application that we considered, i.e. interior utility; its requirements, building objects and their spatial relationships; analysis functionalities; and visualization requirements. This chapter focuses on structuring the data needed to provide a framework for integrated analysis of interior building utilities, considering the complex building structures.

The chapter is structured as follows: In section 4.1, we summary the requirements for the modelling proposal. Section 4.2 describes the modelling proposal, with its two parts. In this first, we discuss the part concerning modelling of the connectivity relationship between network objects in order to support utility network reach-ability analysis functionalities. The second part describes the proposal to represent the relationship between network objects and building structure. We also describe methods to divide large spaces and large building elements. Section 4.3 provides an example for the modelling proposal presented in this chapter, and shows the effectiveness of this approach for supporting maintenance operations, as well as the independencies between the maintenance operation location and the other network systems. We formally define the basic element of the modelling framework in section 4.4, where we also present the resulting data model. In section 4.5 we present a chapter summary.

4.1 Summarized requirements for NIBU

The requirements outlined in the previous chapter refer to different aspects that should be considered to provide information systems that are capable of allowing 3D integrated analysis of interior utilities. The organization of the data in the database must be appropriate for both 3D GIS analysis (thematic and spatial) of individual network as well as the integrated analysis on interior utilities within its building structure. Modelling the interdependence of interior utilities networks or large buildings is a quite different exercise from that for exterior networks. This is due to the fact that an interior utility is more complex. Recalling discussion from previous chapters we can summarize the requirements of the data and their structuring as follows:

- True 3D geometry representation of network objects.
- A logical graph data structure that is capable of facilitating analysis required by the use cases.
- Thematic/semantic information relevant to the network objects (interior-exterior), Which can be used by different domains (e.g. electricity, gas, water).
- Framework that deals with interdependencies between utilities network and building structure.

4.2 NIBU design and development

This section describe the design and development of NIBU. The network model for interior building utilities are consisted from two main parts, connectivity relation allow the modelling of flow within one network system, and framework to model the relationships between network objects and building spatial structure.

4.2.1 Modelling connectivity relation between network elements

An important factor in designing the graph data structure comprises the operations that will be performed on the network (M.Curtin, 2008). Analysis of the use cases as defined in chapter 3, and the use of frameworks for analysing use cases presented in previous studies (Jacobson et al., 1992;

Criteria	Edge list	Adjacency list	"Modern"
Direct accessing to node		*	*
Direct accessing to edge	*		*
Store node attributes		*	*
Store edge attributes	*		*

Table 4.1: Evaluation of graph representation methods

Groneman and Zlatanova, 2009; Biddle et al., 2002; Norman, 1996), both provide us with information about the functionalities that the user needs to perform. Figure 3.5(a-e) in chapter 3 shows the sequence of steps to complete each use case. As the diagram shows, some functions require direct access to flow segment elements, i.e. edges of the network, and others to fittings elements, i.e. the nodes. Translated to graph representation, this will require search methods for both edges and nodes. For example, the operation "find all flow terminals" from a specific controller is performed on nodes. This ought to be easy to achieve using the adjacency list data structure. At the same time, finding the controller in the case of a broken pipe, an operation performed on edges, is also required, and is made possible using the edge list data structure.

As mentioned previously, we give preference to a graph data structure that is similar to the adjacency list data structure "Modern". The "Modern" data structure provides direct access both from the edges to the vertices and from the vertices to their incident edges. For example, if a pipe is not working, then the access to the incident edge is direct. So too is the operation - the function of accessing the edges that are incident upon a vertex is direct, and does not require any exhaustive inspections. This approach has advantages for a number of network searching functions that are required by this study. Table 4.1 compares the three data structure presented in chapter 2 considering four criteria: direct access to nodes and edges and possibilities to store attributes with the nodes and the edges.

In addition to the graph, the geometries of the segments and the fittings are added. The geometry is represented as B-Rep, providing a 3D representation of network objects. It is possible to implement this type using the current spatial DBMS (Breunig and Zlatanova, 2005). The classes *Fitting* and *Segment* correspond to nodes and edges in the graph and hold the connectivity information. Each segment object has "start" and "end" fitting. Similarly, each fitting object holds information for the incoming and outgoing segments. In addition to the graph, NIBU contains the semantics and geometries of the network elements. Figure 4.1 shows the UML diagram of the first part of NIBU.

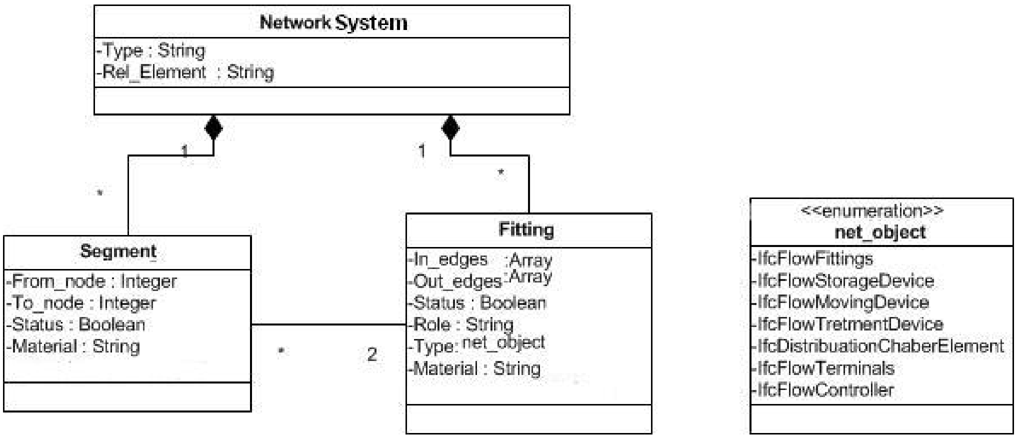


Figure 4.1: Conceptual schema of NIBU (network classes)

- NetworkSystem: The class is an aggregation of nodes and edges; it is a central element in NIBU and corresponds to one network in a building. The class serves to define an entire network, e.g. gas, water or electricity.

- Segment: This class stores the information about the flow segment, and is comprised of pipes, cables, etc. One Segment is limited by two nodes. The class stores the flow segment, as defined by IFC, with description information about the status of these objects and materials. This class is represented by boundary representation, where a planar faces and straight edges enclose the boundary of the network object body.

- Fitting: This is a class that represents the fittings distribution elements subtypes, which are: flow fittings, flow terminals, flow controller, distribution chamber element, flow storage device, flow treatment device, flow moving device, and energy conversion device. These objects can be distinguished by their type and are given as an enumeration. The attribute type is used to define the function of the network object, and also to attribute a role as source or sink to each node in the network, or to say that it has no role. Each fitting can have one or alternatively many segments connected to it. These edges are classified as "inedges" and "outedges". This class *Fitting* is represented by boundary representation.

4.2.2 Integration with building structure

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 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 (Dudenhoeffer et al., 2006).

Our approach to modelling these interactions and interdependencies is based on extending the network graph of each network with explicit interdependency information. Figure 4.2 illustrates our approach to represent 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 homogeneous set of nodes, and each group of nodes is represented as an empty graph. An empty graph on nodes consists of 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 Figure 4.2a. and Figure 4.2c).

Building elements are represented as another group of nodes; these are also represented by an empty graph, see Figure 4.2 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 an undirected edge; this links the nodes of the network element (represented as a node) and the building element. Figure 4.2 d. illustrates this relation. The link is inserted between two such nodes if the intersection of the interior of the two corresponding objects geometries is non-empty. Therefore, the edges represent the Egenhofer relations of ”contains”, ”overlap”, ”equals” and ”meet”' between two objects from service systems and the building elements (Egenhofer and Herring, 1990).

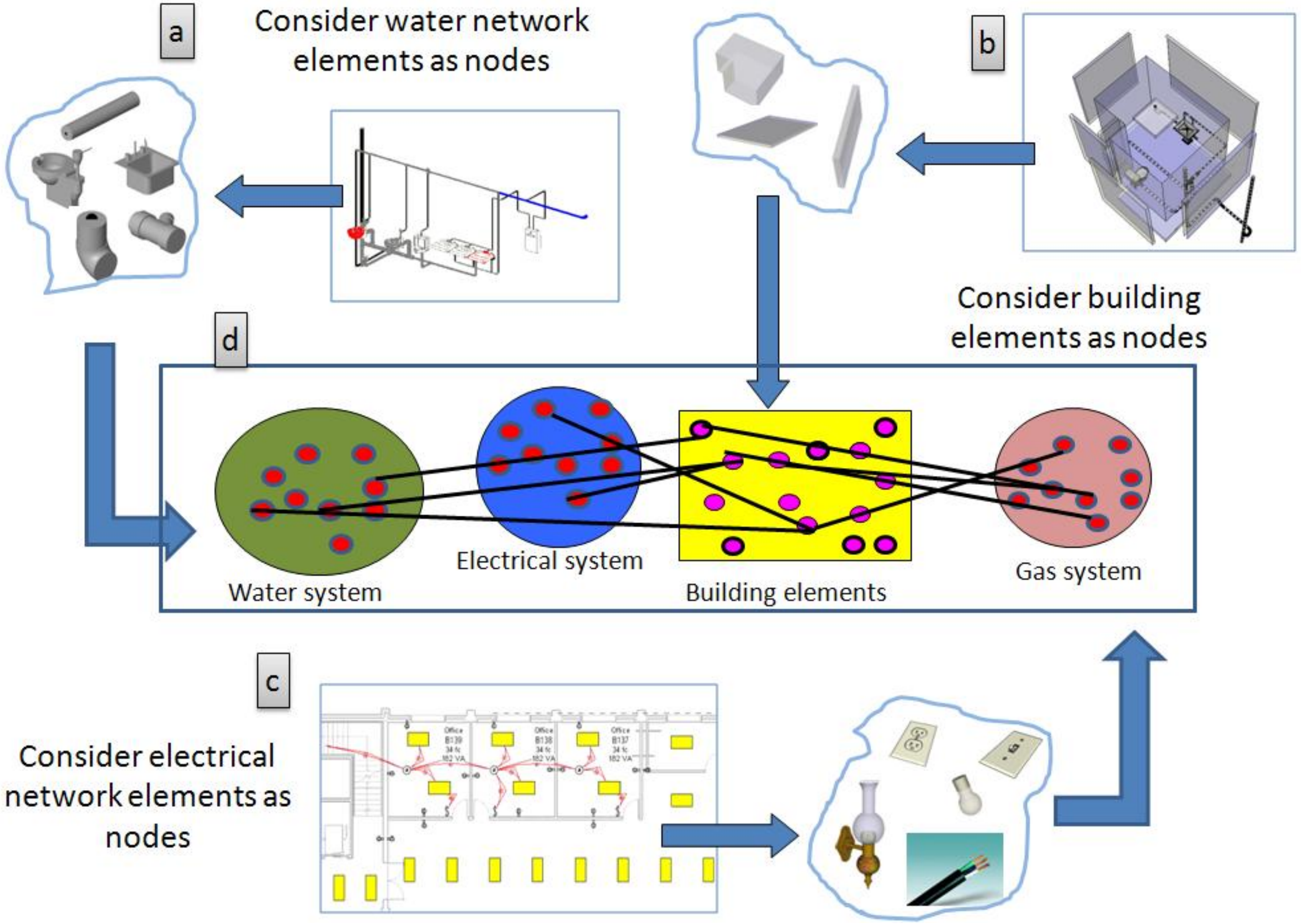


Figure 4.2: The NIBU modelling approach a) represents the water network b) represents the building element c) represents the electrical network, and d) The resulted graph - nodes represent building and network objects, edges represent the relationship between them.

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.

Building hierarchy

In order to support the framework presented in the above section, we need cognitive models of building structure to link network components to its 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 storey ...room no e12 ... in the ceiling". Behind this statement is a one-level (or in general multi-level) hierarchical model of the building that the network components are linked to. An example for this is depicted in Figure 4.3. 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 which is within, and to the whole building.

Figure 4.3: 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 storeys, 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 a wall or slab and then a space, a storey 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 if 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 defined at 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 is 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.

Figure 4.4 provides a UML diagram for the building data model. It considers two important issues: firstly, each building has at least one storey; and each storey must have at least one space. Secondly, the space is defined by the relationship between the space and the building element enclosing its volume and is here 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.

- 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*, *Ceiling* and *Ground*. The boundary sides i.e. the sides that create one boundary can be generated on the fly.

- 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 linking

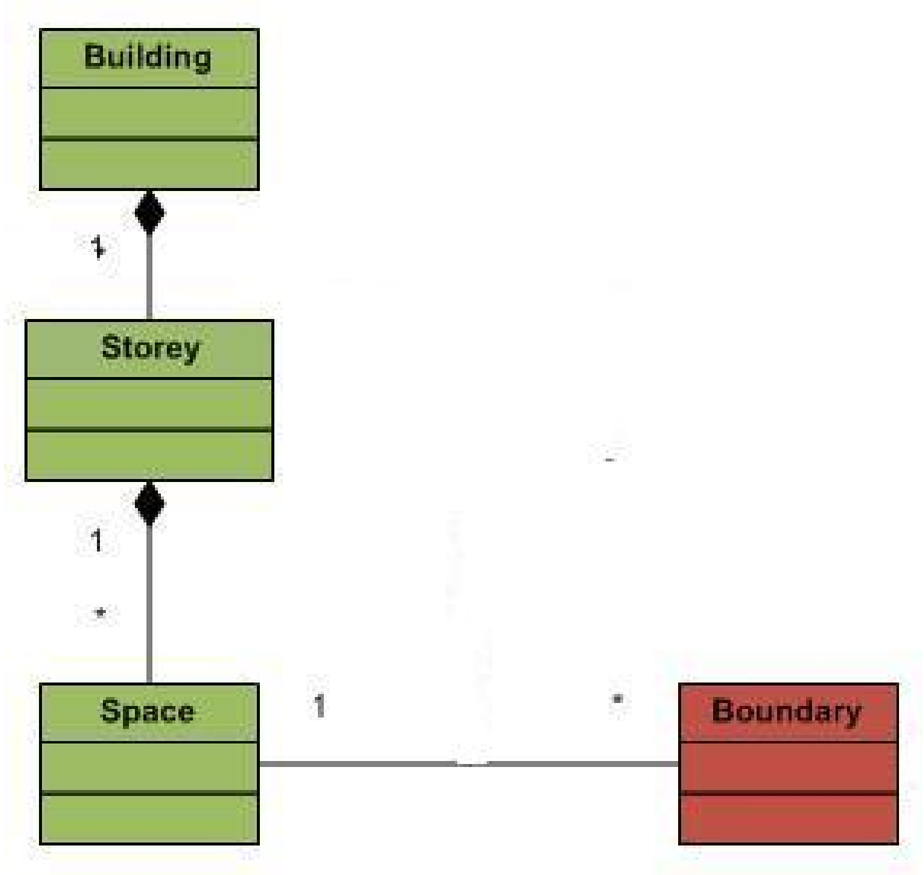


Figure 4.4: UML diagram for the proposed building model

building elements with the space it encloses; and the space is a primary class which should exist in every building storey. The building storey is aggregated by the spaces class. Space faces can be derived on the fly.

Extract space and boundary relations

The duality graph is utilized here to assign the walls, slabs to the space they enclose. Figure 4.5 illustrates the approach. The building element i.e. a slab in the figure would be defined as a node in the dual graph, which is represented as 3D solid primal model. The adjacency between the building elements (e.g. slab and the spaces) would be represented as edge connecting the node of building element with it adjacent spaces. Therefore the relation that is required by the model could be extracted by modification of the methods presented in the background section (i.e AQE, DHE). The relation between the spaces and the building elements it encloses could be simplified in a graph as illustrated in Figure 4.5.

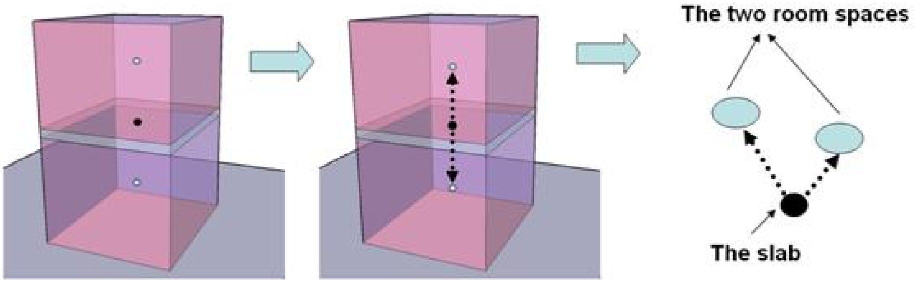


Figure 4.5: Extracting the relation between space and its surrounding elements

Moreover, organizing the spaces that are reachable by a pedestrian that will allow for the people to access the network could be achieved using the exit and entry algorithm as mentioned in (section 2.3.1). The algorithm facilitates the creation of the space hierarchy and organizes the building rooms that are within one storey.

4.2.3 Decomposition of large building elements and spaces

The above-mentioned approach works well for cases of simple plans like the one presented in Figure 4.6. In this case, large building elements, such as storey slabs, can be easily divided into smaller parts based on the intersection between these spaces and storey slabs - see Figure. 4.6b. However, strictly pursing this naive approach becomes difficult for larger buildings with large areas of open spaces, as 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. Stoffel et al. (Stoffel et al., 2007) provide 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 thesis.

The described algorithm by Stoffel et al. (Stoffel et al., 2007) divides the internal spaces based on visibility criteria. The algorithm can handle simple polygons as encountered in storey plans. Figure 4.7. 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

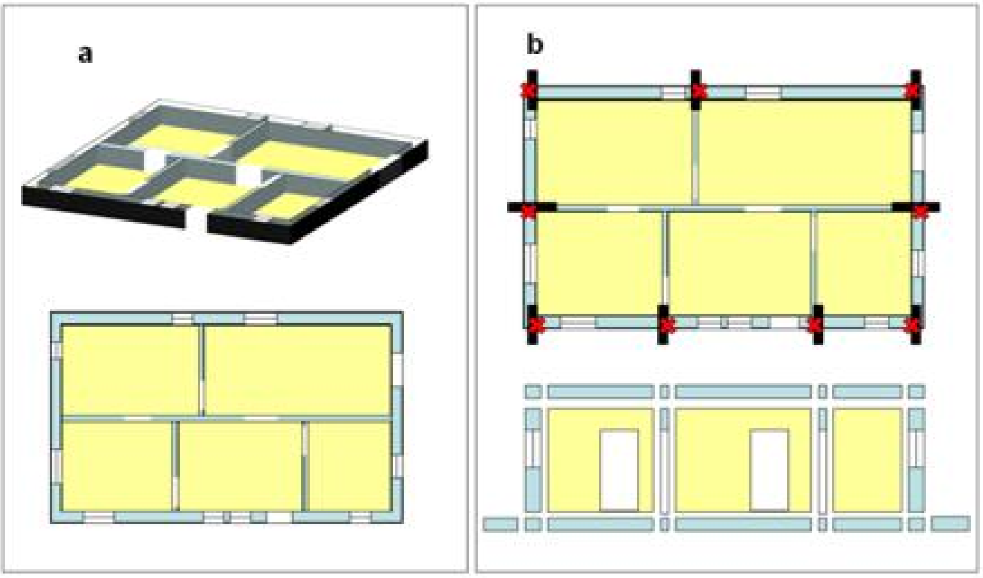


Figure 4.6: a) Simple plan decomposition, b) slab building element decomposed based on intersection between spaces and slabs

to have smaller parts of large building elements such as slabs, and based on the intersect relationship between the sub-spaces that result from this partitioning algorithm and the original slabs. Long walls could be partitioned in a similar way (see Figure 4.7).

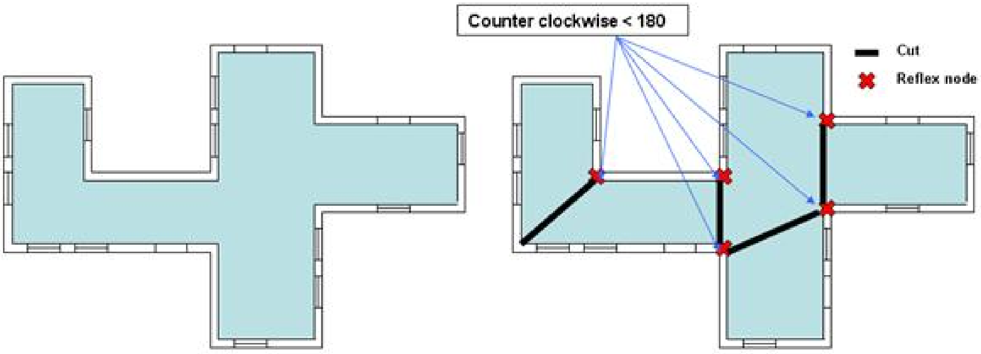


Figure 4.7: Large space pertaining method based on concave-convex algorithm

4.3 Example for modelling proposal

The following example illustrates a real-life example for 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 another building element 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.

Figure 4.8 illustrates a plan and a section view for a building consisting of one storey with two rooms. The building has a network of clean and waste water. This entire building structure is represented as a graph in Figure 4.8, 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 element based on hierarchy. The first level represents the building, the second level represents the two rooms, and the third level represents the building elements bounding the room's volume. The network elements are also represented as two separated homogenous sets of nodes, where each network component is represented as a node and the links represent the connectivity relation between these components. The dotted edges represent the relationship between the network element and a building element, based on containment relations.

Let us assume that a maintenance operation will take place in the wall that is highlighted in Figure 4.9a. Now, if the maintenance team need to know if other building systems are within this element, they can figure it out by tracing the dotted link that connects building element to network element, based on containment relation - see Figure 4.9b. 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 Figure 4.9c. After the maintenance team have 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

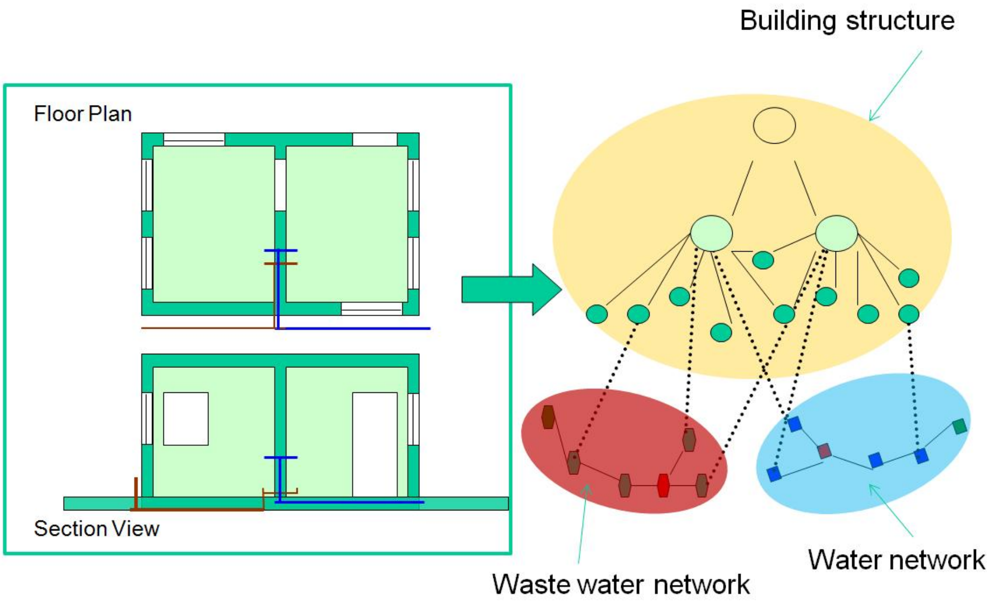


Figure 4.8: Modeling relations between a building structure and its network systems includes: a) a plan and section view of the building, which is composed from two rooms and has two network systems (clean and waste water); and b) the graph with the yellow background representing building structure, the graph with the green background representing the clean water system, and the graph with the pink background representing the waste water network system, the dotted edges represent the relationship between the network elements and the building elements

in the network that would be affected. Then, their locations within the building will be defined based on the edge-joint relation see Figure 4.9d.

4.4 The data model

The UML diagram depicted in Figure 4.10 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.

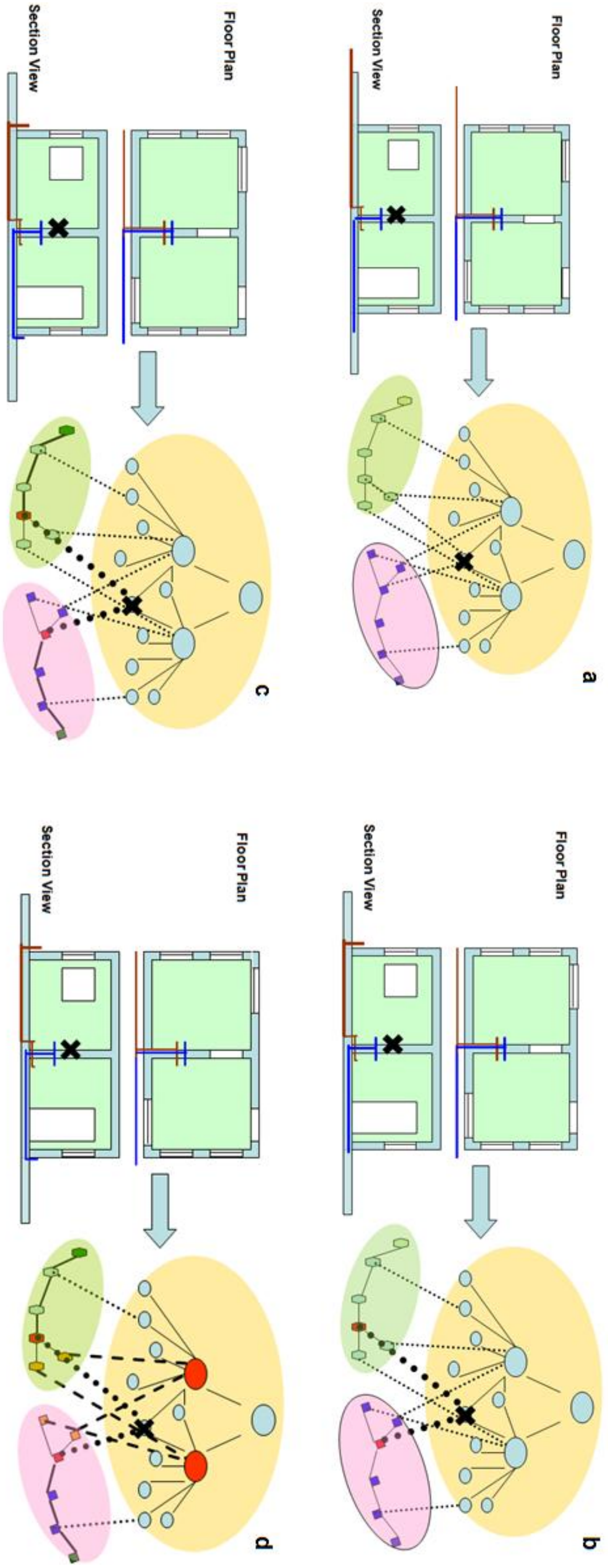


Figure 4.9: Example for supporting maintenance operation using the proposed framework

The utilities network system is represented using the classes' *NetworkSystem* and *Dist_NetworkElement* classes. The class *NetworkSystem* represents a collocation of features that comprises one utility system. The class *Dist_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 the existing semantic 3D models. For example, the CityGML UtilityNetworkADE (Becker et al., 2010b) classes *Network* and *NetworkFeature*, and the IFC classes *IfcSystem* and *IfcDistribuationElement*. The two classes *Fitting* and *Segment* are specialisations of the class *Dist_NetworkElement* and inherit its attributes. *Fitting* represent fixtures that connect two flow segements (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 subtypes listed in the enumeration list. On the other hand, the *Segment* class represents the flow segement, which is an edge in the logical graph structure. Both classes belong to the class *Network-GRAPH* which connects the *Dist_NetworkElement* subclasses.

The building structure is represented using the classes on the right hand side. The classes are structured so that they provide the hierarchy represented in section 4.2.2 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 an interface to connect 3D building semantic models. For example, 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 encloses the volume of the 3D space. Therefore, this class has a composite relationship with the class *Building element*, which also provides 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 which 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: *Building Object*, on the one hand, and the Egenhofer relation on the other hand. The resulting graph can be used for tracking cascading damage result, planning maintenance operations and

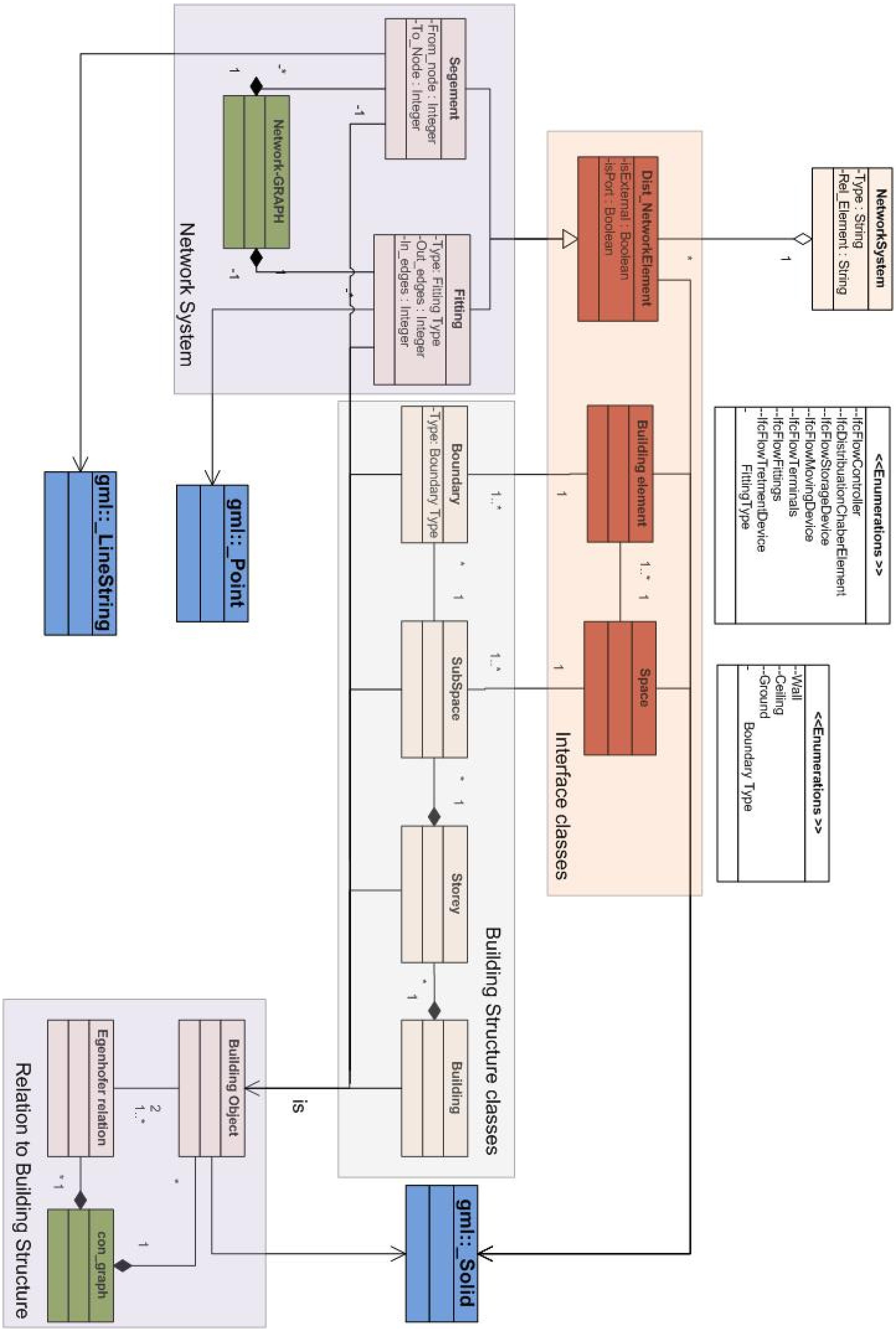


Figure 4.10: UML Digram for the modular framework

other causes related to managing interdependences of interior building utilities.

4.5 Summary

The chapter deals with the spatial organization of interior utilities within a built environment. Building structures are complex, and managing their service systems is a challenging task when compared to exterior utilities. In order to support the use cases presented in chapter 3, a new concept for modeling the individual network system, as well as the interdependencies between building utilities and building structure was presented. The approach is applicable to 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 structures. The model integrates several existing approaches and customizes them for the purpose of interior utilities applications. The NIBU for modeling the flow of network system is composed of a logical graph and 3D geometry of the utility elements. The logical graph of the model utilizes an adjacency list "Modern" as the data structure for performing specific analysis tasks on these networks. This data structure carries additional advantages for analyses performed in the graph, since it offers direct access for both edges and nodes.

The classes and their relationship are formally modeled using UML. The data model is a graph-based spatial model that allows 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; hence it is possible to construct the model from 3D geometric data and current 3D building data model standards. The model is structured hierarchically, and consequently one can relate and reference network elements to building elements. Each of these elements corresponds to a certain domain concept (wall, door, room), which can guide technical staff to network element locations inside a building.

Interdependencies between building structures and utilities services system are modeled using a logical link based on the Egenhofer relations ("contains", "overlap", "equal" and "meet"). The building model presented in this thesis is customized for the purpose of utilities networks. The building structure is complement and plays a crucial role in providing a cognitive and meaningful model that supports the managing of the interdependencies between network components and building structure. 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 cases and to provide the required information.

This conceptual framework is the first step towards integrated modeling of interior utility networks and the building structure.

The work demonstrates a new possible application for infrastructure analysis that includes interior utilities and possible integration with 3D urban GIS.

In the next chapter a linkage between NIBU and the current 3D building model standards will be created. It will also illuminate the possibility of populating NIBU with data using these standards.

CHAPTER 5

Interoperability framework - populating NIBU using standards

Chapter 4 proposed a spatial model to represent the spatial relationship between network objects and building structures in 3D. The purpose of the model, as was clarified in Chapter 4, is multifunctional, i.e. it has to be capable of supporting reach-ability analysis as well as to supply information for integrated spatial analysis of buildings within a geospatial context, including managing interdependencies of network systems and building structures. This chapter is devoted to the potential of the model to be generated using the current building standards in both the BIM and GIS worlds. It is related to the third objective of the research, i.e clarifying links between existing building standards and NIBU; the focus is on providing a mapping guideline for automatic extraction of NIBU classes.

The main problem in the integration of BIMs with geospatial information occurs at the transfer point of geometric information (I-Chen and Shang-Hsien, 2007). Building models use geometric representations such as CSG and SweptSolid geometry in local coordinate systems, while geospatial models mainly use B-Rep in real-world coordinate systems. It is widely known that overcoming the problems associated with heterogeneous environments requires interoperable methodologies and tools. Standardization of data models has been suggested and practiced as a major stride towards achieving the goal of interoperability (Akinci et al., 2008; Peachavanish et al., 2006; Weiming et al., 2010). Researchers have suggested that the best approach for BIM/GIS integration is harmonized semantics, which would allow for formal mapping between the BIM and real-world GIS. The chapter provides ideas and directions for the means of acquiring the required information from BIM/IFC and CityGML, then maps it to the classes of NIBU.

As described in chapter 2, a utility network can be modeled in CityGML using UtilityNetworkADE (Becker et al., 2010b) a generic utility network model that is under development (www.citygmlwiki.org, 2011). The IFC schema has different entities that can support the GIS utility network application. IFC schema contains entities representing different network objects, and classifies them based on semantics, e.g. pipes, lamps. Moreover, connectivity concepts are also involved (Liebich, 2010a). Both standard CityGML and IFC contain building representation. A thorough understanding of semantics is required to achieve integration and schema mapping (converting models, objects, or descriptions from one world into the concepts used in the other world). The investigation undertaken in this chapter follows a pragmatic approach, by means of a manual inspection of both schemas to see which entities and attributes can be used to obtain the required information by NIBU. The work includes analyzing the different concepts of building service systems presented in IFC, and UtilityNetworkADE. It also investigates the possibility of extracting the required building information and spatial hierarchy from IFC and CityGML, and looks for possibilities to represent these concepts in NIBU.

The chapter is organized in two main parts, with the first part investigating the possibility to extract NIBU thematic and connectivity information. The second part investigates extraction of the building structure and hierarchy information as it is described in NIBU.

5.1 Extract NIBU utilities network classes

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The mapping described on this section is grouped into two categories: thematic classes and graph structure.

5.1.1 Deriving the thematic information

NIBU uses two classes to represent networks; these are *Dis_NetworkElement* and *NetworkSystem*. The class *NetworkSystem* represents a collocation of features that comprise one utility system. The class *Dis_NetworkElement* represents a real-world network component and provides a 3D representation of network objects as solid. This class is seen as an interface that connects the NIBU model to existing semantic 3D models describing 3D utility network objects.

The class *NetworkSystem* in NIBU is equivalent to the IFC entity *IfcSystem*. The attributes of *NetworkSystem* class, like unique ID, name and description can be obtained from the attributes of the *IfcSystem* entity: unique ID could be acquired from *IfcGloballyUniqueId*, name from *IfcLable*, and description from *IfcText*. The complete list of the elements participating in an IFC system can be obtained from the *IfcRelAssignsToGroup* (Figure 5.1 taken from (Liebich, 2010a).

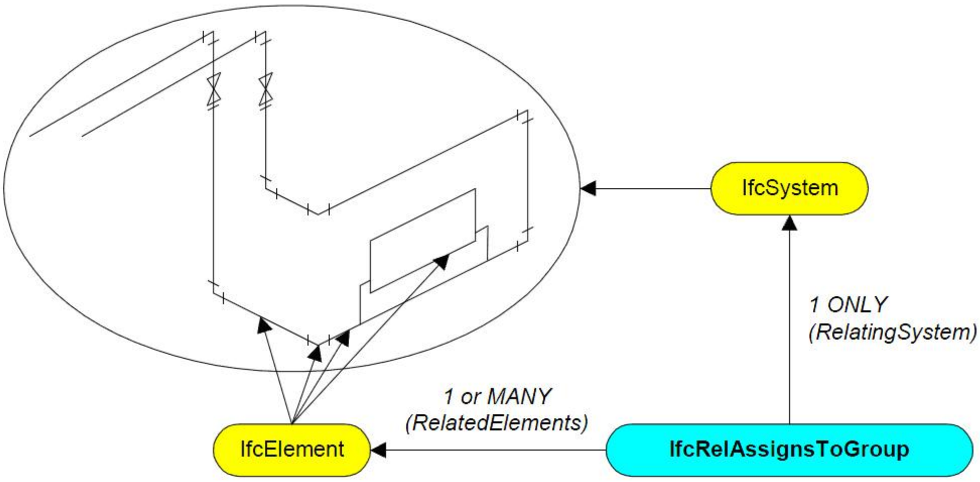


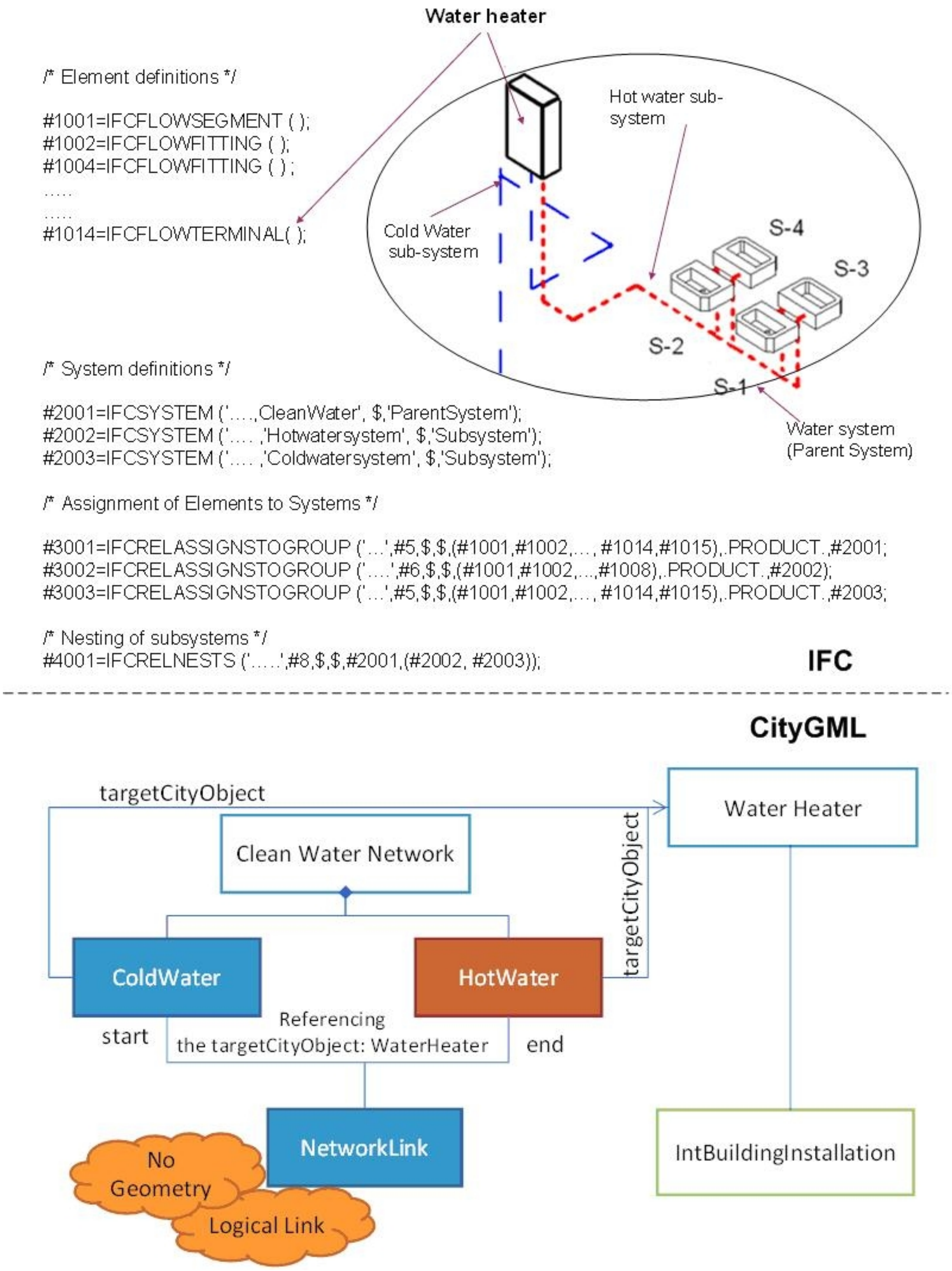
Figure 5.1: Elements aggregated into a system in IFC

The *IfcSystem* entity in IFC is a subtype of the entity *IfcGroup*; it acts as a functional related aggregation of objects, e.g. a system that comprises water distribution elements (pipes or ducts or cables and related items).The *IfcSystem* did not include any rule to sustain connectivity between the different network objects; nonetheless, it is expected that the connectivity that is established between the different network elements will be generated in a systematic way - for example, to establish a flow path, see Figure 5.2.

For CityGML, the class *Network* is equivalent to the class *NetworkSystem* in NIBU; it is a central element in the UtilityNetworkADE data model. It is intended to provide a topographical representation of entire networks (e.g. water, gas). It is derived from the GML *Feature Collection*, and serves therefore as a collection of networks, wherein each network is a collection of *_NetworkFeatures*. The class inherits the following attributes: unique ID, description and name. However the main role of the *Network* class in the data model is to allow the aggregation of different network features to form a specific network. Figure 5.2 provides an example for the representation of a water network in IFC and a proposal for the representation of a water network using UtilityNetworkADE classes.

The class *Dis_NetworkElement* in NIBU is similar to the IFC entity *IfcDistributionElement*. The two classes *Fitting* and *Segment* are specializations of the class *Dist_NetworkElement* and inherit its attributes. *Fitting* subclass represents fixtures that connect two flow segments (e.g. pipes). This class has several sub-types in the enumeration list. On the other hand, the *Segment* class represents the flow segement; these two subclasses can be generated using the IFC entity *IfcDistributionFlowElement* subtypes. Additionally, the information about the *IfcDistributionFlowElement* and its types is derived from the IFC entities *IfcRelAssociatesMaterial* and *IfcRelDefinesByType*. The relationship between the service system subtypes in the IFC and the proposed data model NIBU is illustrated in Figure 5.3. The text below summarizes the subtypes, providing a brief description of their specialized functions:

- *IfcFlowSegment*: defines the occurrence of a segment of a flow distribution system that is typically straight, contiguous and has two ports (e.g. a section of pipe or duct).
- *IfcFlowFitting*: defines a junction or transition in a flow distribution system (e.g. elbow, tee). Its type is defined by *IfcFlowFittingType* or its subtypes.
- *IfcFlowTerminals*: defines a permanently attached element that acts as a terminus or beginning of a distribution system (e.g. air outlet, drain, water closet, sink). A terminal is typically the point at which a system interfaces with an external environment. Its type is defined by *IfcFlowTerminalType* or its subtypes.
- *IfcFlowController*: defines a distribution system that is used to regulate flow through a distribution system (e.g. damper, valve, switch, relay). Its type is defined by *IfcFlowControllerType* or its subtypes.
- *IfcDistributionChamberElement*: defines the place at which distribution systems and their constituent elements may be inspected or through which they may travel.
- *IfcFlowStorageDevice*: defines a device that participates in a distribution system and is used for temporary storage of a fluid, such as a liquid or a gas (e.g. tank). Its type is defined by *IfcFlowStorageDeviceType* or its subtypes.



```
/* Element definitions */

#1001=IFCFLOWSEGMENT ( );
#1002=IFCFLOWFITTING ( );
#1004=IFCFLOWFITTING ( ) ;
.....
.....
#1014=IFCFLOWTERMINAL( );

/* System definitions */

#2001=IFCSYSTEM ('....,CleanWater', $,'ParentSystem');
#2002=IFCSYSTEM ('.... ,'Hotwatersystem', $,'Subsystem');
#2003=IFCSYSTEM ('.... ,'Coldwatersystem', $,'Subsystem');

/* Assignment of Elements to Systems */

#3001=IFCRELASSIGNSTOGROUP ('...',#5,$,$,(#1001,#1002,..., #1014,#1015),.PRODUCT.,#2001;
#3002=IFCRELASSIGNSTOGROUP ('....',#6,$,$,(#1001,#1002,...,#1008),.PRODUCT.,#2002);
#3003=IFCRELASSIGNSTOGROUP ('...',#5,$,$,(#1001,#1002,..., #1014,#1015),.PRODUCT.,#2003;

/* Nesting of subsystems */
#4001=IFCRELNESTS ('.....',#8,$,$,#2001,(#2002, #2003));
```

Figure 5.2: Water network represented using IFC entities and a proposal for modelling the same network using UtilityNetworkADE classes

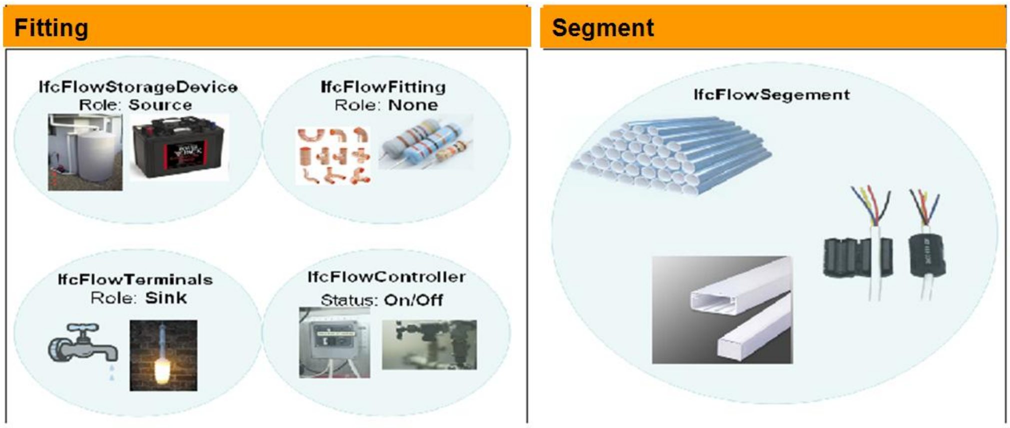


Figure 5.3: Examples for different *IfcDistributionElement* and their relation to the NIBU

- *IfcFlowTreatmentDevice*: defines a device typically used to remove unwanted matter from a fluid, either liquid or gas, and typically participates in a flow distribution system (e.g. air filter). Its type is defined by *IfcFlowTreatmentDeviceType* or its subtypes.
- *IfcFlowMovingDevice*: defines an apparatus used to distribute, circulate or perform conveyance of fluids, including liquids and gases, and typically participates in a flow distribution system (e.g. pump, fan). Its type is defined by *IfcFlowMovingDeviceType* or its subtypes.
- *IfcEnergyConversionDevice*: defines a device used to perform energy conversion or heat transfer and typically participates in a flow distribution system. Its type is defined by *IfcEnergyConversionDeviceType* or its subtypes.

For CityGML, the class *_NetworkFeature* serves as a root class representing any topographical objects of a utility network (e.g. pipes, manholes). The class is derived from the CityGML upper class *CityObject*. Therefore, it inherits all the characteristics of *CityObject* class. All thematic network classes can be derived from this class, and these thematic classes can be used to provide hierarchy subclasses for division of network objects based on their semantics - that is, their functional meaning in the networks. The network object in class *_NetworkFeature* is an abstract feature class in GML. According to the terms of ISO 19109, a feature can have arbitrary attributes, spatial and non-spatial attributes. The spatial attributes serve, for instance, the mapping of actual 3D object geometries in different levels of detail. Therefore the *Dis_NetworkElement* class and its subtypes can be generated using the *_NetworkFeature* (Figure 5.4). While the class is generic in the standard, information about specific network object roles can be assigned to the object as attributes, which can then be used to transform this object to their matching subclass of *Dis_NetworkElement* in NIBU.

IFC represents building service components *IfcDistributionFlowElement* using solid model representation with its specific types: B-Rep, Surface-Model and SweptSolid. Transforming geometrical information from the IFC model of these elements in case of SweptSolid requires conversion operations.

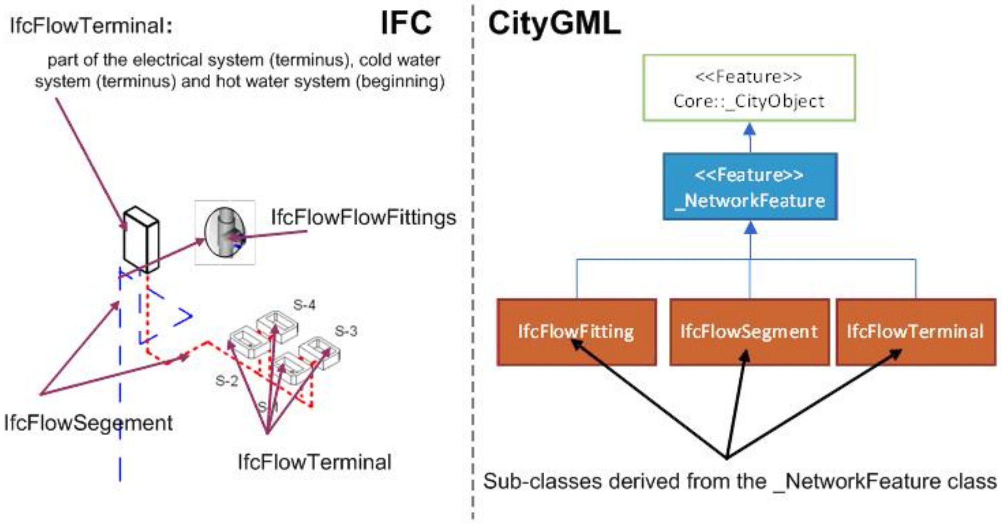


Figure 5.4: IFC thematic classes (left) and its alternative representation in UtilityNet workADE by deriving it from *_NetworkFeature* class (right)

Special network objects, such as pumps or tanks that are composed of several parts can be also represented within *_NetworkFeature*; this class can consists of one or many network objects, therefore it is possible to aggregate these objects and treat them as though they were a single object. In IFC, these types that are represented using the entities: *IfcFlowMovingDevice* and *IfcFlowStorageDevice*. Information about the list of aggregate objects to form one object can be obtained from the entity *IfcRelAggregates*.

5.1.2 Deriving the connectivity information

In NIBU, the concept of connectivity is introduced as a method to represent the relationship between the different *Dis_NetworkElement*. The connectivity is represented logically and attached directly to the network objects. *Dis_NetworkElement* sub-classes are holding the connectivity information.

The *Segment* class always represents the link in the network model; it is always a straight feature where it can only be connected to two objects, and therefore the class holds two attributes *from* and *to* about objects connected to the segement. *Fitting* class represents the nodes, and it is possible for this object to be connected to more than two network objects. The *Fitting* class holds connectivity information and is represented using two attributes, which are *in* and *out*; hence the flow direction can be easily determined.

The connectivity information of NIBU can be generated using the IFC entities. The IFC distinguishes between two types of connectivity - logical and physical. They are both represented by the same entities in case of connectivity with ports; i.e. ports provide the means for an element to be connected to other elements. The physical connectivity concept is generally associated with things that are directly or physically connected. However, there are circumstances where it is important to know that there is a connective relationship between two (or more) objects, but where there is no physical connection to ascertain this fact. In this case, the idea of non-physical connection is termed logical connectivity, in the sense that there is a logical or implied connection between objects. An example for this connectivity can be seen in a light switch, where the lights are turned on and off by that switch (see Figure 5.5). Frequently, the cable that connects the switch with the light will not be instantiated in a model, and so the physical connection cannot be achieved. In this case, the cable making the connection has to be considered. The entire methodology for constructing the graph is based on the following IFC entities:

1. The connectivity relationship between different network objects in case of physical and logical connectivity with ports is represented using the same entities. The connectivity information is extracted from the entity *IfcRelConnectsPortToElement* and *IfcRelConnectsPorts*. *IfcRelConnectsPortToElement* defines the relationship that is made between a port and the *IfcDistributionFlowElement*. Ports contained in different elements are connected to each other using the *IfcRelConnectsPorts* relationship (Figure 5.6).

2. The flow - the direction of the network - can be obtained for each network object directly from the ports; each port possesses a value as being either a *Source* or a *Sink*, and these port attributes provide the information to set the flow direction for each *IfcDistributionFlowElement*, and, indeed, for the whole network. Figure 5.6 represents these relationships and their corresponding classes in NIBU.

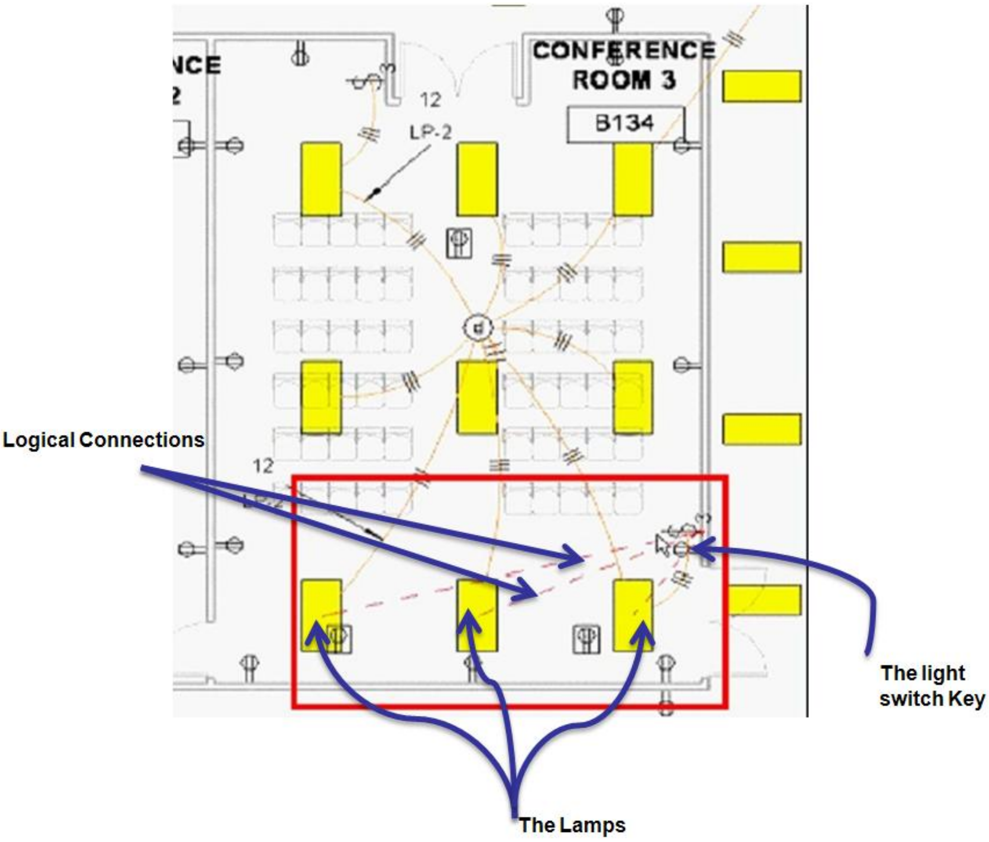
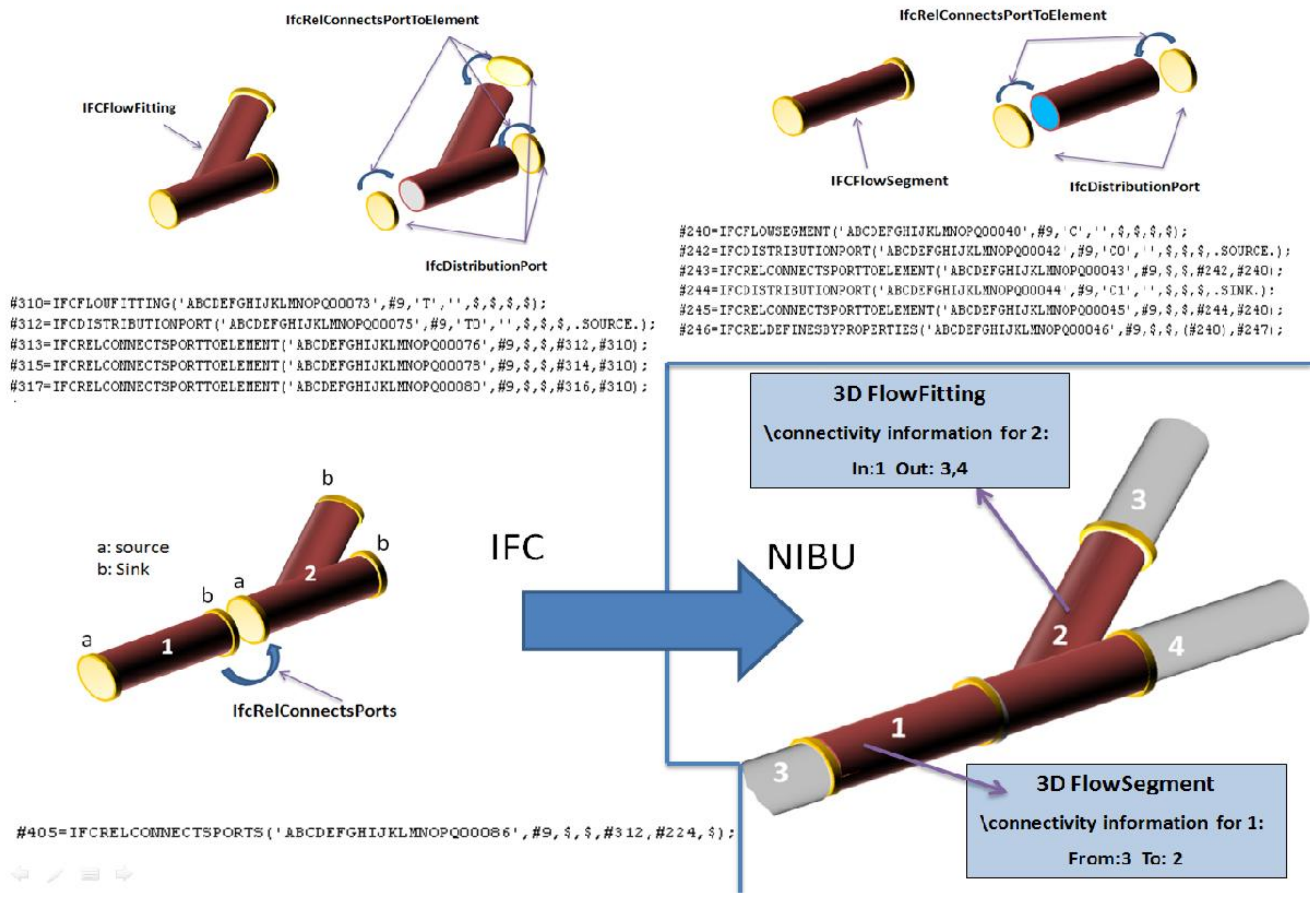


Figure 5.5: The logical connection between light and light switch key, the route of electrical wire is not available

In CityGML-UtilityNetworkADE, the connectivity between the network objects is given with a graph structure. Each topographic object *_NetworkFeature*, as well as each *Network* class, can be associated with graph representation. In the following text, we will discuss the different classes that comprise the graph in UtilityNetworkADE, and further investigate both the related concept in NIBU, and also the possibilities of generating it using the UtilityNetworkADE graph classes.

The class *NetworkGraph* in UtilityNetworkADE represents the topological view of the utility networks in CityGML. Each thematic network object *_NetworkFeature* has a graph representation using the class *FeatureGraph*. The graph representation for one feature can be simple - composed of one node derived directly from *node* class - or a composite, where a group of nodes and edges is needed to represent one network feature. In the second case the internal node is distinguished by an interior node *(Type: interior)*



```
#310=IFCFLOUFITTING('ABCDEFGHIJKLMNOPQ00073',#9,'T','',$,$,$,$);
#312=IFCDISTRIBUTIONPORT('ABCDEFGHIJKLMNOPQ00075',#9,'T0','',$,$,$,.SOURCE.);
#313=IFCRELCONNECTSPORTTOELEMENT('ABCDEFGHIJKLMNOPQ00076',#9,$,$,#312,#310);
#315=IFCRELCONNECTSPORTTOELEMENT('ABCDEFGHIJKLMNOPQ00078',#9,$,$,#314,#310);
#317=IFCRELCONNECTSPORTTOELEMENT('ABCDEFGHIJKLMNOPQ00080',#9,$,$,#316,#310);
```

```
#240=IFCFLOWSEGMENT('ABCDEFGHIJKLMNOPQ00040',#9,'C','',$,$,$,$);
#242=IFCDISTRIBUTIONPORT('ABCDEFGHIJKLMNOPQ00042',#9,'C0','',$,$,$,.SOURCE.);
#243=IFCRELCONNECTSPORTTOELEMENT('ABCDEFGHIJKLMNOPQ00043',#9,$,$,#242,#240);
#244=IFCDISTRIBUTIONPORT('ABCDEFGHIJKLMNOPQ00044',#9,'C1','',$,$,$,.SINK.):
#245=IFCRELCONNECTSPORTTOELEMENT('ABCDEFGHIJKLMNOPQ00045',#9,$,$,#244,#240);
#246=IFCRELDEFINESBYPROPERTIES('ABCDEFGHIJKLMNOPQ00046',#9,$,$,(#240),#247);
```

```
#405=IFCRELCONNECTSPORTS('ABCDEFGHIJKLMNOPQ00086',#9,$,$,#312,#224,$);
```

Figure 5.6: Connectivity derivation from IFC entities

from the *node* class. Additionally, the connecting links between these nodes are further specified using an interior feature link subtype (*InteriorFeatureConnection*) derived from the *edge* class. See Figure 5.7 taken from (Becker et al., 2010b) for an illustration of these relations.

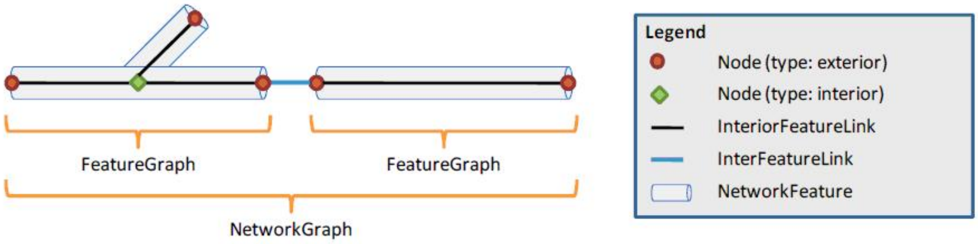


Figure 5.7: Graph representation in UtilityNetworkADE (composite case), a node type interior is used to connect more than one *InteriorFeatureLink* (T-fitting) (left)

If two network objects *_NetworkFeature* (using Feature graph representation) are connected, then their relations can be represented using the *NetworkGraph* class (Figure 5.7). The connectivity is expressed using the class *InterFeatureConnection*, which is derived from class *edge*. This holds two attributes: *direction*, to specify the flow direction in the edge; and *link control*, which allows for the controlling of the flow in the network and, by extension, of the commodity within the network.

The classes that comprise the class *Network* graph are derived directly from the classes *Nodes* and *Edges*, which are directly derived from *gml::feature* and represent a feature in terms of ISO 19109. Its geometry is realized using simple point *gml::point* and simple curve *gml:_curve*.

NIBU connectivity information can be derived from UtilityNetworkADE classes. Figure 5.8 provides examples representing the connectivity information of network objects in UtilityNetworkADE, and the possible transformation to represent those using NIBU classes. The geometry of network graphs in UtilityNetworkADE is represented using *Node* and *Edge* classes, which are derived from GML feature class, which in turn can be associated with simple geometry representation. NIBU attaches the connectivity information directly to the network objects; therefore, the connectivity information needs to be collected for each network object from each *FeatureGraph* that represents *_NetworkFeatrue*, and transformed into NIBU classes *Fitting* and *Segment*.

Another approach to extracting the connection information from IFC in case of physical connectivity would be by using the entities *IfcRelCon-*

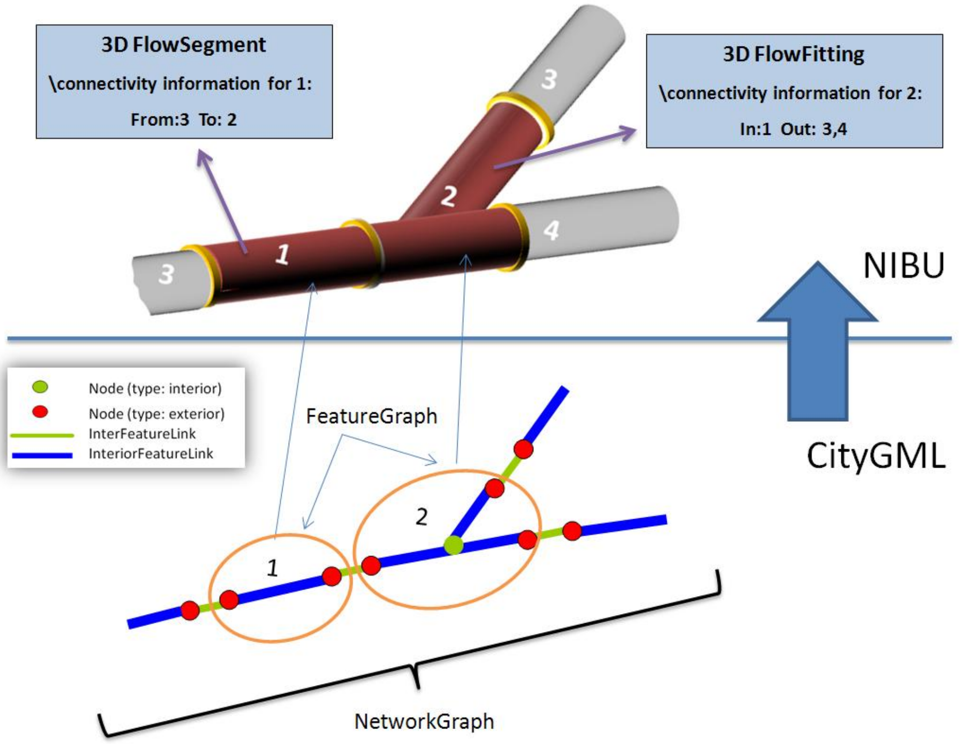


Figure 5.8: *NetworkGraph* is compsed two *FeatureGraph* and its corresponding representation in NIBU

nectsElements, where each network object has attributes represented by the *IfcDistributionFlowElement* that this object is connected to or from.

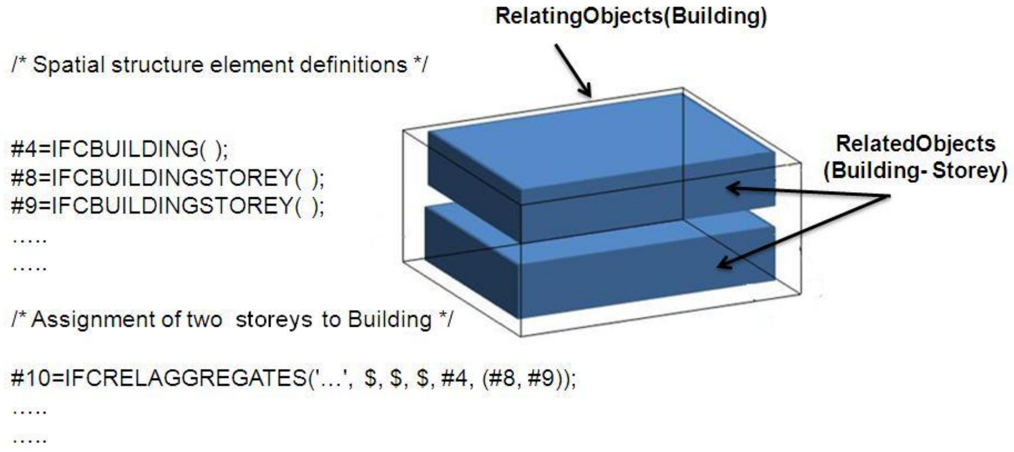
5.2 The building hierarchy

NIBU presents a data model for buildings, and their thematic decomposition. It is customized for the purposes of the application presented in this thesis. The organization of building spatial structure in NIBU is direct, i.e. it provides one way to link a building to building storeys, to space and to its bounding building elements. In this section, we will present the way in which we can extract the required information from IFC and CityGML and populate the NIBU classes. The focus is on the extraction of a relationship between different building elements, as it is described by NIBU. Therefore, the geometry extraction of *Building* and the *Storey* classes is beyond the scope of this section. The emphasis here is on deriving the hierarchy information and the relationship of building elements. While CityGML provides us with a direct representation of the building geometry by its bounding surfaces, *IfcBuilding* and *IfcBuildingStorey* do not contain their own shape representations, as these are provided by the constituting elements. Therefore, geometry representation needs further processing for extraction and representation using NIBU. This section is organized in two sub-sections: first, we present the extraction of building, building storey and space relation, and, in the second sub-section, we present the extraction of space and its bounding element.

5.2.1 Extract building, building storey and space relation

NIBU has two classes that provide an interface to connect it to the current building models i.e. IFC and CityGML. These are *Space* class and *Building element* class, the space class providing a similar concept to the *Room* class in CityGML and *IfcSpace* entity in IFC. These two classes represent the volume of the space. In NIBU, however space is further subdivided into sub-spaces, using the methods as described in chapter 4, and therefore the building element can be also subdivided into parts. The CityGML *Room* class and *IfcSpace* entity holds the required information to populate the *Space* class attribute. Its attributes describe the space usage, specific name and unique ID, and therefore this class provides the required information for *Space* class in NIBU.

NIBU maintains the relationship between building, storey and space. The *Building* class in NIBU is the uppermost container, to which all building sub-components need to relate, directly or indirectly. It can be defined as a breakdown of the building into subsets according to its spatial arrangements. Building includes reference to the *Storey*, which belongs to the building. Every building must have at least one storey, and every storey must have at least one space. In IFC, the relationship between the classes that represent high-level elements (*IfcProject*, *IfcSite*, *IfcBuilding*, *IfcBuildingStorey*) are established using the entity *IfcRelAggregates*. This is used to establish the hierarchical structure of the building. *IfcRelAggregate* is used to link the *IfcBuilding* to *IfcBuildingStorey*, and, in some cases, it includes a reference to the *IfcSpace* (if given) which belong to that building storey. Figure 5.9 provides an illustration for these relations. Information on how these elements are connected to each other can be obtained from the attributes of the *IfcRelAggregate* entity. The *RelatingElement* attribute points to the IFC entity in the higher level; the attribute *RelatedElements* points to the IFC entities at the lower level of the hierarchy and can have anything between one and many relationships. *IfcBuildingStorey* allows for partial building storeys, such as split levels. This would be referenced by *Ifcbuilding*. CityGML represents a simple hierarchy, by contrast with IFC and NIBU. The *Building* class, which is a specialized version of the class *_AbstractBuilding*, represents the higher level. In LOD4, which is the highest level of resolution, the schema also represents the interior of the building. Therefore, the *Room* class is introduced. CityGML does not provide a specific concept for the representation of storeys, as it is available in the AEC/FM and IFC. However, it is possible to aggregate rooms at specific height levels using the CityGML notion of *CityObjectGroups*,



```
/* Spatial structure element definitions */

#4=IFCBUILDING( );
#8=IFCBUILDINGSTOREY( );
#9=IFCBUILDINGSTOREY( );
.....
.....

/* Assignment of two  storeys to Building */

#10=IFCRELAGGREGATES('...', $, $, $, #4, (#8, #9));
.....
.....
```

Figure 5.9: *IfcBuilding* and *IfcBuildingStorey* relationship in IFC

Room normally contains all building service or interior elements, such as electrical elements, furniture, fixture and equipment. In IFC, this relationship between room and the objects inside can be obtained from the entity *IfcRelContainInSpatialStructure*; the entity connects building furniture, or network elements, to a specific space if they are located within a single space. However, in most cases large network elements, such as ducts, or pipes, which span multiple spaces, can be only contained within the building storey; the same relationship is used in IFC to link them to the *IfcBuildingStorey*. The information about this relationship is assigned to the *IfcRelContaininSpatialStructure* attributes; the *RelatedElement* attribute points to elements (e.g. network elements, furniture), and the *RelatingStructure* attribute points to the structure wherein are the network elements, e.g. space, storey or building.

However, in most cases IFC editors (e.g. AutoCAD, ArchiCAD) assign the relationship of network fixtures to the storey. This is not useful for the approach presented in the thesis. Therefore, the required relationship could be extracted using the approach presented in chapter 4. In CityGML, network objects that are attached to a specific room (e.g. radiators or lamps) can be represented by the class *intBuildingInstallation* and can be recognized in terms of which room they belong in by means of associating them with the *Room* class.

5.2.2 Extract space and building element relation

The NIBU building element class, i.e. *Boundary*, and its subclasses, (*walls*, *Ceiling*, and *Ground*), provide similar concepts to the building elements in current building standards; that is, the purpose is to provide an interface between NIBU and these standards. The *Boundary* class can be populated using the IFC entity *IfcBuildingElement*. IFC exchanges all building elements by subtypes of this entity. Figure 5.10 provides a diagram for all the *IfcBuildingElement* currently defined by IFC; those on top of the gray area are part of the stable IFC2x platform. It is important to mention here that these elements need further subdivision to support the approach presented in this thesis (see section 4.2.3 in chapter 4). For example, *IfcSlab* or *IfcWall* normally represent a complete floor slab or a complete external wall. Therefore, further division is needed in order to support the approach presented in this thesis.

NIBU maintains the relationship between the space and its bounding elements. Such relationships could be obtained from IFC (if given) and defined by the entity *IfcRelSpaceBoundary* (Figure 5.11). Each *IfcRelSpaceBoundary* defines a 1:1 relationship between space and a single bounding building element. In IFC, space boundaries are defined logically or physically. For the purpose of our thesis, the case intended is ”physical space boundary”. It is important to mention at this point that this route is an optional one in IFC schema; therefore, it is not guaranteed to be always available in every IFC data file. Where this information is there, then building elements *IfcWall* and *IfcSlabs* need further breaking down, as described in chapter 4.

CityGML does not represent building structural elements (walls, roofs, slabs). The standard maintains a direct relationship between any room and its bounding surfaces; these are the only visible surfaces of the room that can be semantically structured into specialized boundary surfaces, representing floor (*FloorSurface*), Celling (*CellingSurface*) and interior walls (*InteriorWallSurface*).

NIBU building element class - *Boundary* as well as the relationship between NIBU *Space* and *Boundary* classes cannot be populated directly using CityGML.

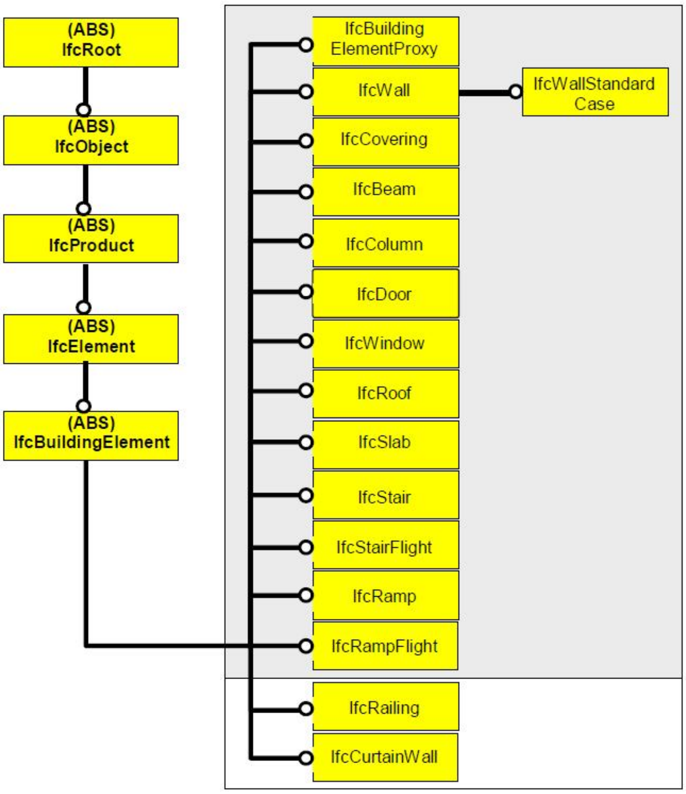
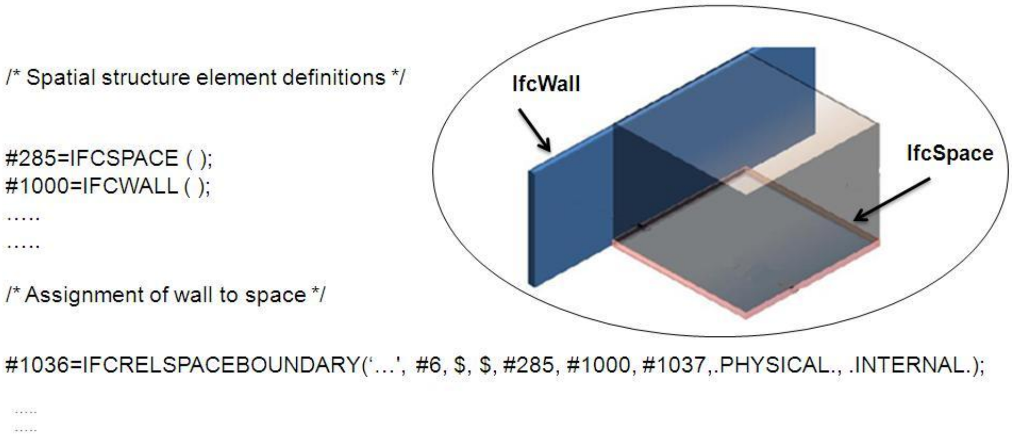


Figure 5.10: Building elements in IFC



```
/* Spatial structure element definitions */

#285=IFCSPACE ( );
#1000=IFCWALL ( );
.....
.....

/* Assignment of wall to space */

#1036=IFCRELSPACEBOUNDARY('…', #6, $, $, #285, #1000, #1037,.PHYSICAL., .INTERNAL.);

.....
.....
```

Figure 5.11: *IfcWall* and its relation to *IfcSpace* using the *IfcRelSpaceBoundary* entity

5.3 Summary

The chapter aims to create a linkage between NIBU and current building standards used in both the BIM and GIS industries. The two prominent standards in the two worlds are IFC and CityGML. The chapter investigates the possibilities of deriving the NIBU information from IFC and CityGML. The development of the mapping follows a pragmatic approach by manual inspection of both standards to see which entities and attributes correspond. The purpose is to allow a formal mapping between the NIBU, BIM and real-world networks in UtilityNetworkADE - CityGML (core model). The information provided in this chapter can contribute to the efforts to enrich 3D city models with urban knowledge, so as to extend their functionality and usability.

The investigation is undertaken in two parts. First, it considers the utility network classes and the possibilities for populating NIBU semantic and connectivity information, based on information from BIM and UtilityNetworkADE of CityGML. The investigation has proved that semantic and connectivity information for NIBU can be derived from BIM and UtiltiyNetworkADE. Most building service concepts in IFC schema can be mapped to NIBU. UtilityNetworkADE is a core model and does not provide enough semantic categorization of network objects. Therefore, additional attributes should be assigned to network objects in order to achieve interoperability with NIBU. *NetworkSystem* in NIBU has a similar concept to the *Network* class in CityGML and *IfcSystem* entitiy in IFC. The NIBU *Dis_NetworkElement* and its subclasses are equivalent to the IFC *IfcDistributionFlowElememt* and its subtypes. *_NetworkFeature* in CityGML involves a similar concept but it does not further provide semantic categorization of network objects.

The graph structure in NIBU is logical; the connectivity information is attached to the 3D network objects. The NIBU is considers that the *Segment* class is always a straight network element connected by two fittings at its ends. Therefore, this always represents the link in the logical graph with information about from-to nodes. Moreover, the *Fitting* class represents the node in the graph, and has both in and out connectivity information, NIBU conncevitiy information can be derived from IFC and UtilityNewtworkADE. In IFC the *IfcRelConnectPortToElement* and *IFCRelConnectPorts* can easily allow the generation of connectivity information of NIBU. In UtilityNetworkADE of CityGML, *_NetworkFeature* with detailed *_FeatureGraph* requires special consideration; a transformation approach would be needed to tackle problems that can be associated by moving different nodes and edges to the logical graph in NIBU. Some nodes are considered as interior nodes, while others represent the ports and are considered as exterior nodes. It is important to notice that this problem needs harmonizing in all cases of *Dis_NetworkElement* except the *Segment* (e.g. pipes). The *Segment* is typically represented as a straight element in NIBU, and therefore represents an *Interfeaturelink*, where the ports can be transformed to provide the from-to connectivity information. Table 5.1 presents the corresponding elements for the mapping from IFC and CityGML into NIBU.

The second part of the investigation is on populating the building structure to provide the intended hierarchy and to represent the spatial relationships. IFC maintains information about the relationship between different building elements. It is possible to obtain the hierarchical relations between building, storeys, spaces and building elements surrounding the space. However, such information contains optional levels and does not guarantee that it is always there. Where this information is there, it need further processing, as described in chapter 4, in order to be customized for the requirement of the application described in this thesis.

CityGML maintains a simple hierarchy: it maintains relationships between building and rooms, and also an optional level related to groups of room objects together. Many building elements such as walls and slabs are not represented in the standard; therefore, only the rooms and building relationships can be derived and transformed to NIBU.

The information gained in the chapter will provide information for the implementation of the system in the next chapter. It will allow the development of a parser that can populate NIBU with the required information.

	IFC	NIBU	CityGML
Service system - Network	IfcSystem	NetwrokSystem	Network
	IfcDistributionFlowElement	Dis_NetworkElement - Segment - Fitting	_NetworkFeature
	IfcRelConnectPorts IfcRelConnectPortToElement	Dis_NetworkElement - From:...To: - In:...Out:	NetworkGraph -Node(type: exterior) -Node(type: interior) -InteriorFeatureLink -InterFeatureLink
Building structure	IfcBuilding	Building	_AbstractBuilding
	IfcBuildingStorey	Storey	CityObjectGroup(optional)
	IfcSpace(optional)	Space	Room
	IfcBuildingElement - IfcWall - IfcSlab - IfcRoof	Boundary - Wall - Ground - Ceiling	-

Table 5.1: IFC - NIBU - CityGML

CHAPTER 6

BIM4GeoA: integration, interaction and visualization strategy

This chapter aims to provide a system that can be used to implement the modelling framework (NIBU) and the concept presented in the previous chapters (3,4,5). It covers issues specified by the second objective of this thesis, i.e. it is devoted to system architecture for integration, analysis and visualization of BIM in the web. The idea for the approach is inspired by recent developments of the semantic 3D city models and BIM object modelling approach, specifically IFC. The chapter uses the web as a mechanism to provide a 3D GIS environment for integrating, analyzing, and visualizing BIM in a geospatial context.

The chapter identifies specific software technologies (BIM4GeoA) that facilitate the use of buildings described in BIM for both analysis and visualization. The study focuses on the development of tools to fulfil the transformation needs for both semantics and geometry of BIM to GIS. The newly developed IFC parser tool interacts with the BIM server and translates BIM open-file standard IFC data into a format that is understood by the PostgreSQL/POSTGIS spatial DBMS software. The tool is built based on semantic harmonization on the data level, as described in chapter 5. Part of the developed tools aim to link the different software technologies, in order that they may behave as one integrated system. The study utilizes the KML and Google Earth plug-in as a visualization mechanism that provides a 3D virtual environment. A tool developed during the study, PostGIS2KML, converts GIS data into the KML scene language, which is understood by the Google Earth plug-in 3D viewer. The database enables not only data storage and retrieval, but also data manipulation (e.g. coordinate transformation, 3D object creation) and analysis. Many analysis functions are written in PostgreSQL's procedural languages, in order to perform the analysis required by the use cases presented in chapter 3. PlpgSQL is used to generate the logical graph structure of 3D network and to perform a reach-ability analysis on network.

The chapter is organized in two parts: 1) we introduce the system architecture, the origin and relationship among the OSS and OS we used. We also point to their relevance for the creation of the web-based geo-processing functionality. 2) the prototype BIM4GeoA is presented with its three components: the IFC parser, the analysis functions, and the Graphical User Interface (*GUI*) for user interaction and visualization.

6.1 BIM4GEOA design and architecture

The system architecture proposed in this chapter is developed using OSS and OS. OSS is defined as computer software whose license "permits users to use, change, and improve the software, and to redistribute it in modified or unmodified form. It is very often developed in a public, collaborative manner" (http://www.opensource.org, 2011). OSS presents a healthy competition with proprietary software and may lead to affordable pricing and increased access (Moreno-Sancheza et al., 2007).

Among the well known OSS projects are the Linux operating system and the Apache web server. A comprehensive list of GIS related OSS can be found at (http://opensourcegis.org/). As of January 2011, the open source GIS website has listed more than 247 of GIS related OSS projects (http://www.opensource.org, 2011).

OS promotes interoperability through its pubic availability, it provides software developers with information about a given specification as well as specific programming rules and advice for implementing the interfaces and/or protocols (www.opengeospatial.org, 2011). It allows the systems to work easily with each other and overcome tedious batch conservation tasks and import/export obstacles (Geoffrey and Moreno-Sanchez, 2003). Among OGC specifications are KML and CityGML, two standards for 3D GIS. The next sections provides background information about the origin, relationships among the OS and OSS, and their relevance for the creation of the 3D geoprocessing web GIS.

6.1.1 Reasons for an open source information system

There is a growing interest in the use of OSS and OS, the term open source gains more attention (http://europa.eu.int, 2011; Boulanger, 2005; Wheeler, 2011). According to (Lowe, 2002), the OSS market is growing rapidly; its products fed by small organizations and regional government agencies that cannot afford proprietary software's.

The idea of creating the system based on OSS and OS emerged from the need to address two sets of challenges. Firstly, current commercial GIS software does not offer 3D functionalities. Secondly, developing a system with new functionalities is much more flexible with OSS, because developing such a system based on commercial software is expensive and requires special training to become familiar with their software operation and maintenance. Moreover, open standard is fully transparent software solutions lead to a stronger cross linking of knowledge and data itself. Thirdly, there is a demand for a flexible and low-cost systems, due to limited funding. License fees have to be paid for commercial systems and spatial add-ons. Cost-saving solutions are especially required by institutions with low budget.

6.1.2 System architecture

An important phase was the selection of the OSS and technologies (Hijazi and Ehlers, 2009b), where different aspects have been considered to select the appropriate OSS. We concentrated on mature OSS projects with clear identification core development teams and wide development and broad active users communities (particularly at the international level). We also sought projects with well-established records of success in developing simple prototype systems as well as large mission-critical applications. Other important aspects were the available resources such as books, user forums, user conferences, and online documentation (Moreno-Sancheza et al., 2007).

After considering several options we decided to use the OSS and OS described in the next section. The key principle is to use existing functionalities and combine them in an optimized way for the requirements of urban management (e.g. the visualization capabilities of KML). The proposed system architecture aims to provide a flexible workflow, while the BIM users can interact and update their design using a building information server. At the same time the GIS users can retrieve the up-to-date BIM data and use it for their analysis. The system architecture is intended as a client-server application with thin client for non-IT specialists. Therefore we assume that the functionality should be realized at the server side. As we decided to use spatial DBMS at the server for storage of the information we have also developed the needed functions in the spatial DBMS.

The current version of the BIM4GeoA is the result of a first development cycle. Figure (6.1) presents the system integration, the part of the system highlited in red represents the tools that are developed to link the different OSS component to interact with each other.

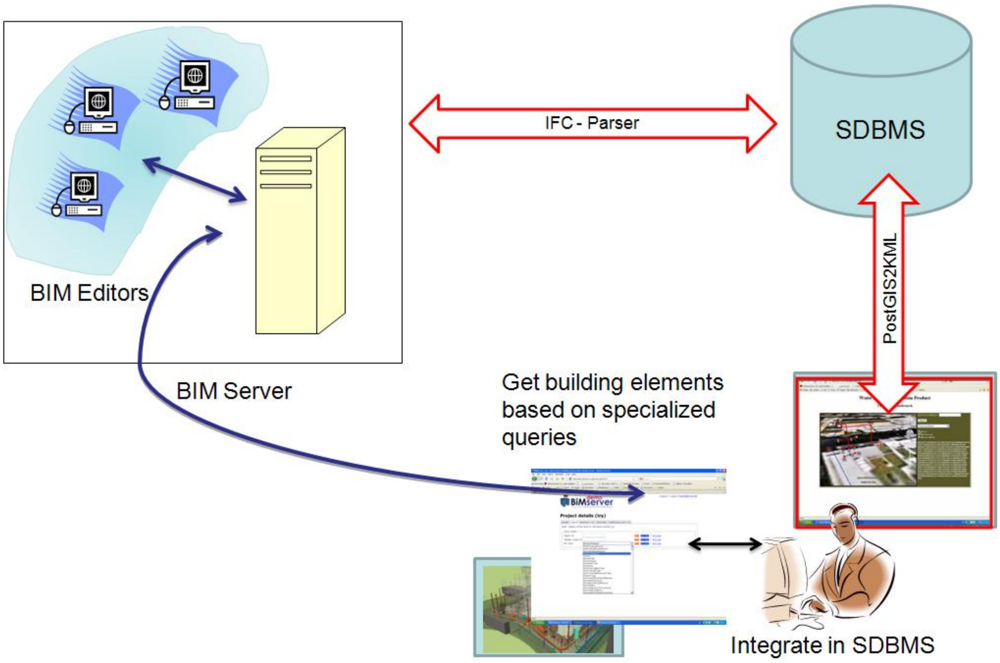


Figure 6.1: Architecture of the prototype - BIM4GeoA, the parts highlited in red represent the tools that are developed

6.1.3 Specific OS and OSS used to develop the system and its role

IfcXml has been developed by the IAI since 1994. Its latest release is IFC 2x3. The IFC 2x release has introduced the IfcXml specification that use XML schema to define the IFC models in parallel with EXPRESS. The target application of this standard is to provide a comprehensive description of the building and the construction site (Nisbat and Liebich, 2010). The data stored in this format is the data source for the system presented in this chapter.

BIMServer is an open-source project developed by the Netherlands organisation for applied scientific research (TNO) and the Eindhoven University of Technolgy. It is enabling the centralization of the information for a construction (or other building related) project. The core is based on the open standard IFC, and therefore knows how to handle IFC data. The BIMserver is not a fileserver, but uses instead a model-driven architecture approach. The main advantage of this BIM server is its ability to query, merge and filter the BIM-model and generate ad-hoc IFC files (www.bimserver.org, 2011).

Google Earth plug-in is a JavaScript API that allows for the embedding of Google Earth into web pages, Google Earth is the most popular 3D geospatial browser. It can visualize 3D models in web browsers (www.google.com, 2011). It provides powerful 3D web visualization functionalities. Google Earth provides terrain representation for most parts of the world. It is available in the form of DTM for terrain visualization.

KML is an XML data format that has a tag-based structure with names and attributes to display geographic data in an Earth browser, such as Google Earth. KML allows the definition of styles to specify feature appearance, icons, and labels to identify locations. It can also display textured objects. KML files have been generated on the fly to visualize the result of the queries and the 3D model of the campus building (Wilson, 2008; Isikdag and Zlatanova, 2010). Through Java script code it is possible to adjust several visualization properties of these models such as "hide texture" and "change visibility". The representation of the building in Google Earth is B-Rep. In KML, the building geometries are represented with polygons. Two distinct methods exist to represent the building geometries. The first one defines a base polygon that corresponds to the floor plan of the building and extrudes this polygon to the height of the building. The second method for representing the buildings geometry is using multiple polygons. This method enables more detailed geometrical representation of the building elements and is currently used by several different applications that acquire/transfer information from digital building models into Google Earth. The 3D geobrowser will visualize every face of the building one-by-one, based on the parameters provided in the KML code for representing the same building with multiple-polygons.

PostgreSQL/PostGIS is an OSS object-relational database system and support almost all SQL functions including sub selects, transactions, and user defined data types and functions (www.PostgreSQL.org, 2011). The PostGIS extension offers the capability to store spatial features with x,y,z coordinates and to perform more than 80 spatial and geoprocessing operations including limited 3D spatial analysis such as 3D BOX (www.postgis.org, 2011). It is used to process spatial and attributes queries and to store the network and other building elements as spatial tables with its attributes.

PHP is a general-purpose scripting language originally designed for web development. It was used to create inter-application communication and to process the user's input and send it back to the web interface. An SQL query to the attributes and the network that are stored in PostGIS spatial tables is built using customized user interfaces, such as buttons, checkboxes, or text fields. The query is then submitted to the server using an HTML form that captures the user's input. At the server, a PHP script converts the user's input into an SQL statement that is submitted to PostgreSQL/PostGIS for processing. The geometry texts that are returned by PostgreSQL/PostGIS are converted to KML code format using PHP and then visualized in the Google Earth plug-in (www.php.net, 2011).

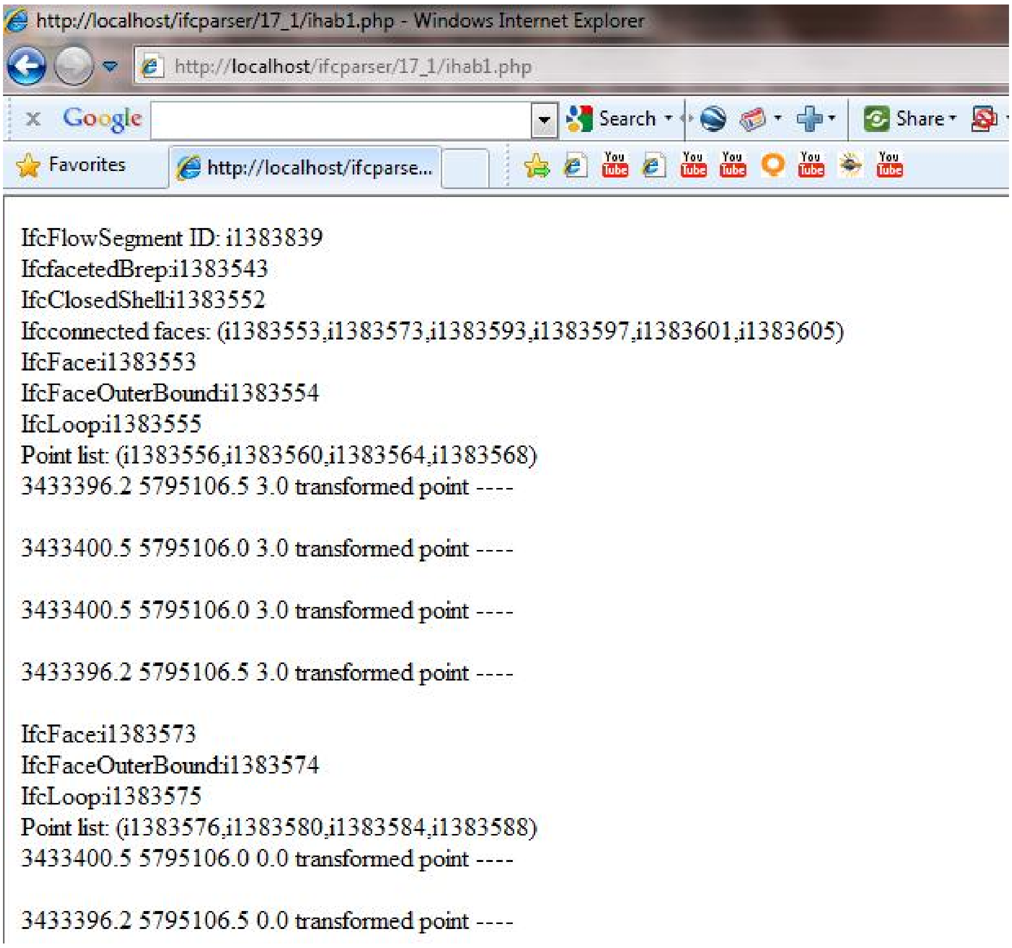
CityGML is an OGC standard, which provides a specification for the representation of 3D urban objects (Kolbe et al., 2009). Some functions are developed to output utilities network object for exchange using this standard.

6.2 The information system-BIM4GeoA

The prototype named BIM4GeoA is composed of three components: The IFC parser, the GUI (3D viewer) and the 3D functionalities implemented in RDBMS. The following will provide brief information about each component and its functionalities.

6.2.1 IFC parser

The IFC parser is developed in PHP scripting language using a combination of DOM and XML-reader libraries. The user can interact with the BIM server and query specific building element; and, when the output is delivered to the server as IfcXml file, the file is parsed on the fly and the required information is extracted. The parser has conversion functionalities that allow the translation of geometry representation from SweptSolid to B-Rep, Moreover the IFC parser performs geometry transformation from local coordinate systems to the real word coordinate system. After performing the transformation operation, the parser inserts the building object into the database as a 3D object. Figure (6.2) provides an illustration of parser running in a web browser.



```
IfcFlowSegment ID: i1383839
IfcfacetedBrep:i1383543
IfcClosedShell:i1383552
Ifcconnected faces: (i1383553,i1383573,i1383593,i1383597,i1383601,i1383605)
IfcFace:i1383553
IfcFaceOuterBound:i1383554
IfcLoop:i1383555
Point list: (i1383556,i1383560,i1383564,i1383568)
3433396.2 5795106.5 3.0 transformed point ----

3433400.5 5795106.0 3.0 transformed point ----

3433400.5 5795106.0 3.0 transformed point ----

3433396.2 5795106.5 3.0 transformed point ----

IfcFace:i1383573
IfcFaceOuterBound:i1383574
IfcLoop:i1383575
Point list: (i1383576,i1383580,i1383584,i1383588)
3433400.5 5795106.0 0.0 transformed point ----

3433396.2 5795106.5 0.0 transformed point ----
```

Figure 6.2: The IFC parser.

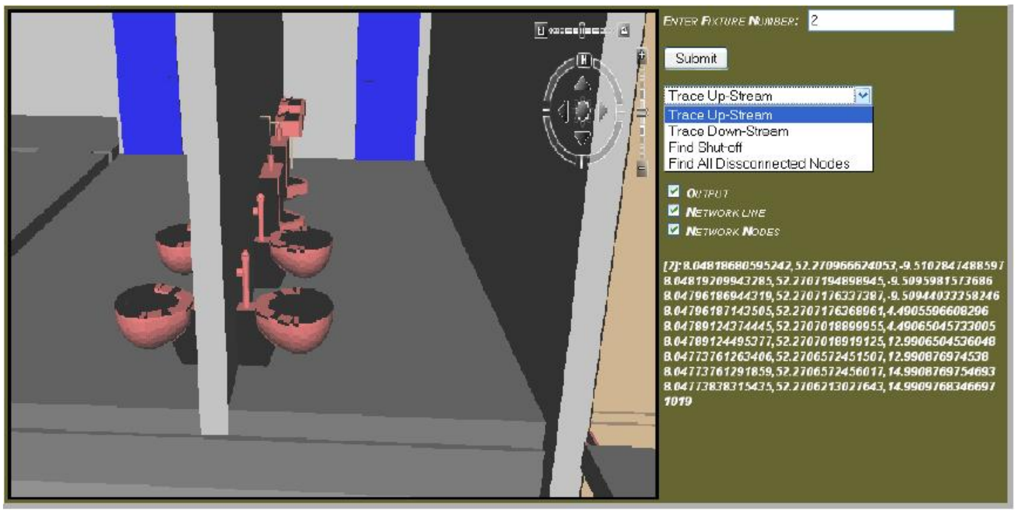
6.2.2 Analysis functionalities

BIM4GeoA offers simple geometric and topological analysis functionalities, the functions is implemented within PostgreSQL environment. Most of the commercial DBMS enable users to create new user-defined data types and functions. In this research, the user-defined data type and functions are written in PlpgSQL, These functions include:

- 3D object creation function (polyhedron).
- Graph creation functionality of true 3D utilities network objects.
- Reach-ability analysis functionalities for utilities network.
- Shortest route analysis functionalities including graph creation functionalities for networks with x,y,z coordinates.

6.2.3 GUI for query and visualization

To allow a system user to both interact with and visualize the analysis result in 3D, a web site is customized that can be accessed from any client's PC or mobile device. It is organized in two mainframes (Figure 6.3). The right frame includes a drop-down menu, which provides analysis functionalities and a text field to enter functions parameters, while the lower part of the frame provides a space where the textual result of the query can be displayed. The 3D viewer is located in the right frame. It is based on the Google Earth plug-in. Several functionalities were customized and added to the viewer using Google Earth APIs, e.g. zoom-in and zoom-out, and a special functionality that provides smooth movement and keys that allow the user to change the camera view. The user can interact with the 3D view and click on any 3D object and get the attribute of this object.



ENTER FIXTURE NUMBER: 2

Trace Up-Stream

☑ OUTPUT
☑ NETWORK LINE
☑ NETWORK NODES

```
[2]:8.04818680595242,52.2709666624053,-9.5107847488597
8.04819209943285,52.2707194898945,-9.5095981573686
8.04796186944319,52.2707176337387,-9.50944033358246
8.04796187143505,52.2707176368961,4.4905596608296
8.04789124374445,52.2707018899955,4.49065045733005
8.04789124495377,52.2707018919125,12.9906504536048
8.04773761263406,52.2706572451507,12.990876974538
8.04773761291859,52.2706572456017,14.9908769754693
8.04773838315435,52.2706213027643,14.9909768346697
1019
```

Figure 6.3: General view of the application - Google Earth plug-in is customized and used for visualisation of the results within their broader context.

6.3 Summary

In this chapter we present an approach to integrate BIM into a more comprehensive 3D Geo-information System. The approach is highly important for both AEC and the geospatial industry. It is a combination of open-source tools, which are used to create a vehicle to integrate BIM data (IFC) into a user-accessible 3D navigation and viewing environment, which also provide analytical operations such as routing and utility network analysis.

The system architecture presented here allows fast development of free applications. The client site has to be equipped with Google Earth plug-in and other freeware Web-browsers such as Mozilla Firefox. The server site requires a web server, BIM server, spatial DBMS and software for communication (i.e. the Common Gateway Interface (*CGI*) scripts).

The prototype demonstrates the potential for using OS to provide highly interactive 3D GIS applications on the Web. From this experience, we can conclude that, for organizations with limited resources, such as academic institutions, sophisticated GIS solutions can be implemented through the WWW with software that is free of cost.

IFC is used as a data source for the system, and several essential aspects can be extracted from the standard for the purpose of 3D GIS. 1) semantic information can be obtained, 2) detailed geometry can be successfully utilized for use in 3D analysis. Google Earth and KML standard proved to be easy-to-use tools for 3D visualization with powerful functionalities: 1) it has the potential to represent the 3D objects with the maximum level of detail as a polyhedron both for interior and exterior objects; moreover, it provides a mechanism for achieving realism such as texturing. The viewing point can be easily organized, linking to other kml or html documents. 2) KML files can be easily integrated with Google Earth terrain data, and can enhance the 3D scence by overlaying images. Postgres/PostGIS provide a robust database management system that offers a considerable and continuously increasing number of 2D geoprocessing functions. The lack of 3D query/-analysis capability, however, places some limitation on the options. Due to the current lack of 3D functionalities (as compared to the 3D query/analysis capability provided in the commercial software Oracle), specific data types, as well as query functionalities, are developed to meet the requirement of these 3D applications.

In Chapter 7, the developed system implementation is described. The chapter will also present a number of tools for the benefit of the utility network application to perform a variety of operations on 3D GIS data.

CHAPTER 7

Implementation

This chapter is devoted to the implementation of the concepts discussed in the previous chapters, NIBU has been developed to meet the requirement of integrated management of 3D utility networks in built environments. It provides a novel approach based on customization of current building models. The modeling example presented in chapter 4 proves the applicability of the modeling proposal. Chapter 5 has already demonstrated the linkage between the NIBU and current standard in BIM and GIS industry. It provides a guideline for deriving NIBU using these standards.

This chapter focuses on the validation of the concepts presented in this thesis. It presents the mapping of NIBU classes to spatial DBMS, as well as the method implemented for the purpose of extracting the required information from the IFC standard and mapping it to the NIBU classes. Finally, a demonstration of the implemented analysis functionalities is presented, and the queries as defined in the use cases in chapter 3 are used to validate these analysis functionalities.

7.1 Mapping NIBU in PostgreSQL/PostGIS

The NIBU model presented in chapter 4 is projected in the DBMS tables. The following discussion is organized into two categories, the first concerning the network classes and the second the building structure classes.

7.1.1 Network classes

Every class of the UML chart presented in chapter 4 (utility network classes) is projected onto one table. Hence the NIBU model consists of 3 main classes that represent utility networks, one for the network, and two for the Segment and Fitting. The attributes and the geometry of the network objects are stored in the tables as columns. The types of the attributes are customized to the PostgreSQL/PostGIS data types. In the following paragraph, the tables and their columns of the relational schema are described in detail.

1. A Network sysetm is represented and stored entirely in the *Network* table; it includes information about the network type and its use.
2. The table *Segment* contains the information about the 3D segments of a network.
3. The table *Fitting* contains all the information of the objects represented in the following types: *IfcFlowFittings*, *IfcFlowTerminals*, *IfcFlowController*, *IfcDistributionChaberElement*, *IfcFlowStorageDevice*, *IfcFlowTreatmentDevice*, *IfcFlowMovingDevice*, *IfcEnergyConversionDevice.*

The following SQL statements are used to create the tables and their columns.

CREATE TABLE "Network"("ID" integer, "Type" text, "Rel_Element" text)

CREATE TABLE "Segment"("ID" integer, "From_Node" integer, "To_Node" integer,"Status" bytea, "Material" text,"The_geom" geometry)

CREATE TABLE "Fitting"("ID" integer, "Type" text, "In_Edges" integer[], "Out_Edges" integer[], "Status" bytea,"Role" text, "Material" text,"The_geom" geometry)

7.1.2 Building structure classes

The building structure classes of the UML chart presented in chapter 4 are projected into several tables. The *Building*, *Storey*, *Subspace* and *Boundary* classes are each projected into just one table. The *Space* and *Building element* classes are not mapped, since we do not implement the function for space and building element partition. The *Boundary* subclasses are mapped into the *Boundary* table and distinguished by domain attribute as specific types. The attributes and the geometry of the space and boundary objects are stored in the tables as columns. The types of the attributes are customized to the PostgreSQL/PostGIS data types. In the following paragraph, the tables and their columns of the relational schema are described in detail.

1. A building object is represented and stored in the *Building* table; it includes information about the building and the storeys that comprise it.
2. The *Storey* table contains the information about the storeys, with the spaces making up a storey.
3. The table entitled *Sub_space* contains all the information about the space and its bounding elements, and has also a pointer to the building network object within a space:
4. The *Boundary* table contains all the information of the objects represented in the following sub classes: *Wall*, *Ceiling*, *Ground*

The following SQL statements are used to create the tables and their columns.

```
CREATE TABLE ”Building”( ”ID” integer, ”Name” text,
”Related_Objects” integer[])

CREATE TABLE ”Storey”( ”ID” integer, ”Name” Text,
”Related_Object” integer[])

CREATE TABLE ”Sub_Space”( ”ID” integer, ”Type” text,
”Related_Element” integer[], ”NetworkObjectsWithin” integer[],
”The_geom” geometry)

CREATE TABLE ”Boundary”( ”ID” integer, ”Type” text, ”The_geom”
geometry)
```

7.2 IFC parser and converter to NIBU

7.2.1 Populating the network classes

Building service systems are represented in IFC as 3D objects within local coordinate systems (see appendix A). They are usually created using Swept-Solid methods or Boundary representation (B-Rep) (I-Chen and Shang-Hsien, 2007; Benner et al., 2005). The proposed data structure, by contrast, maintains the data in both a geographical coordinate system and in boundary representation. Therefore, the transformation of building objects from the IFC to the NIBU structure involves transformation of both geometry and coordinate systems. As mentioned previously, IFC provides information on how network objects are connected. The transformation method employed consists of 4 steps:

1. **Parse the IFC file and store the data in a temporal schema:** The diagram in Figure 7.1 illustrates the temporary schema. The table names correspond to the IFC entities that are required to populate NIBU attributes. The schema is used to collect the required information from the whole IFC file and store it in the temporary schema for further processing.

2. **Convert the information from the temporary schema to NIBU:** The class *NetworkSystem* in NIBU is populated using the tables *IfcSystem* and *IfcRelAssignToGroup* in the temporary schema. These tables include information representing the relationship between the network system *IfcSystem* and the distribution elements that comprise the system. Based on the information collected from the previous step, network objects are examined from the *IfcDistributionElement* table and, based on their type, are inserted into their matching class in NIBU; e.g. the network fittings are inserted to the *Fitting* class in NIBU. The attribute material in these classes is populated using the tables *IfcRelAssociatesMaterial* and *IfcMaterialLayerSets* in the temporary schema. In the final step, the *IfcRelConnectsPortToElement* and *IfcRelConnectsPorts* allow us to determine the connectivity relationship between network objects. The information is extracted and assigned to appropriate classes in the database, as described in section 7.1.1.

3. **Extract and transform the geometry:** The geometry of each object is collected from the IFC file. Based on the representation method, the geometry is extracted and stored temporarily (B-Rep

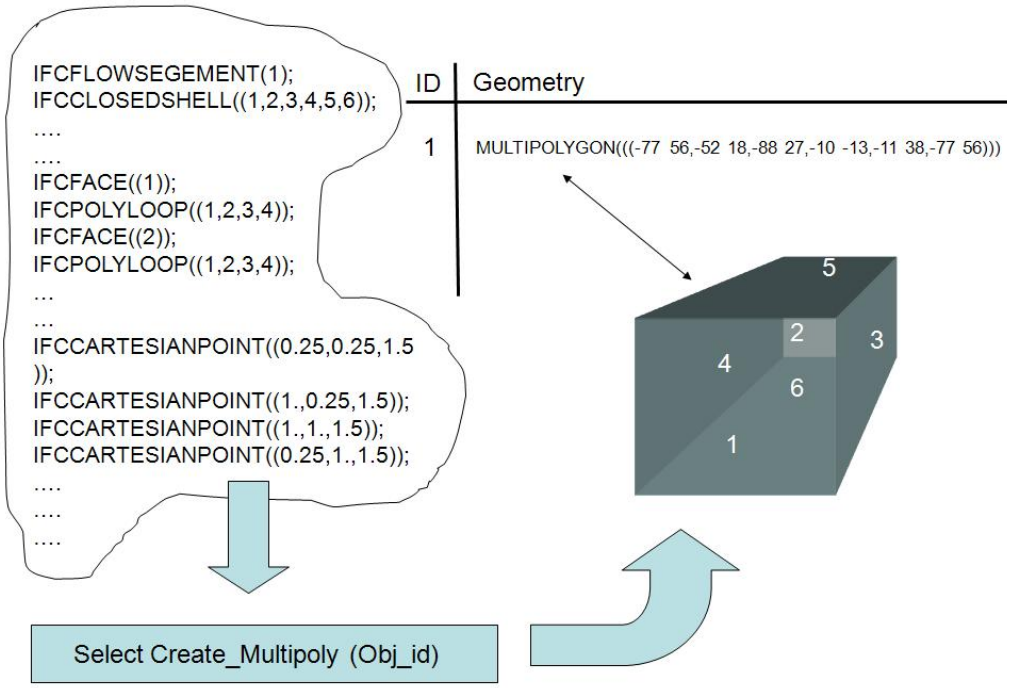
Figure 7.1: Temporary schema to collect the required information from IFC entities - utility relation

or SweptSolid). In cases where the network object is created using SweptSolid representation, this representation is transformed into B-Rep, applying methods presented in (I-Chen and Shang-Hsien, 2007). In order to represent the elements in a geographic coordinate system, a coordinate transformation matrix is applied. Thereby, coordinate values expressed in one system are transformed into coordinate values of another coordinate system. In addition, we apply here three-dimensional transformation operations, using the method presented in (I-Chen and Shang-Hsien, 2007; Benner et al., 2005; Hearn and Baker, 1997; Isikdag et al., 2008)

4. **Create the polyhedron:** PostGIS does not support 3D primitives. Instead, it maintains a 2D data type with 3D coordinates, using 3D polygons. 3D objects can be represented as polyhedrons by means of two approaches: as a list of data-type polygons, or as data-type multipolygons. The method implemented here belongs to the second approach; its advantage is a one-to-one correspondence between a record and an object. For this purpose, we have implemented an in-house function that considers the structure of a B-Rep. An object described by a B-Rep resembles the structure of a polyhedron as follows: a body, representing a set of records containing pointers to the faces that close the volume of the body; faces, representing a set of records containing a unique pointer to vertex that make a closed face; and finally, the list of vertices that make up the faces. The function searches the previous structure and generates a multipolygon-collection of polygons for each network object, and stores it as one record in one table. Figure 7.2 below illustrates the process.

7.2.2 Populating the building classes

Each building structure is represented in IFC as collection of entities where the building entity and building storey entity do not contain their own shape representations. Their shapes (building and storey) are provided by its constituting elements. Therefore, the focus here is on extracting the hierarchy relationship between the building structure component, and not on the creation of the building envelope or storey envelope. The space and building element entities include a 3D representation within a local coordinate system. They are usually created using the SweptSolid or B-Rep. Transformation of the geometry of these entities is considered in the method presented below. The extraction of the relationship between different build-



```
IFCFLOWSEGEMENT(1);
IFCCLOSEDSHELL((1,2,3,4,5,6));
....
....
IFCFACE((1));
IFCPOLYLOOP((1,2,3,4));
IFCFACE((2));
IFCPOLYLOOP((1,2,3,4));
...
...
IFCCARTESIANPOINT((0.25,0.25,1.5
));
IFCCARTESIANPOINT((1.,0.25,1.5));
IFCCARTESIANPOINT((1.,1.,1.5));
IFCCARTESIANPOINT((0.25,1.,1.5));
....
....
....
```

```
Select Create_Multipoly (Obj_id)
```

ID	Geometry
1	MULTIPOLYGON(((-77 56,-52 18,-88 27,-10 -13,-11 38,-77 56)))

Figure 7.2: 3D object stored in Multipolygon data type using the in-house developed function.

ing components and network elements consists of 4 steps, similar to the steps in the previous section:

1. **Parse the IFC and store the data in a temporal schema:** As in the previous section, the IFC building components are parsed and stored in a temporal schema. The diagram in Figure 7.3 illustrates the temporary schema. The table names correspond to the IFC entities that are required to populate NIBU building classes attributes. The schema is used to collect the required information from the whole IFC and store it in the temporary schema for further processing.

2. **Convert the information from the temporary schema to NIBU:** The class *Building* in NIBU is populated using the tables *IfcBuilding*, and *IfcRelAggregate*. It defines the building and the storeys compose it. The *IfcBuilding* entity provides the building's attributes (*ID*, *name*, and *description*), while the *IfcRelAggregate* attribute *RelatedObjects* provide a list of the storeys that comprise the building. In addition, the information of *Storey* class in NIBU is collected using the tables *IfcBuildingStorey* and *IfcRelAggregate*. The *ID*, *name*, and *description* attribute are collected from *IfcBuildingStorey*, and the

spaces comprise the storey information collected from the *IfcRelAggregate* table using the attribute-*Related objects*. The *SubSpace* class is populated using the *IfcSpace*, *IfcSpaceBoundary*, *IfcWall* and *IfcSlab*. The space attributes, such as *ID*, *name*, and *description*, are collected from *IfcSpace* table in the temporary schema. The *IfcRelSpaceboundary* table attribute *Related building element* provides the attribute for the bounding elements, while *IfcRelContainedInSpatialStructure* contains information about a list of the network elements contained in space. The *Boundary* subclasses in NIBU (*Wall*, *Ceiling* and *Ground*) and their attributes (*ID*, *name* and *description*) are populated using the tables *IfcWall* and *IfcSlab*.

3. **Extract and transform the geometry:** The geometry of the *Boundary* and Space classes are extracted and transformed in similar fashion to that explained at step 3 in the previous section.

4. **Create the polyhedron:** This step is also undertaken in a similar way to the method explained at step 4 in the previous section.

7.3 NIBU analysis functionality

To allow a system user to perform an analysis, the GUI presented in the previous chapter is used, and the developed analysis functionalities are integrated in the GUI. Therefore, the user needs to select the required analysis functions from the drop-down menu, enter the arguments for these functions, and click the "Submit" button. A solution is calculated and visualized in 3D. By selecting the analysis function from the drop-down menu, an SQL statement is sent to the spatial DBMS server, which passes the argument to the developed functions. Table 7.1 provides a complete list and brief description of the implemented functionalities for the different use cases. The study area for the system is a real dataset from the University of Osnabrueck. The water utility in one block of the building is selected for the spatial operation.

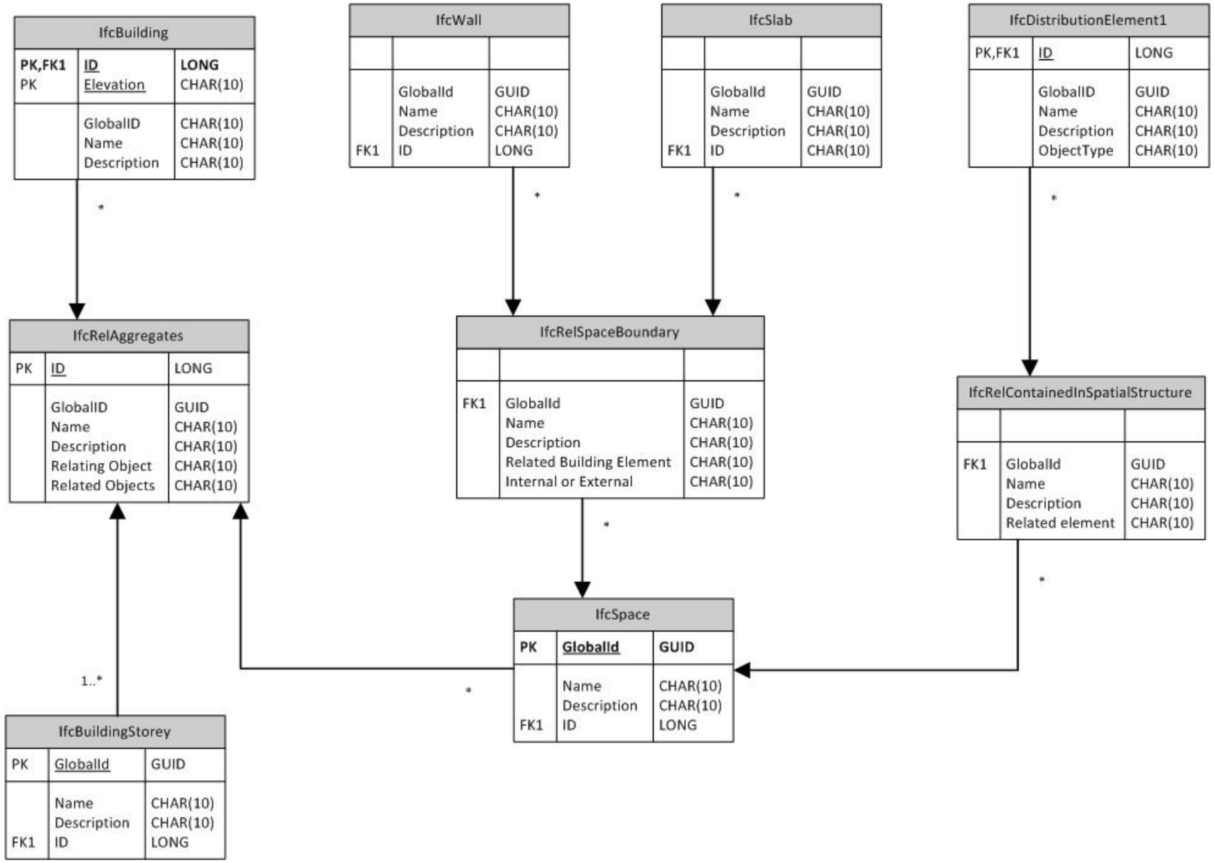


Figure 7.3: Temporary schema to collect the required information from IFC entities - building hierarchy classes

Function name	**Description**
Find Ancestor	This function finds the ancestor of a group of selected network elements. The procedure starts by taking an argument concerning the elements of the network that have a problem, then tracing upstream and select features, and highlighting the feature that is common to all. *Select Find_ancestor(failure 1_id, failure2_id, .failure 4_id)*
Trace Downstream	This procedure traces the complete network, from a given point therein to all the open points. Firstly, the starting station is taken as an argument. All the "on" elements within the network, both flow segments and junctions, are pushed into the stack, and then an element of the stack is popped repeatedly, and the connecting station of the switch in that element is looked up. The operation of pushing on the stack continues until a closed point or an end junction is reached. The procedure terminates when the stack is empty. *Select Trace_downstream (id)*
Trace Upstream	The procedure traces all the connecting elements of the given network. It traces and highlights a given junction to all open points of the network, until it reaches the source point. It takes the same steps as the trace downstream procedure, except that it traces the network in the opposite direction, up to the source point. *Select Trace_Upstream (id)*
Find Disconnected Terminals	This procedure will highlight all the terminals of the network that would be out of service or off from a given network element. Firstly, the user has to give the element of the network that is turned off as an argument. All the elements of the network that go in the direction of the flow from the given element will be traced; the terminals will be selected and highlighted. *Select Find_dissTerminals (id)*

Find Source	This procedure will highlight and select the source of the network from a defined location on the network *Select Find_Source(id)*
Find Shutoff	This procedure will highlight the element within the network that can disconnect the selected point in the network. *Select Find_Shutoff(id)*

Table 7.1: Implemented analysis functions

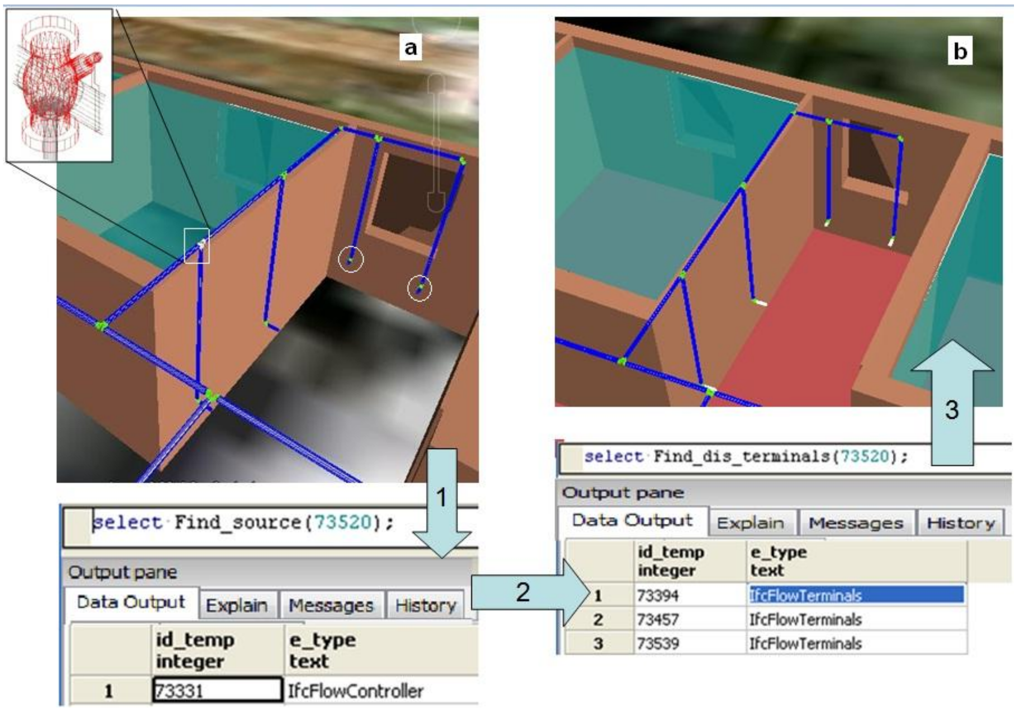
7.3.1 Demonstration of NIBU for the use cases

To demonstrate the applicability of the analysis functionalities for the previously presented scenarios, we implemented selected queries. These queries were posed during the execution of the operation undertaken during these use cases (see Section 3.4.1).

The first three queries involve operations from the first case study, that is, maintenance operations (in the initial two forms of repair or prevention). For a maintenance highlighted by a white circle in Figure 7.4(a), the person responsible for the facility management needs to find the location of the shut-off valve (*Ifcflowcontrol*) that can stop the flow in the network device. Using the function ”find_source”, he can find the location of the shut-off valve (*IfcFlowControl*). To turn off the valve, he needs to know all the network terminals, e.g. sink, water closet (*IfcFlowTerminals*), that will be out of service. He will use the function ”find disconnected terminals” - see Figure 7.4(b) - so that he can know the locations at which there will be a shortage of service, of which he can inform people.

Another scenario for maintenance operations that was included in query number 3 in section 3.4.1 is illustrated in Figure 7.5. The implementation of this query requires the selection of that part of the network that causes a shortage of service in different locations (in case of casual repair). Let us assume that a shortage of service is reported for several locations, the network terminals (*IfcFlowTerminal*) in locations highlighted by white circles in Figure 7.5. The persons in facility management can then use the function ”find ancestors” to select the element of the network that could cause the problem.

The fourth query is related to the second use case of ”inspection operation”, where a team from the city needs to locate a treatment device to ensure that it functions properly. The process starts by defining the location



```
select Find_source(73520);
```

	id_temp integer	e_type text
1	73331	IfcFlowController

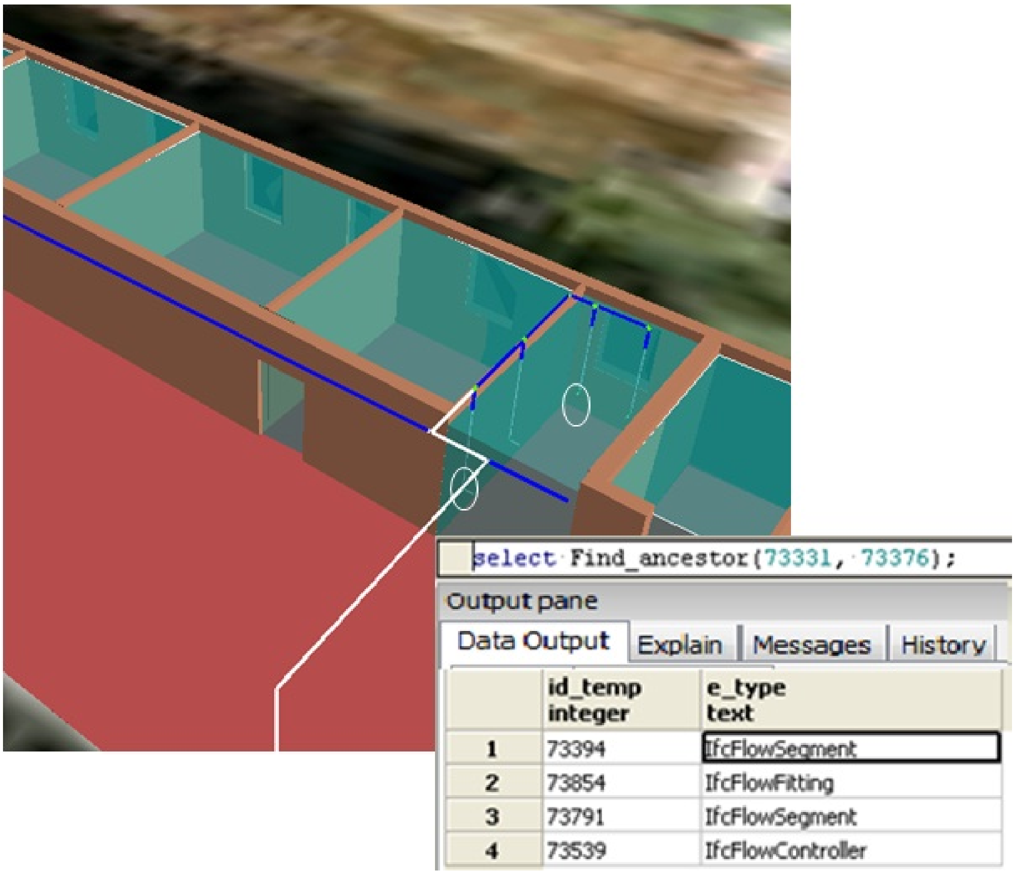
```
select Find_dis_terminals(73520);
```

	id_temp integer	e_type text
1	73394	IfcFlowTerminals
2	73457	IfcFlowTerminals
3	73539	IfcFlowTerminals

Figure 7.4: The workflow for maintenance operation (the roof has been removed for visualization purposes): a) the location of the *IfcFlowController* (white rectangle) has to be determined using the function "find_source". b) The next step is to find the location of *IfcFlowTerminals* that will be affected (highlighted in white colour) using the function "Find_disconnected_terminals"

in the network and then proceeds by selecting "Trace_Downstream" with the treatment devices (*IfcFlowTreatmentDevice*) as argument (Figure 7.6).

The last query is related to the emergency use case. The system user needs to select the location of the shut-off valve (*IfcFlowControl*). Then he needs to select all the elements of the network from this source, and to check their type, so that proper action based on this type can be taken in case of devices containing hazardous materials (*IfcFlowStorageDevice*). Figure 7.7 illustrates the implementation of "Trace_Downstream" function, where all the elements of the network are selected (all *IfcFlowDistribution* subtypes) from a specific point location (highlighted in white) to the network terminals (*IfcFlowTerminals*).



```
select Find_ancestor(73331, 73376);
```

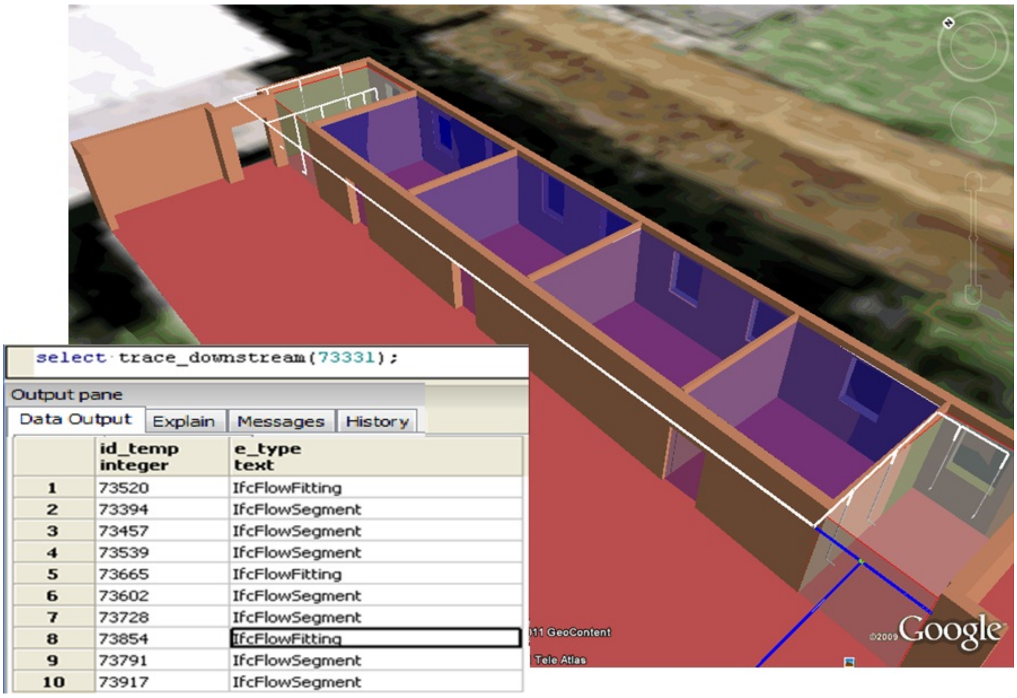
	id_temp integer	e_type text
1	73394	IfcFlowSegment
2	73854	IfcFlowFitting
3	73791	IfcFlowSegment
4	73539	IfcFlowController

Figure 7.5: After reporting of problems with *IfcFlowTerminals* (white circles), the "Find_ancestor" function identifies and locates those network elements that are suspected to be causing the problem (white circles).

```
select trace_downstream(73331, 'IfcFlowTreatmentDevice')
```

	id_temp integer	e_type text
1	73520	IfcFlowTreatmentDevice

Figure 7.6: Illustration for the "Trace_Downstream" function



```
select trace_downstream(73331);
```

	id_temp integer	e_type text
1	73520	IfcFlowFitting
2	73394	IfcFlowSegment
3	73457	IfcFlowSegment
4	73539	IfcFlowSegment
5	73665	IfcFlowFitting
6	73602	IfcFlowSegment
7	73728	IfcFlowSegment
8	73854	IfcFlowFitting
9	73791	IfcFlowSegment
10	73917	IfcFlowSegment

Figure 7.7: The result of trace downstream query highlighted in white also the rooms that *IfcFlowTerminals* within are selected

7.4 Summary

The implementation issue discussed above demonstrates and verifies several basic concepts addressed in this thesis. It concentrates on management of utility networks in buildings for the benefits of groups of users such as facility managers, emergency crews, and city authorities.

The test illustrates the overall feasibility of the client/server approach presented in chapter 6. The system components are capable of integrating, analyzing and visualizing 3D BIM data in a geospatial context. The implementation demonstrates that an appropriate GUI (for different users) can be developed in order to specify queries and visualize 3D spatial analysis. The NIBU model has been implemented using PostgreSQL/PostGIS software, but the approach can be modified for any DBMS. The prototype software components, i.e. IFC parser and analysis functionalities, developed during the research have demonstrated a technical proof-of-concept for the transfer of interior building utilities information and the use of BIMs as a data source to provide the data required to support the analysis of these networks in geospatial environments.

In the current implementation, we store the building service system and link it to the other building elements (after transforming them into the GIS environment). We do not consider the implementing functions for space and building element partition that are described in chapter 4, nor do we implement tools to transform CityGML utility network into NIBU. The CityGML UtiltiyNetworkADE standard is still under development and there is no dataset available in this format. Moreover, the implementation does not take into account undertaking elaborated tests in order to evaluate and enhance performance issues.

The research results demonstrate that, based on the interoperability framework presented in chapter 5, we have indeed been able to develop a tool that can extract the required information from BIM (geometric, semantic, and topological) information (about interior building utilities) for the seamless automation of the data management and analysis of interior building utilities. Additionally, the BIM schema includes information that can be used to populate NIBU building structure classes and to provide information on how to relate the building elements to each other.

NIBU proves that it is capable of providing the required information for the integrated analysis of interior building utilities. It has a suitable level of semantic information that allows us to generate generic analysis functions that are enabled for all systems, regardless of the materials that flow within them. The adjacency list data structure ”Modern” carries additional advantages for analysis performed in the graph, since it offers direct access to both edges and nodes.

CHAPTER 8

Conclusions and further research

In this doctoral thesis, a new approach for integrated management of utilities has been presented (interior-exterior), which demonstrates how a GIS can be used to conduct different type of utilities network spatial analysis and visualization for facilities, both in and between buildings. It has described an attempt to integrate available technology components and to develop new concepts in order to attain a system that better meets the requirements of users. It deals with utilities network problems within built environments by considering the integration of design document (BIM) in a 3D geo-context and by providing analysis opportunity through the whole facility life cycle.

The thesis is focused on developing a concept for structuring the utilities network and building structure, thereby allowing network analysis and manage their relation to building structure. It is a step towards the simulation of infrastructural interdependencies and their complex behavior. These simulations can support different situations, such as the cascading effects of damage on other building elements. It can support maintenance operations, and other networks system operations, all with 3D context analysis and efficient retrieval and display.

This chapter will now recapitulate the results of the thesis and their significance for GIS research. A perspective on future work in this research field is developed subsequently.

8.1 Summary of the results

The following text summarizes the strategies and basic approaches applied during the research with respect to the objective of the thesis

Identification of 3D spatial relationships and analysis functionalities in built environment with regards to interior building utilities

The first objective specified was achieved following a three- step strategy: first, a study on common business models for the investigation of requirements and structuring of information; second, an exploration of user requirements for the use of GIS for building; and third, the formulating of user requirements and outlining the scope of the thesis.

The study has provided knowledge on the methods for defining users and on the techniques to investigate their requirements. The determination of user requirements in this thesis is organized according to Tomlinson's approach for determination of the process, function and data on the basis of global and individual methods. First, the thesis revised and evaluated several case-studies for using GIS to manage their campuses and interior spaces. Second, a number of interviews for defining the mandates and responsibilities and the data to be used have been conducted within the University of Osnabrueck.

The objective of the first part of the study was to investigate the early users of GIS for buildings, and their purposes of use, as well as to gain knowledge about the problems associated with using GIS on this detailed scale. The study shows that current 2D GIS analysis functionalities have limitation when they try to use them in urban context.

The study has presented a group of IPs that are considered potential applications for implementing and promoting the use of 3D GIS in a building. The study focuses on utilities network and provides detailed description of three use cases. Bases on the analysis of the use cases, a list of analysis functionalities, spatial relationships and visualization requirements is determined.

A conceptual model for 3d integrated analysis of building utilities with building structure

The clarification of user requirements contributed to the development of the NIBU data model. The defined use cases provided the basis for clarifying the required analysis functionalities, spatial relationships and visualization requirements.

The developed data model is a graph-based spatial model considers providing 3D geometry representation of network objects and maintains their connectivity relationships and their relationship to the building structure. The model is formally modeled using an UML class diagram; its classes are organized into two main parts, as follows.

NIBU- network classes

The model concentrates on utilities networks. A crucial aspect for the management of utilities network in GIS is the ability to provide semantic and connectivity information, supporting reach-ability analysis operations. NIBU provides semantic categorization of utilities based on their functions in the network. The semantic representation of network elements allows the generating of generic analysis functions that are enabled for all systems, regardless of the materials that flow within them. The network model composed of a logical graph and 3D geometry of utility network elements. The logical graph of the model utilizes adjacency list structure ”Modern” for the performance of specific analysis tasks on these networks. This data structure carries additional advantages for analyses performed in the graph, since it offers direct access for both edges and nodes.

NIBU-relation to building structure

The second part of NIBU concentrates on modeling the relationships between building structures and utilities network. The building model in NIBU 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, room - which can guide technical staff to network element locations inside building. The approach is appropriate for different situations, such as supporting 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 any building structure. The model extends several existing approaches and re-use them for the purpose of interior utilities applications, by explaining ideas and the requirements of the utilities network interdependencies. Interdependencies between building structure and utilities services systems are modeled using a logical link that is created based on the Egenhofer relations (”contains”, ”overlap” or ”equal”). The building model in NIBU is customized for the purpose of utilities networks. 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.

Links between the model and the current building standards

With respect to the third research objective, existing building models, both in GIS and AEC, are studied and adapted (BIM-IFC and CityGML). The aim is to derive the NIBU classes with its geometric and attributes information. To experience the complexity of generating NIBU classes using these standards, a manual inspection for these standards is undertaken, a mapping approach is adapted to achieve harmonization of semantic at data level, and similar concepts are matched and discussed together. The investigation shows that NIBU provides classes that facilitate the interface between the data model and the current building standards, such as CityGML and BIM/IFC, and therefore that it is possible to obtain the required information from the current 3D building data model standards, both the network classes as well as the intended building structure and populate NIBU classes.

The research results have demonstrated that BIMs provide the required level and amount of (geometric, semantic, and connectivity) information (about interior building utilities) for the seamless automation of the generation of NIBU network classes. Furthermore, the investigation has proved that UtiltiyNetworkADE provides the primary classes, which can be easily extended to provide information about the interior building utilities. Most building service concepts in IFC schema and UtilityNetworkADE can be mapped to NIBU with less loss of data. Specialized classes can be easily derived from the class *_NetworkFeature* to represent the different thematic concepts in interior building utilities. The graph structure in UtilityNetworkADE provides the required information to populate NIBU connectivity information. Additionally, IFC semantic categorization of network elements can be used to extract NIBU connectivity information.

System architecture for integration, analysis and visualization of BIM in geo-context

The fourth objective of the thesis was to propose system architecture for integrating and analyzing BIM in Geo-Context (BIM4GeoA). The strategy followed was as follows. 1) The problems associated with integrating BIM in Geo-context was defined and analyzed. 2) The system architecture was assembled. One important consideration was to maintain the privacy of the BIM contents by maintaining BIM in a separate server, and providing access to the GIS users to integrate the required BIM information based on specified queries. 3) The software and related technologies were selected and combined in an optimized way. The software component of the system was selected according to two major criteria, i.e. mature OSS projects, and projects with wide development communities.

The system proposed in the thesis is highly important to both AEC and the geospatial industry. The system simplifies the process and facilitate the integration by creating a vehicle to integrate BIM data (IFC) into a user-accessible 3D navigation and viewing environment, which also provides some analytical operations, such as routing and utility network analysis.

The prototype demonstrates the potential for using OS to provide highly interactive 3D GIS applications on the Web. PostgreSQL/PostGIS provides a robust database management system that offers a considerable and continuously increasing number of 2D geoprocessing functions. The lack of 3D query/analysis capability puts some limitation on the options, due to the current lack of 3D functionalities (as compared to the 3D query/analysis capability provided in the commercial software Oracle). Specific data type as well as query functionalities are developed to meet the requirement of these 3D applications. Google Earth and KML standard proved to be easy means to use 3D visualization tools with powerful functionalities.

Evaluation and verification of the proposed concept.

The final verification of the proposed data model NIBU and its related functions were completed by tests using the prototype system proposed in chapter 6, i.e BIM4GeoA. The prototype was composed of open-source and freeware modules, i.e. BIM server, PostgreSQL/PostGIS DBMS, PlpgSQL, PHP scripting language, and Google Earth plug-in. The GUI was organized in two frames: one to allow the user to interact and formulate the queries, and the second a 3D viewer allowing direct visualization of the spatial queries.

The implementation presents the outcomes of the presented method in chapter 4 and 5 to extract the semantic and connectivity information. A water utility network system at the University of Osnabrueck's Campus was used to test the method. NIBU was generated directly using the IFC parser.

The use cases presented in chapter 3 and the defined queries is performed using the prototype. Through performing the queries specified in chapter 3, the NIBU logical graph structure and the relationship with other building elements and spaces were tested, the developed analysis functionalities (trace up stream, trace downstream, find ancestor, find shut off) were able to answer the questions raised by the queries, and the relationship between the network component and the building spaces provided information for the location of the network objects within spaces.

8.2 Conclusions

This thesis has provided a case study of how GIS can be integrated into, and extend the capabilities of, CAD and BIM to provide facility mangers with insight into the ”where” questions that they ask on a daily basis. The technology presented in this thesis removes the artificial boundaries resulting from the current technology in both CAD/BIM and GIS. While the experiment undertaken in this thesis is related to utilities networks, it still provides directions on practical considerations that are required for integrating BIM and GIS and taking GIS inside buildings. These considerations can be summarized in the following points:

- The key issue in the bringing of GIS to buildings is to define the use cases. We need to define valid use cases for the possible use of GIS in building, to define the business process, and then to define the constraints and investigate what can be done in terms of a GIS process.

- There is a need to focus the scale of GIS to a finer level of granularity, and to represent the spatial relationships in large-scale areas, as well as provide analysis functionalities that can work in this intense environment.

- There is a need to allow interchange between BIM/GIS. The semantic approach presented in this thesis has provided a workable method to integrate interior utilities into the 3D geo-context.

- The developed system does not aim to provide an upper tool that can replace the CAD technology; instead, the focus was given to provide an upper connector that allows the interchange and integration of the data for further analysis within GIS.

8.3 Future work

The work presented in this thesis can be extended in different directions. Some of these are:

1. The user requirements study define several IPs related to the management of the built environment and performing of analysis inside buildings. The research presented in this thesis is limited to the utility network IP. Further research should be undertaken to investigate other IPs.

2. This conceptual framework is the first step towards integrated modeling of interior utility networks and the building structure. Future work might consider the following:

    - Implementing some of the presented methods for space partition, or building element partitions
    - Custumizing the method presented by Loerenz (Lorenz and Ohlbach, 2006) to further fit the need of referencing network element to other building elements
    - Concentrating on testing of this approach with real datasets. Special attention will be given to the structuring methods and the possibility of creating the model in a totally automated way from the IFC and CityGML.

3. The NIBU data model integrates the utility networks within the whole building model. The current CityGML data model is not including some building elements, e.g. walls. There is a need for further investigation of the relationship between these elements within the building structure. There is a need for some extensions and modifications of CityGML to provide these elements.

4. Future research can focus on defining new classes that will help to customize the UtilityNetworkADE to represent the interior Utility. The relation between the UtilityNetworkADE and GeoBIM ADE (Berlo and de Laat, 2011) could be investigated. Moreover, a bidirectional transformation should be considered and investigated, since the current work concentrated on unidirectional information transformation (i.e. from a BIM to NIBU models). Other important direction would be from NIBU to CityGML; such a transformation might also be required to support urban upgrading and renovation-related tasks where an information model of a building usually does not exit.

5. The system architecture can be extended to include more analysis functionalities. Currently, the system can perform utilities network and thematic analysis queries. Further functionalities would include

functionalities that are capable of extracting metric properties (e.g. length, diameter, volume) of 3D network objects. This will be useful for other analysis operations related to the flow accumulation and maximum flow problems - edges can be assigned values for their stated capacity. These calculations are essential for checking the greatest rate at which material can move from source to sink without violating any capacity constraints.

6. The B-Rep is not the optimal soluation to store network objects in the spatial DBMS. There is a need to develop a new data type in spatial DBMS that is appropriate to utility network objects. SweptSolid representation used in CAD can be utilized for this purposes. The new data type specification, as well as its function to input and output, all need to be investigated.

7. The research did not discuss performance in detail. There is a need to undertake elaborated tests in order to evaluate and enhance performance issue. The code is written using scripting languages, e.g. PHP, PlpgSQL. It could be expected to achieve better performance if the code were transformed and written in core programming language such as C++ or Java. Additionally, the code could be optimized to achieve better performance.

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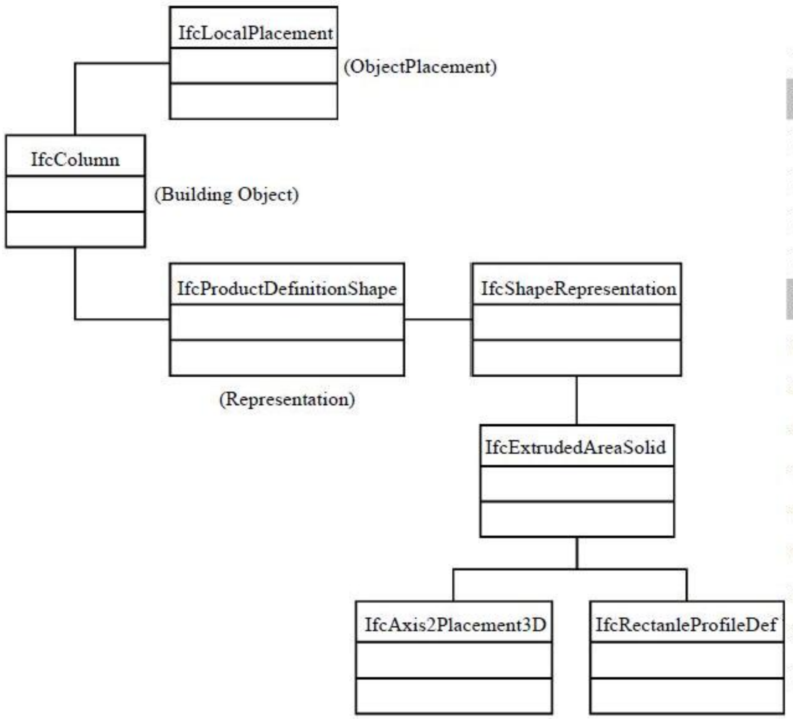
APPENDIX A

IFC product representation concept

All building elements in IFC are derived from the *IfcProduct* entity, which can refer to a location (*IfcLocalPlacement*) and a geometrical representation (*IfcShapeRepresentation*). Any building object in the IFC model, has the following two attributes to assist one in describing geometric representation. One is called *ObjectPlacement*, and describes the placement of the object in the spatial context. The other one is called *Representation*, and defines the object's representation. See Figure A.1 taken from (I-Chen and Shang-Hsien, 2007).



```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION ();
FILE_NAME ();
FILE_SCHEMA ();
ENDSEC;
DATA;
#247= IFCCOLUMN('3HXVZ12RT7b9hiltGm$bCZ',#13,'Col-057',$,$,#290,#283,$)
#290= IFCLOCALPLACEMENT (#72,#288);
#283= IFCPRODUCTDEFINITIONSHAPE($,$(#272,#279));
#272= IFCSHAPEREPRESENTATION(#40,'Body',SweptSolid],(#271));
#271= IFCEXTRUDEDAREASOLID(#269,#270,#32,999);
#269= IFCRECTANGLEPROFILEDEF(.AREA.,$,#268,600.,600.);
#270= IFCAXIS2PLACEMENT3D(#35,#32,#28);
ENDSEC;
END-ISO-10303-21;
```

Figure A.1: Informal schema for geometry representation that is associated to IfcProduct entities

APPENDIX B

Geometric representation of IFC

The geometric representation of IFC is broad and provides different alternatives that allow the detailed representation of the *IfcProduct*, i.e. building elements. Most of geometries used for representing building elements are solid models. A Solid model is defined by the shape of an *IfcProduct*. Solid objects are closed volumes, that have both an inside and an outside, of which all interior points are connected. Solid models are always represented in 3D. The following specific solid model types are used in IFCs:

- B-rep - this represents solids by its surface boundaries. IFC B-Rep further restricts the representation type solid model to only include faceted B-rep with and without voids. B-rep models require satisfaction of the stipulated Euler formulas. No additional types of manifold boundary representations other than faceted B-rep are currently within the scope of IFC edition 2x3.

- SweptSolid - this further restricts the representation type solid model to only include swept area solids, including both SweptSolid by extrusion and SweptSolid by revolution; i.e. the SweptSolid by extrusion is formed by taking a line or a surface and extruding it to form a volume. The revolution SweptSolid representation is defined by taking a surface and rotating it around an axis.

- CSG - this is an approach that uses simple primitives of spheres, cubes and cylinders for 3D representation. It restricts the representation type solid model to only include Boolean results of operations between solid models, half spaces and other Boolean results. Operations include union, intersection and difference.

- Clipping - this further restricts the representation type CSG to only include Boolean results resulting in the clipping of a solid, and thus restricts the Boolean operation to difference and the second operation to a half-space solid.

APPENDIX C

CityGML UtiltiyNetworkADE semantics

The following defintions of different UtilityNetworkADE classes. It's based on UtilityNetworkADE standard (Becker et al., 2010b)

- _NetworkFeature: provide the actual topographical representation of utility network objects such as tubes, lines, connecting pieces, switchgear cabinets, etc. *_NetworkFeature* is the base class for the thematic modeling of concrete utility networks. Therefore, independent sub-class hierarchies can be put into place directly below *_NetworkFeature* for the modeling of relevant objects in power, gas or water utilities.

- Network: Network is a collection or arrangement of items (*_NetworkFeature* or *NetworkGraph*) to resemble a utility network.

- FeatureGraph: is a structure that represents a *_NetworkFeature* as set of *nodes* and *edges*.

- NetworkGraph: is a composition of linked real-world objects to form a network.

- Node: is the dual representation of a real-world phenomenon for a point-like object; for instance, a terminal in a computer network. There is a distinction between interior and exterior nodes. An interior node is used to connect edges within the *InteriorFeatureGraph*, whereas the exterior node is used as port or connection to link different features to each other.

- _Edge: is the element which links two nodes to each other to form a *FeatureGraph* or a *NetworkGraph*.
- InteriorFeatureLink: is the element links the interior and exterior nodes of one *_NetworkFeature* to each other, so as to form a *FeatureGraph*.
- InterFeatureLink: is the element which connects the exterior nodes of two or more *_FeatureGraph* instances to form a *NetworkGraph*. The *_FeatureGraph* instances must belong to the same Network.
- NetworkLink: is the element to connect different *NetworkGraphs* to each other to form a Multi-Modal (multiutility) Network.

APPENDIX D

CityGML building class

The following two digrams are taken from the CityGML standard and represent the building class. The building class allows the representation of thematic and spatial aspects of buildings, building parts and installations in four levels of detail, LOD1 to LOD4.

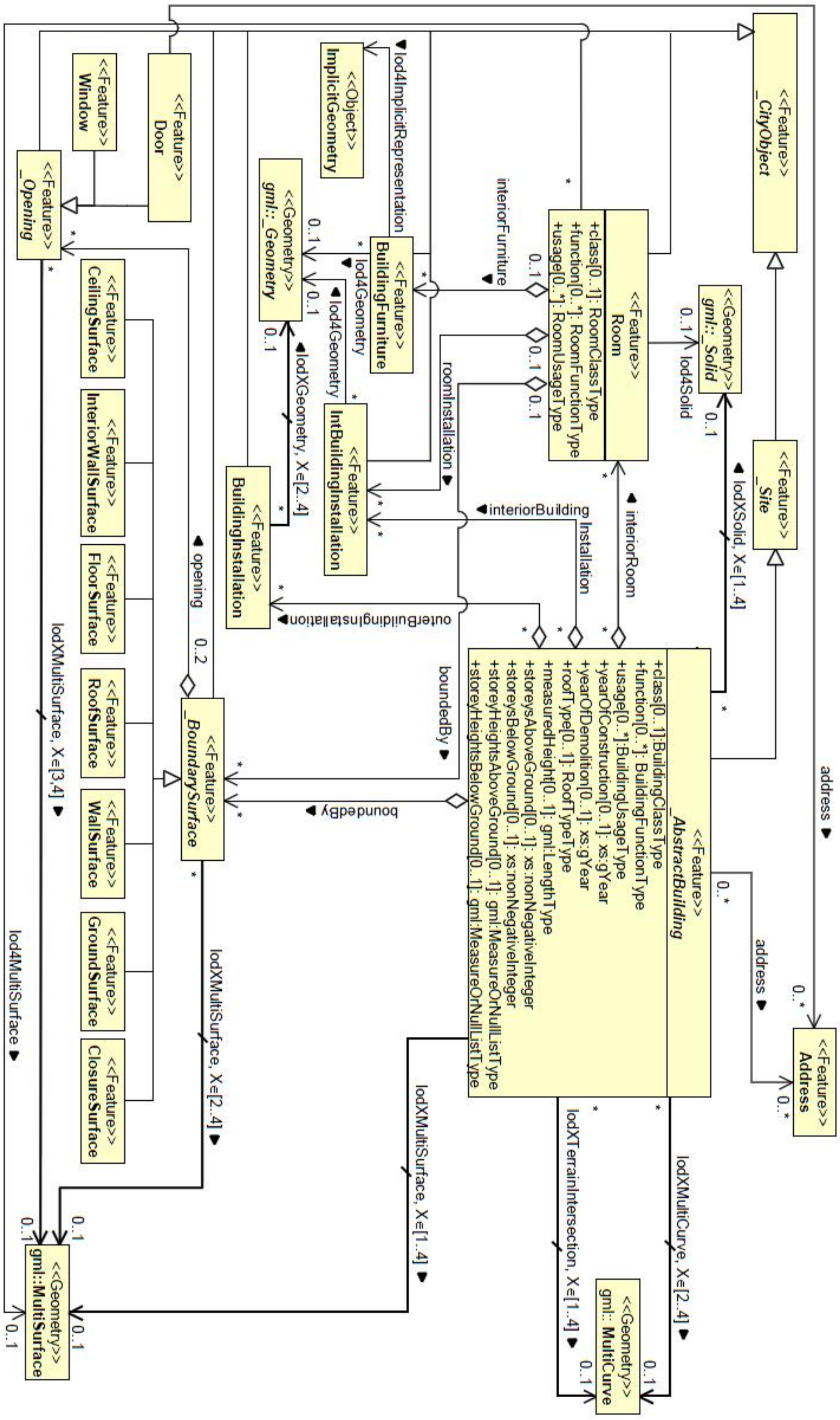


Figure D.1: UML diagram of CityGMLs building model, part 1: pivotal class AbstractBuilding, Room, and thematic surfaces.

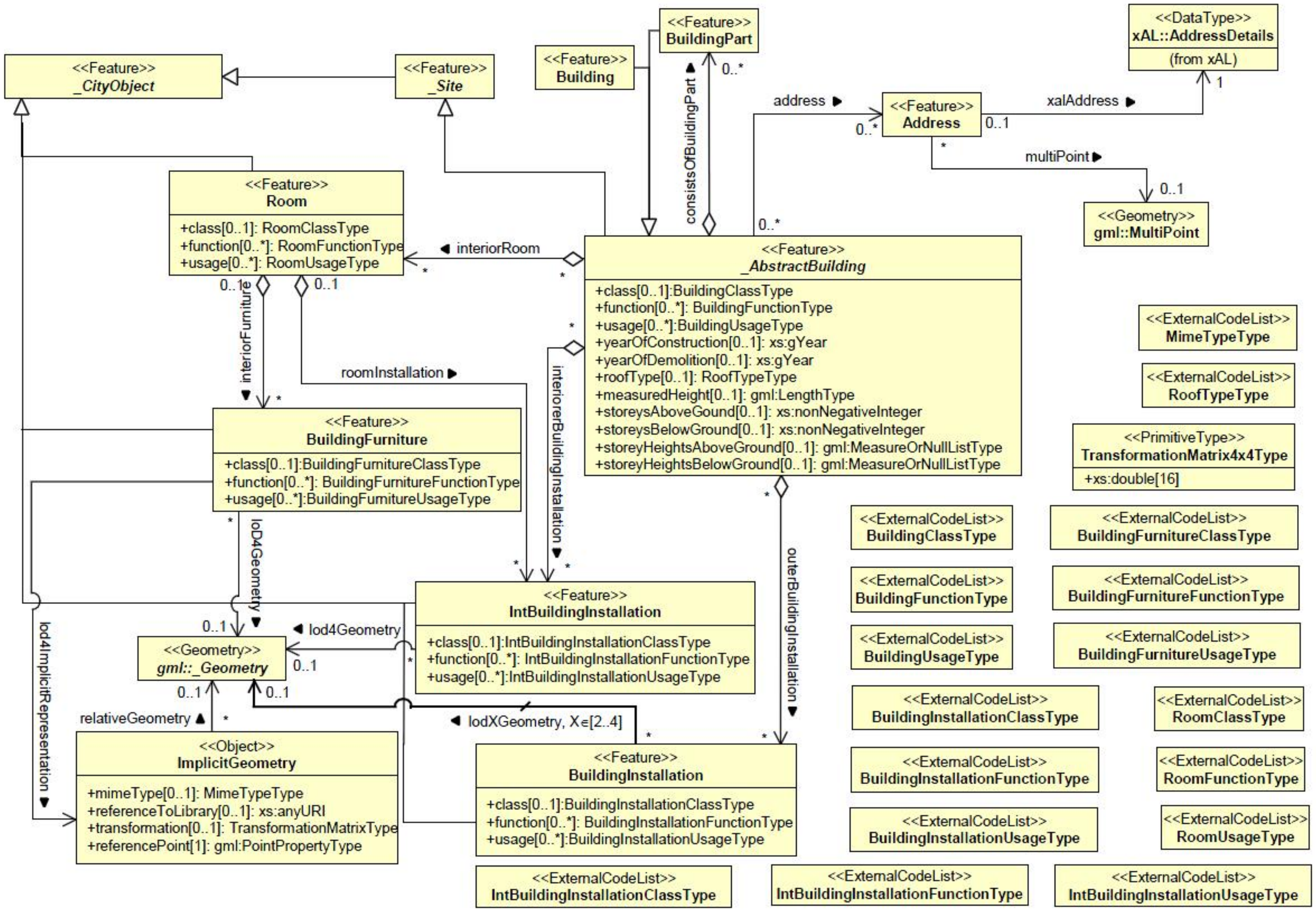


Figure D.2: UML diagram of CityGMLs building model, part 2: Building, BuildingPart, BuildingInstallation, IntBuildingInstallation, BuildingFurniture, and Address.