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USING VOLUNTEERED GEOGRAPHIC INFORMATION FOR AN AUTOMATED PROVISION OF INDOOR LOCATION BASED SERVICES

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This dissertation is dedicated to my parents

for their endless support

and encouragement

"I believe in intuition and inspiration. Imagination is more important than knowledge. For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution. It is, strictly speaking, a real factor in scientific research"

by Albert Einstein, In Cosmic Religion: With Other Opinions and Aphorisms (1931), p. 97

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Abstract

Using Volunteered Geographic Information for an Automated Provision of Indoor Location Based Services

<u>Keywords</u>: *3D City Models, CityGML, Crowdsourced Geodata, Evacuation Simulation, Indoor Geodata, Indoor Routing, Indoor Spaces, OpenStreetMap, IndoorOSM, Routing Graph, Volunteered Geographic Information*

In the last years, urban built environments and the individual buildings grew tremendously, and with the increasing size of the buildings also the internal structure gets bigger and more complex. Furthermore, people in developed countries spent most of their time in indoor spaces, often confronted with foreign and unknown buildings. Therefore, both research and economy see an emerging field in indoor location based services (LBS) which allow for exploring built environments not only from the outside, but also from the inside. However, the increasing demand for indoor information cannot yet be satisfied and commercial data providers cannot capture detailed indoor geodata on a large scale. Regarding the outdoor environment, it has been proven that crowdsourced geodata or volunteered geographic information (VGI) is able to stimulate the demand for geodata whereby – especially in urban areas – both the quantity and quality of VGI is able to compete or sometimes even surpass proprietary data of public authorities or commercial data providers. Especially OpenStreetMap (OSM) as one of the most prominent VGI communities has proven to be utilizable in professional and standard-based geographic information systems (GIS) for various application domains, such as urban planning, route computation or evacuation simulation. Trying to use the phenomenon of VGI and to benefit from humans acting as major information providers, it is therefore important to furthermore develop methodologies for crowdsourcing geodata and information about indoor environments. This will counteract the increasing demand for indoor geodata and furthermore provide a global and open access to detailed information about urban built environments and their indoor spaces. Within this thesis, an extensive and comprehensive methodology for crowdsourcing detailed geometries and (semantic) information of buildings and their interior structures in OSM is introduced. With the existing OSM data schema and this newly invented IndoorOSM methodology it is possible to automatically generate standard-based CityGML models, turning (Indoor)OSM into a major data source for professional (and standard-based) applications and analyses, such as navigation, environment simulations, emergency preparedness and response, architecture or city planning. Thereby – depending on individual requirements and the scale of the applications – models with different Level-of-Details (LoDs), ranging from coarse blocks models up to detailed models with interior structures, can be automatically generated. In addition, this IndoorOSM data can be used for automatically generating a length-optimal routing graph for complex indoor environments. In combination with such a graph, two application examples demonstrate the manifoldness and large potential of IndoorOSM. The first application demonstrates the development of an indoor route planning service for computing individual routes in a multi-level building, whereby the developed application is ubiquitously accessible in common browsers via a web-based 3D application. The second applications discussed the utilization of crowdsourced indoor geodata for complex multi-agent indoor evacuation simulations. For static aspects of the building and the geometry, IndoorOSM is perfectly suitable, whereas in contrast fast-changing dynamic aspects, such as building population or moving objects, cannot be simulated when purely using crowdsourced indoor geodata. This thesis concludes that extending OSM with IndoorOSM allows moving significantly forward to the major goal of “Using VGI for an automated provision of Indoor LBS”. Without expensive data acquisition or license costs, both standard-based 3D city models and indoor LBS can be generated fully automatically.

Kurzbeschreibung

Verwendung von freiwillig zusammengetragenen geographischen Informationen zur automatischen Bereitstellung von ortsbezogenen Diensten für Innenräume

In den letzten Jahren sind Städte und deren einzelne Gebäude immer größer geworden. Mit der wachsenden Höhe und Größe von Gebäuden, werden auch deren innere Strukturen größer und komplexer. Es hat sich außerdem gezeigt, dass Menschen in entwickelten Ländern den Großteil ihrer Zeit im Inneren von Gebäuden verbringen, wobei sie sich oftmals auch in fremden und unbekannten Gebäuden aufhalten. Sowohl die Forschung als auch die Wirtschaft sehen deshalb einen aufkommenden Markt im Bereich der ortsbezogenen Dienste für Innenräume (auch Location Based Services oder kurz LBS) welche es ermöglichen, bebaute Umgebungen nicht nur in Bezug auf das Äußere zu untersuchen, sondern auch deren Innenräume zu erkunden. Die ansteigende Nachfrage nach Informationen über Innenräume kann allerdings bisher nicht befriedigt werden und kommerzielle Datenanbieter sind nicht in der Lage Innenrauminformationen großflächig zu sammeln und anzubieten. In Bezug auf Geodaten über den Außenbereich wurde bereits bewiesen, dass freiwillig zusammengetragene geographische Informationen (auch Volunteered Geographic Information oder kurz VGI) genutzt werden können, um die Nachfrage nach Geodaten zufrieden zu stellen. Speziell in städtischen Gebieten hat sich außerdem gezeigt, dass VGI sowohl in Bezug auf Menge als auch auf Qualität, vergleichbar und teilweise sogar umfangreicher als eigene Geodaten von öffentlichen Behörden oder kommerziellen Datenanbietern sind. Insbesondere Daten aus OpenStreetMap (OSM) – eines der bekanntesten VGI Projekte – können bewiesenermaßen für professionelle und standard-basierte Geographische Informationssysteme (GIS) in vielen verschiedenen Anwendungsfelder wie etwa städtebauliche Planung, Routenberechnung oder Evakuierungssimulationen, genutzt werden. Um das Phänomen des VGI zu nutzen und von Menschen als eigenständige Daten- und Informationsanbieter zu profitieren, ist es wichtig Methodiken für das kollektive Sammeln von Daten und Informationen über Innenräume, zu entwickeln. Dies wirkt zum einen der steigenden Nachfrage nach Daten über Innenräume entgegen und zum anderen ermöglicht es einen globalen und offenen Zugriff auf detaillierte Informationen über Städte und deren Innenräume. Im Rahmen dieser Doktorarbeit wurde eine umfangreiche und vielfältige Methodik für die kollektive und kollaborative Erfassung von detaillierten Geometrien und (semantischen) Informationen von Gebäuden und deren Innenräumen in OSM entwickelt. Basierend auf dem bestehenden OSM Datenschema und dieser neuartigen IndoorOSM Methodik ist es möglich, standard-basierte CityGML Modelle voll-automatisiert zu erzeugen. Dies macht (Indoor)OSM zu einer wichtigen Datenquelle für professionelle (und standard-basierte) Anwendungen und Analysen, wie etwa Navigation, Umweltsimulationen, Notfallvorsorge und Gefahrenabwehr, Architektur- oder Stadtplanung. Abhängig von den individuellen Anforderungen sowie dem Maßstab der Anwendung, können Modelle mit verschiedenen Detailgrad (auch Level-of-Detail oder kurz LoD) automatisiert erzeugt werden. Der Detailgrad reicht dabei von einfachen Klötzchenmodellen bis hin zu detaillierten Gebäudemodellen mit Innenräumen. Darüber hinaus können IndoorOSM Daten auch für die automatische Generierung von optimalen, längentreuen Routinggraphen for komplexe Innenräume genutzt werden. In Verbindung mit einem solchen Routinggraphen, wird anhand von zwei exemplarischen Anwendungen die Vielfältigkeit sowie das Potential von IndoorOSM veranschaulicht. Die erste Anwendung demonstriert die Entwicklung eines Dienstes für die Berechnung von individuellen, kürzesten Wegen in einem Gebäude mit mehreren Stockwerken. Dieser Dienst kann mittels einer web-basierten 3D Anwendung von nahezu jedem beliebigen Computer oder Smartphone bequem im Browser genutzt werden. Der zweite Anwendungsfall betrifft die Nutzung von kollaborativ zusammengetragenen Innenrauminformationen für die komplexe Simulation der Evakuierung mehrerer Personen in einem Gebäude. IndoorOSM eignet sich bestens für die Beschreibung von statischen Aspekten und der Geometrie eines Gebäudes, wohingegen schnelllebige und dynamische Aspekte, wie etwa aktuelle Bevölkerungszahlen eines Gebäudes oder sich bewegende Objekte, nicht zufriedenstellend simuliert werden können wenn nur kollaborativ gesammelte Geodaten zum Einsatz kommen. Durch die Erweiterung von OSM mit IndoorOSM, können wesentliche Schritte in Richtung des Ziels der “Verwendung von freiwillig zusammengetragenen geographischen Informationen zur automatischen Bereitstellung von ortsbezogenen Diensten für Innenräume” gemacht werden. Ohne eine teure Datenbeschaffung oder Lizenzkosten können sowohl standard-basierte 3D Stadtmodelle als auch ortsbezogenen Dienste für Innenräume voll-automatisiert erzeugt und bereitgestellt werden.

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1 Introduction

1.1 Motivation

Within the last years, urban environments and built areas grew tremendously – not only in terms of extent but also regarding the height. Thereby, not only the urban areas themselves grow, but also the individual (newly built) buildings. That is, public, commercial and private buildings become higher and bigger and therefore also their internal structure also gets more complex. It already seems as if there is an unexpressed competition for constructing the largest and most sophisticated buildings, and architects, institutions, cities and countries are trying to overtrump each other. According to *Wikipedia (2012a*), *Wikipedia (2012b*) and *Wikipedia (2012c*) some of the (publically accessible) largest buildings of the world are the *Burj Khalifa* with a height of 830 meters and 189 floors, *Terminal 3* in Dubai with 1,500,000 m^2 floor space, the Wholesale *FloraHolland* with a floor space of nearly one million square meters, the *Las Vegas Venetian Resort* with more than 7,100 rooms, the *Mall of America* with more than 520 shops or the *Warren G. Magnuson Health Sciences Building* with approximately 533,000 m^2 floor space. These examples are somehow extreme ones, but it is apparent that also ordinary buildings in our surrounding grow, thus that their internal complexity increases. Therefore, the opportunity to *"explore built environments moving from the inside of buildings to the whole metropolis"* (*Craglia et al. 2012*) becomes more important. There is an increasing attention on indoor applications in science (*Jensen et al. 2011*) and there is a huge demand for indoor information which cannot yet be satisfied (*Kolbe et al. 2008a; Winter 2012*). This demand is furthermore driven by the fact that people in developed countries spend most of their times indoors: a study of the *American Physical Society APS (2008*) revealed that the average North American spends about 90% inside buildings. It seems very likely that similar rates are valid for other developed countries, such as Germany or France, as well as in megacities. It can be stated that with people spending so much time indoors, they are also often confronted with foreign and unknown building structures, and there is a strong need for proper guidance inside such buildings (*Raubal & Egenhofer 1998; Holscher et al. 2006*). Therefore, there is a great potential in indoor information systems and services, such as indoor routing, indoor location based services (LBS), or facility management, and also global companies, such as *Bing (2011*), *Google (2011)* or *Navteq (2011)*, are trying to gain traction in this field.

As stated above, there is an increasing need and demand for information about indoor spaces which cannot yet be satisfied. One possibility for solving this issue would be to extend established and successful Volunteered Geographic Information (VGI) communities towards indoor spaces. VGI (also known as crowdsourced geodata) is a special type of user-generated content (UGC) – an increasingly powerful and growing phenomenon of the Web 2.0. In contrast to normal UGC communities (mentioning Wikipedia as probably one of the most successful one) the term VGI describes that users – both amateurs and professionals – collect geo-referenced data rather than ordinary data. Couple of years ago, *Goodchild (2007)* stated that there is an enormous potential arising from "*billions of humans acting as remote sensors*". Furthermore, VGI has been titled to represent a "*paradigmatic shift in how geographic information is created and shared and by whom, as well as its content and characteristics*" (*Elwood et al. 2012*).

There are quite a lot of different VGI communities, such as *Flickr*, *Google Map Maker*, *FixMyStreet*, *Foursquare* etc., whereby those all vary regarding the type of collected data, the data granularity and the usage license. In contrast to the aforementioned communities – in which the community members are typically data providers but no real consumers (in terms of developing own applications with the data) – there is one big community which essentially enables arbitrary users to download and use the data at no charge: OpenStreetMap (OSM). That is, the data of OSM can be downloaded and used for individual purposes, such as the provision of an Open Geospatial Consortium (OGC) Web Map Service (WMS) or Web3DService (W3DS), free of charge. This represents an enormous source of free and open geodata. In contrast to many other VGI communities, OSM does not only contain geo-referencing information (such as a picture with longitude and latitude) but real two-dimensional (2D) geometries. That is, the members of OSM – currently there are more than 650,000 (*OSM 2012a*) of them – do provide real geometries, such as points, linestrings or polygons. Furthermore, OSM community members do also contribute additional (semantic) information, such as names, addresses, building types etc., which describe the different objects in more detail. It has already been demonstrated that crowdsourced geodata from OSM can serve as a major data source for complex applications and analyses with Open Geospatial Consortium (OGC) standard technologies, such as Web Map Services (*Goetz et al. 2012*), Open Location Services and Routing Applications (*Neis & Zipf 2008*) or Web 3D Services (*Over et al. 2010*) in 3D Spatial Data Infrastructures (SDIs, *cf. Zipf et al. (2007*)). Furthermore, it has also been revealed by *Zielstra & Zipf (2010*), *Haklay (2010*) and *Neis et al. (2012*) that – especially in urban areas – VGI from OSM features a good quality and completeness (with regional variations) and is therefore able to compete or even surpass commercially collected geodata from commercial data providers or public authorities.

Trying to combine the phenomena of VGI with the need for detailed indoor information, this work concentrates on the possibilities of crowdsourcing information about indoor environments in OpenStreetMap. Thereby, it is important to collect detailed information about both the geometry and the semantics of an indoor environment. In doing this, VGI (and OSM) will become an even more important and powerful data source, and furthermore the philosophy of free and open access to (geo-) data will be manifested. Taking into account that today's Geographic Information Systems (GIS) are more and more distributed, as well as (open) standard-based, the need for standard-based or standard-compatible data sources becomes evident. It is of high importance that future (open) data sources follow open standards or are transferable to those, because this allows a ubiquitous and universal utilization of different data sources in various kinds of applications, application domains and analyses. Despite the fact that official data needs to be acquired, which typically is subject to monetary costs, it is furthermore obvious that official data sources feature long updating cycles. Taking into account that our world is fast changing, whereas recent and up-to-date information is required for reasonable decisions or planning activities, it therefore becomes even more obvious that crowdsourced (and crowd monitored) data can surpass officially collected data. That is, both application developers and consumers will benefit (and potentially profit) from using crowdsourced indoor information as an (additional) data source for their (standard-based) applications.

1.2 Research Methods and Objectives

Within this thesis, the development of indoor space oriented applications, such as indoor routing, indoor evacuation simulations or 3D indoor model generation, is conducted. The principle workflow for the development of such applications is depicted in Figure 1-1. As a first step, spatial data is acquired via several techniques, such as GPS measurements, field surveys, Light Detection and Ranging (LiDAR) etc. In addition to that, local knowledge (especially about semantics) is added on top to the acquired data. By processing this data, spatial data is stored in some kind of common format. For example, the hand-made drawings and measurements of an architect are typically transformed into a Computer Aided Design (CAD) plan, or an OSM member uploads his GPS data to the OSM community.

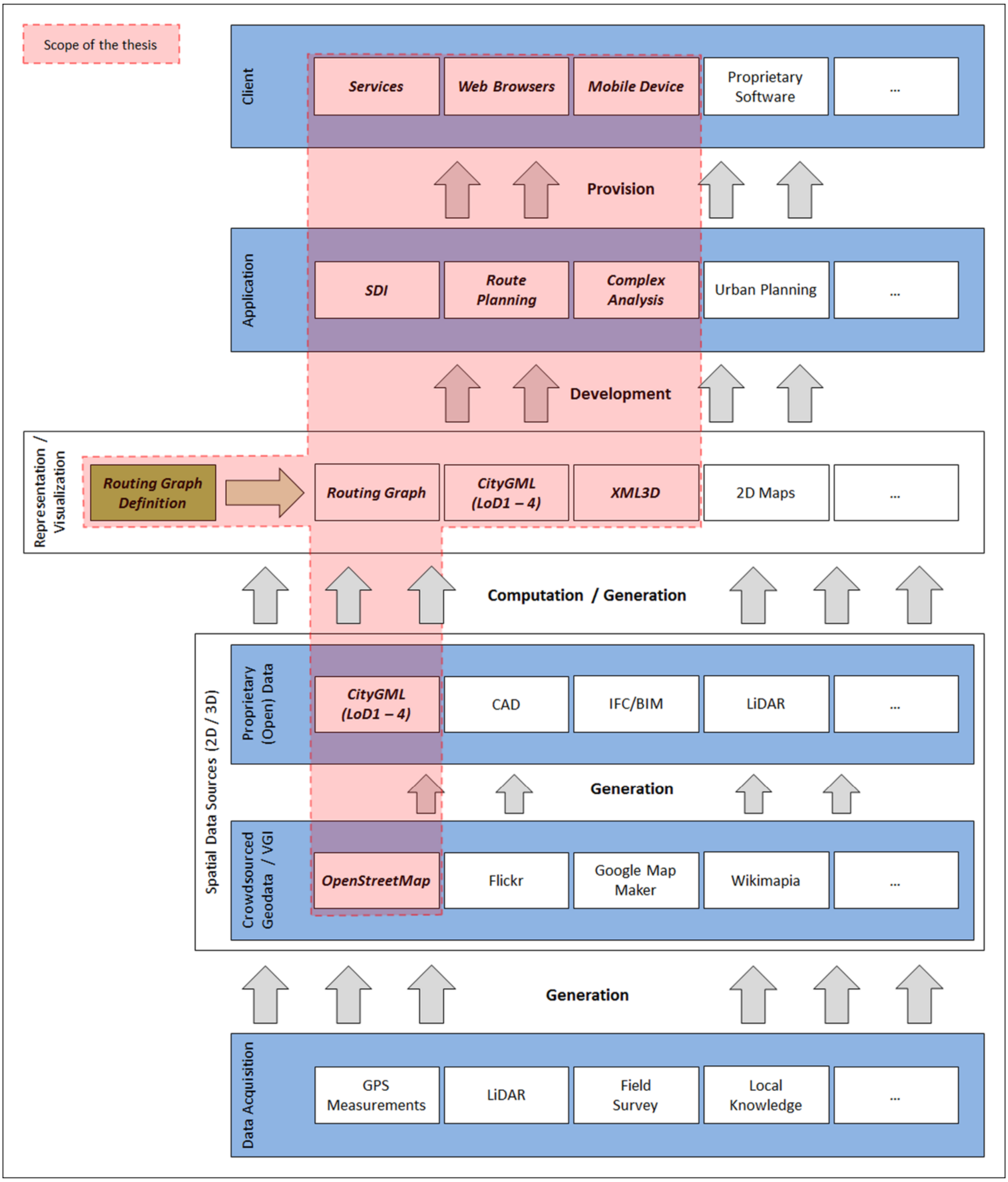

Figure 1-1. Principle workflow from data acquisition, to spatial data sources (data management), to data representation, to visualization, for different types of applications, consumable via different kinds of services/client devices. The red square emphasizes the scope of research.

Basically, this edited spatial data can be divided into crowdsourced geodata which is typically stored in a community, such as OSM or Flickr, and proprietary data formats, such as CityGML or CAD. However, also standard-based formats can be available as open data, but those are typically not crowdsourced.

Based upon this data, various representations and information can be derived from the different data sources, whereby comprehensive processing and computation efforts are required. Depending on the corresponding application area, such as indoor route planning, urban planning or the usage within SDIs, different client applications can be developed for the actual consumption of the geodata.

The focus of the here conducted research (which is visually emphasized by the red box in Figure 1-1) evolved from the necessity to satisfy the beforehand elaborated demand for detailed indoor information. As a potential and yet very promising data source for satisfying this demand, crowdsourced indoor geodata has been chosen. Such data can potentially be used as an additional (or alternative) data source for the creation of applications dealing with indoor environments, such as indoor routing, indoor evacuation simulations or 3D building models with indoor features for SDIs. Furthermore, using VGI is a very cost-effective solution, because it is typically available at no charge. Moreover, due to the crowd intelligence, it is likely that VGI is more recent than proprietary data sources.

1.2.1 Crowdsourced Geodata from OpenStreetMap

For the conduction of this dissertation it has been decided to concentrate on VGI from OSM. Thereby, several reasons and arguments have been considered:

At first – in contrast to other crowdsourcing geo-communities, such as *Google Map Maker* (*Google 2012a*) – OSM provides unlimited access to the underlying raw data. That is, the data can be downloaded by everyone. Essentially, everybody can download as much data as desired from every region in the world. Furthermore, the data download can be performed anonymously via several platforms, such as the OSM webpage (*OSM 2012b*), the OSM Application Programming Interface (API) (*OSM 2012c*) or the OSM download page (*OSM 2012d*). Additionally, various data providers, such as *Geofabrik (2012)*, offer OSM data extracts for different continents, countries or regions. In contrast to that, in *Google Map Maker* for example (*Google 2012b*), users have to apply for the download of a distinct region – a tedious process which takes some time and additionally is not always granted.

Second, OSM is one of few communities offering real 2D geometries, rather than providing geo-referenced images, information or the like. That is, when downloading the data one gets 2D geometries of the different objects with semantics attached to it. Therefore, a comprehensive preprocessing of the data (as for example the extraction of building footprints from images (*Shackelford 2004; Sahar et al. 2010*)) is not required.

Third, OSM does contain 3D information, such as the height of a building or its roof shape. Again, this data – if provided – can be used directly, for example for the generation of 3D city models (*Over et al. 2010; Goetz & Zipf 2012a*, *2012c; Uden et al. 2012*), and does not need to be extracted beforehand.

Moreover, it has already been demonstrated that OSM can serve as a (alternative or additional) data source for the development of different outdoor-related applications, such as online maps (*Goetz et al. 2012*), routing services for vehicles and pedestrians (*Neis & Zipf 2008*), routing for wheelchairs (*Müller et al. 2010*), traffic flow simulations and analyses (*Zilske et al. 2011*) or 3D virtual city models (*Over et al. 2010; Goetz & Zipf 2012a, 2012c; Uden et al. 2012*). Furthermore, it has been demonstrated that – with regional variations – the quantity and quality of OSM is comparable to official data sources (*Haklay 2010; Helbich et al. 2010; Neis et al. 2012*). Additionally, it has been revealed that in some regions OSM even exceeds the information amount and granularity of proprietary data sets, as for example in Germany OSM contains 27% more roads than a comparable proprietary dataset (*Neis et al. 2012*).

Despite its success in mapping the outdoor environment, OSM did not yet gain traction in mapping indoor spaces. Therefore, the first objective of this thesis is to develop an extensive and comprehensive indoor mapping schema for OSM (*cf.* Chapter 6). Thereby, it needs to be considered that the schema on the one hand contains detailed information about the geometric, topologic and semantic characteristics of indoor environments, but on the other hand is still easy to understand for non-professional OSM contributors. Thereby, not only 2D aspects but also 3D information, such as the height of a room or a door, shall be integrated. Another important requirement is that the mapping schema is based on existing OSM mapping methodologies and data structures, because this allows a smooth and straightforward integration into the existing OSM system environment and its tools. The integration of indoor data into OSM establishes a new (powerful) data source for a multitude of applications, such as indoor routing or 3D indoor model generation.

1.2.2 Representing and Exchanging 3D City Models in Spatial Data Infrastructures

Today's GIS are typically distributed in SDIs which provide an interoperable access to various kinds of spatial data (*Craig 2005*). Thereby, not only 2D information, but also 3D data is provided, furthermore turning ordinary SDIs into 3D-SDIs (*Zipf et al. 2007*). For a ubiquitous accessibility to 3D city models for different applications, such as 3D globe visualization or urban planning, the Special Interest Group 3D (SIG 3D) developed the City Geography Markup Language (CityGML) for representing urban objects (*Kolbe et al. 2005*). In contrast to other 3D data formats, such as Virtual Reality Modeling Language (VRML) or Extensible 3D (X3D), CityGML does not only visualize geometric information, but also contain semantic information about the building and it's individual parts. That is, CityGML can also be used for conducting complex analyses about urban areas (*Winter 2012*). For satisfying the varying demands of different applications (in terms of data granularity), CityGML provides specific Level-of-Details (LoDs) which vary regarding information resolution and generalization. The LoD concept comprises a total of five classes (as depicted in Figure 1-2) ranging from a strictly terrain-focused visualization without any buildings (LoD0), over coarse building blocks models (LoD1) up to highly detailed building models including interior features (LoD4).

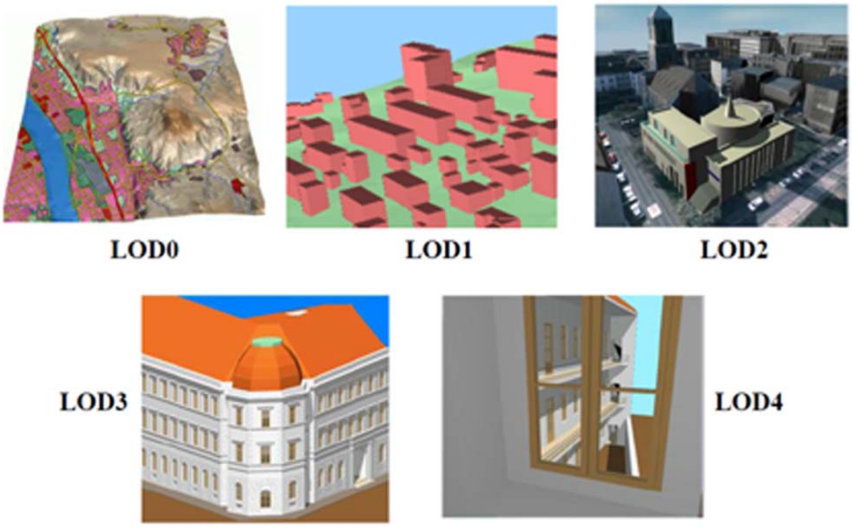

Figure 1-2. The five different Level-of-Details in CityGML (Gröger et al. 2008).

Today, CityGML is the international OGC standard for exchanging semantically enriched 3D city models in SDIs and more and more cities and municipalities generate and publish their 3D city models as CityGML datasets, such as for example *Rotterdam (2012)*. However, most of those model do not contain indoor information, as they are typically generated automatically from LiDAR (*Malambo & Hahn 2010*) or aerial imagery (*Falkowski et al. 2009*). In contrast, the models with indoor features are typically generated manually by using 3D modeling software and converting those to CityGML (*e.g.*, with Sketchup as described by *Geores (2012)*). Considering standards for the representation of buildings in the Building Information Modeling (BIM) domain, it has already been discussed that Industry Foundation Classes (IFC) can be transferred into CityGML models (*Isikdag & Zlatanova 2009; Hijazi et al. 2009*), but IFC is normally also not available as open data on a large scale.

The second research objective of this dissertation aims to develop a transformation framework from OSM to CityGML. Thereby, an extensive state-of-the-art report on existent OSM datasets (*i.e.*, OSM data without the developed indoor extension) is conducted for investigating the initial situation. It is investigated what information of CityGML can already be populated from OSM, and what information is still missing (*cf.* Chapter 5). Thereby, both the semantic information and the geometric aspects of the building models are considered. Building upon the newly invented indoor extension for OSM (*cf.* Chapter 6), the automatic procedural generation of detailed CityGML models with interior spaces is discussed, as well as limitations and restrictions of the crowdsourced indoor geodata in OSM (*cf.* Chapter 7). That is, it will be demonstrated that VGI from OSM is utilizable for automatically generating detailed CityGML models with indoor spaces, applicable in standard-based applications and SDIs.

1.2.3 Graph-based Indoor Route Planning

The task of routing, not only indoors but also outdoors, can be generalized to the problem of finding the shortest path (according to a distinct parameter) in a network. Therefore, routing is a classic application field of shortest-path algorithms such as the Dijkstra algorithm (*Dijkstra 1959*) or the faster A* algorithm (*Hart et al. 1968*). For sure, utilizing one of those algorithms for route calculation requires the creation of a proper route network beforehand. For outdoor and vehicle routing, this network is mostly obtained from the street network, usually provided by surveyors or cartographers (*Frank 2007*), as well as VGI contributors (*Schmitz et al. 2008*). However, for indoor environments there is not such a thing like a street network, thus there are methodologies and frameworks required for the creation of an indoor routing graph. Nevertheless, indoor routing is an essential technique often requested by users, providing them with proper routes and route descriptions within buildings (*Dudas et al. 2009*). There are various graph models available, as for example described by *Raubal & Worboys (1999)*, *Lee (2004)*, *Lorenz et al. (2006)*, *Stoffel et al. (2007)* or *Yuan & Schneider (2010)*, which mainly vary in granularity. However, they do not discuss relevant details of indoor environments, such as obstacles or walls inside rooms, different areas in a room, or directed paths in indoor environments (*e.g.*, security controls), although such details can increase navigation accuracy. Furthermore, there is no formal definition of any of those graphs available yet.

Therefore, the third research objective of this dissertation is to develop a formal definition of a detailed routing graph for indoor route planning in complex indoor environments (*cf.* Chapter 8). By defining a weighted indoor routing graph in a formal way, it is possible to create a detailed and user-adaptive model for route computation. With such a graph, it will furthermore be possible to compute length-optimal routes between arbitrary points in multi-level indoor environments.

1.2.4 Indoor Location Based Services and Simulations

In recent years, both research and economy started to adapt well-known LBS (*e.g.*, route planning) and complex analysis (*e.g.*, evacuation simulation) from outdoor environments to indoor environments. The so far developed applications and services, as for example *Gilliéron & Bertrand (2003*), *Inoue et al. (2008*), *Ruppel & Gschwandtner (2009*), *Bing (2011*), *Google (2011*) or *Navteq (2011*), provide basic route computation functionality with a 2D representation. Those examples for indoor route planning, as well as the existing indoor evacuation simulations, as for example described by *Hajibabai et al. (2007*), *Shi et al. (2008*), *Okaya et al. (2009*) or *Yamashita et al. (2009*), are furthermore mainly based on proprietary data sources. The major disadvantage of such proprietary data is reasoned by the facts that different sources for indoor information typically have various kinds of data formats, different granularity, are they furthermore unreferenced to each other. Moreover, proprietary data is often subject to high license costs. In contrast, crowdsourced indoor geodata from OSM can be regarded as standardized (all buildings are mapped according to one mapping proposal), geo-referenced, and free of charge.

In addition to that, it furthermore needs to be stated that information about building interiors – especially in multi-level buildings – is typically 3D as several rooms or building parts overlap each other (from a bird’s perspective). Therefore, a pure 2D representation of the application is in most cases not sufficient (*Coors & Zipf 2007*). Furthermore, the specific need for 3D information for the conduction of complex simulations for indoor evacuation simulations – a complex type of multi-user LBS – from the field of emergency planning and response has been elaborated by *Zlatanova (2008*).

Therefore, the forth research objective arises as utilization of crowdsourced indoor geodata for the development of indoor LBS. This forth objective can be seen as a complement for demonstrating the power and opportunities arising from crowdsourcing indoor information. With the development of a browser-based 3D routing application (*cf.* Chapter 9) and the conduction of indoor evacuation simulations (*cf.* Chapter 10), it will be demonstrated that crowdsourced indoor geodata is not only suitable for generating CityGML building models, but also for developing and providing complex indoor routing services and analyses. These two applications will show and demonstrate the manifoldness and diversity of the developed indoor mapping proposal and furthermore underpin the potential power arising from the usage of crowdsourced indoor geodata as an additional or alternative data source for various kinds of applications.

1.3 Summary of the Research Aim

The aim of the here conducted research is to extend one of the major sources for crowdsourced geodata, namely OpenStreetMap, towards indoor environments. In doing so, the contributed information can be utilized for complex applications and analyses within standard-based environments and SDIs. Furthermore, own dedicated applications for various purposes, such as indoor route planning, can be developed based upon OSM data. As a consequence, added value is generated by using open and freely available geodata as an addition or replacement to proprietary and commercially collected information.

The goals of this thesis are defined as follows:

(1) to investigate the current possibilities of crowdsourcing indoor geodata in OpenStreetMap

(2) to develop and introduce a comprehensive but easily and quickly comprehensible mapping proposal as an extension of OpenStreetMap towards indoor environments

(3) to invent a comprehensive transformation framework from OSM to CityGML for strengthening OSM as an additional or alternative data source for 3D city models in distributed OGC web service-based GIS environments

(4) to demonstrate the manifoldness and potentials of this new indoor mapping proposal by utilizing available data for the development of complex indoor routing services and mass simulations based upon a detailed routing graph for formally representing complex indoor environments.

1.4 Thesis Outline

This Section describes the structure of this cumulative dissertation. Furthermore, additional research publications, presentations and press releases are mentioned.

1.4.1 Structure

The cumulative dissertation comprises six peer-reviewed papers (*cf.* Chapters 5-10). In addition to this, several other publications have been conducted, which furthermore complement the outline of this thesis (*cf.* Section 1.4.3).

As an initial situation, Chapter 5 (Publication 1) investigates if, and to what extent, the existent OSM data can be used for automatically generating CityGML building models. This investigation is the basis for all further developments, as it reveals what kind of data and information about buildings and their interiors is still missing in OSM. Based on the discovered lack of data, a comprehensive and detailed proposal for mapping indoor information in OSM can be developed. This extension (namely *IndoorOSM*) is presented in Chapter 6 (Publication 2). Building upon the previous two chapters, Chapter 7 (Publication 3) discusses the automatic generation of detailed CityGML building models with interior structures based on crowdsourced indoor geodata from OSM. Essentially, this demonstrates that *IndoorOSM* data can be utilized in standard-based SDIs and professional applications or services. Furthermore, Chapter 7 discusses necessary data requirements and constraints which need to be fulfilled in order to generate the CityGML models, and additionally reveals various limitations of *IndoorOSM*. Since indoor routing comprises one of the major indoor LBS, but currently there is no formal definition of a detailed indoor routing graph available, Chapter 8 (Publication 4) introduces a user-adaptive and length-optimal routing graph for complex indoor environments. For demonstrating the manifoldness and power of crowdsourced indoor geodata from OSM, Chapter 9 (Publication 5) describes the development of a web-based 3D application for indoor route planning, and Chapter 10 (Publication 6) elaborates the possibilities of using *IndoorOSM* for indoor evacuation simulations (*i.e.*, a more complex type of multiple single-routing applications). Both applications (Chapter 9 and 10) make use of the beforehand developed graph definition of Chapter 8.

Chapter 2 complements the most important findings of the single papers, discusses the cumulative results of this thesis, and additionally underlines the inherent connection between the different publications. In Chapter 3, the contributions of this thesis are concluded and an outlook on the next steps of future work is provided.

1.4.2 Selected Publications

Four of six papers have multiple authors and it has been clarified that Marcus Goetz is the lead author of all of them. The other two publications have been single authored. A detailed description on the contributions of the authors of the different papers is discussed in the corresponding chapters (*i.e.*, Chapter 5-10). All papers in this dissertation are included as they have been published. For convenience, the format has been adjusted to one equal style.

Publication 1:

Goetz, M., Zipf, A. (2012): Towards Defining a Framework for the Automatic Derivation of 3D CityGML Models from Volunteered Geographic Information. International Journal of 3-D Information Modeling (IJ3DIM), 1(2).1-16.

Publication 2:

Goetz M., Zipf A. (2011): Extending OpenStreetMap to Indoor Environments: Bringing Volunteered Geographic Information to the Next Level. In: Rumor, M., Zlatanova, S., LeDoux, H. (eds.) Urban and Regional Data Management: Udms Annual 2011. CRC Press. pp. 47-58.

Publication 3:

Goetz, M. (2012): Towards Generating Highly Detailed 3D CityGML Models From OpenStreetMap. International Journal of Geographical Information Science (IJGIS). (accepted).

Publication 4:

Goetz, M., Zipf, A. (2011): Formal Definition of a User-adaptive and Length-optimal Routing Graph for Complex Indoor Environments. Geo-spatial Information Science (GSIS), 14(2), 119-128.

Publication 5:

Goetz, M. (2012): Using Crowdsourced Indoor Geodata for the Creation of a Three-Dimensional Indoor Routing Web Application. Future Internet, 4 (2), 575-591.

Publication 6:

Goetz, M., Zipf, A. (2012): Using Crowdsourced Geodata for Agent-Based Indoor Evacuation Simulations. ISPRS International Journal of Geo-Information. 1 (2), 186-208.

1.4.3 Additional Publications

During the preparation of this thesis, I have authored or co-authored several other publications which are not part of this thesis, but are related to its context:

Jochem, R., Goetz, M. (2012). Towards Interactive 3D City Models on the Web. Special Issue of the International Journal of 3-D Information Modeling (edited by Goetz, M., Rocha, J.G., Zipf, A.) on Visualizing 3D Geographic Information on the Web 1(3), 26-36.

Goetz, M., Zipf, A. (2012). Indoor Route Planning with Volunteered Geographic Information on a (Mobile) Web-based Platform. Proceedings of the 9th Symposium on Location Based Services, Munich, Germany, 16-18 October 2012, p. 16 (accepted).

Goetz, M. (2012). OpenStreetMap – Datenqualität und Nutzungspotenzial für Gebäudebestandsanalysen. Proceedings of the 4th Dresdner Flächennutzungssymposium, Dresden, Germany, 14-15 June 2012, p. 8.

Li, M., Goetz, M., Fan, H., Zipf, A. (2012). Adapting OSM-3D to the Mobile World - Challenges and Potentials. Proceedings of the 9th Symposium on Location Based Services, Munich, Germany, 2012, p. 14 (accepted).

Uden, M., Schilling, A., Li, M., Goetz, M., Zipf, A. (2012). Creating a worldwide 3D globe from user-generated data. Paper presented at the DGFK Workshop on "Map creation from user generated data", Hannover, Germany (together with Deutscher Kartographentag), Hannover, Germany, 8 October 2012.

Goetz, M., Zipf, A. (2012). OpenStreetMap in 3D - Detailed Insights on the Current Situation in Germany. Proceedings of the AGILE 2012, Avignon, France, 24-27 April 2012, p. 5.

Goetz, M., Zipf, A. (2012). The Evolution of Geo-Crowdsourcing: Bringing Volunteered Geographic Information to the Third Dimension. In: Sui, D., Elwood S., Goodchild M.F. (eds.): Volunteered Geographic Information, Public Participation, and Crowdsourced Production of Geographic Knowledge. Springer, pp. 139-160.

Goetz, M., Lauer, J., Auer, M. (2012). An Algorithm Based Methodology for the Creation of a Regularly Updated Global Online Map Derived From Volunteered Geographic Information. Proceedings of the 4th International Conference on Advanced Geographic Information Systems, Applications and Services (GEOProcessing 2012), Valencia, Spain, 30 January - 04 February 2012 2012, pp. 50-58.

Goetz, M., Zipf, A. (2010). Open Issues in Bringing 3D to Location Based Services (LBS): A Review Focusing on 3D Data Streaming and 3D Indoor Navigation. Proceedings of the 5th 3D GeoInfo Conference, Berlin, Germany, 3-4 November 2010, pp. 121-124.

Schilling, A., Goetz, M. (2010). Decision Support Systems using 3D OGC Services and Indoor Routing – Example Scenario from the OWS-6 Testbed. Proceedings of the 5th 3D GeoInfo Conference, Berlin, Germany, 2010, pp. 159-162.

Furthermore, I have been invited to give various presentations about (parts of) my dissertation research:

Goetz, M. (2012): OpenStreetMap – Datenqualität und Nutzungspotenzial für Gebäudebestandsanalysen. 4. Dresdner Flächennutzungssymposium "Genauere Daten – informierte Akteure – praktisches Handeln". Dresden, Germany.

Goetz, M. (2012): Towards Crowdsourcing Indoor Geodata: Potentials and Applications. Lunch Meetings at the OTB Research Institute for the Built Environment (TU Delft). Delft, Netherlands.

Goetz, M. (2012): Virtuelle 3D Stadtmodelle für die moderne Stadtplanung. Stadtplanung in Deutschland. Heidelberg, Germany

Goetz, M., Hubel, A., Kerber, F. (2012): Indoor OSM - Mapping the World Indoors. FOSSGIS 2012. Dessau, Germany

Goetz, M. (2011): Converting OpenStreetMap Data to CityGML. OGC TC/PC Meetings, 3DIM. Brussels, Belgium.

Goetz, M. (2011): Qualitative und quantitative Entwicklung von Geodaten Infrastrukuren in der zweiten und dritten Dimension. 10. VoGIS Fachforum „Geodaten - Infrastrukturen?“. Feldkirch, Austria

Goetz, M. (2011): Deriving Standardized 3D City Models From Crowdsourced Geodata. Hengstberger Symposium „Towards Digital Earth - 3D Spatial Data Infrastructures“. Heidelberg, Germany

Goetz, M. (2011): Towards Defining a Framework for the Automatic Derivation of 3D CityGML Models from Volunteered Geographic Information. Joint ISPRS Workshop on 3D City Modelling & Applications and the 6th 3D GeoInfo Conference. Wuhan, China

Additionally, several posters about related work have been presented:

Jochem, A., Höfle, B., Goetz, M. (2011): Fusion of VGI and highly accurate laser scanning data for 3D city modeling. Poster @ Hengstberger Symposium „Towards Digital Earth - 3D Spatial Data Infrastructures“. Heidelberg, Germany

Lauer, J., Goetz, M., Auer, M., Zipf, A. (2011): Processing and Visualizing Dynamic Global Geo Data - OGC WMS based on VGI. Poster @ AGIT 2011. Symposium für Angewandte Geoinformatik. Salzburg, Austria.

Goetz, M., Zipf, A. (2010): Open Issues in Bringing 3D to Location Based Services (LBS) - A Review Focusing on 3D Data Streaming and 3D Indoor Navigation. Poster @ 5th 3D GeoInfo Conference. Berlin, Germany.

1.4.4 Press Releases

Various press agencies and news pages became aware of the idea of crowdsourcing indoor geodata in OSM and therefore published press releases about this idea. Furthermore, Alexander Zipf and I have been invited to write a featured article.

Goetz, M., Zipf A. (2012): Mapping the Indoor World – Towards Crowdsourcing Geographic Information about Indoor Spaces . Invited Feature Article for GIM International. March 2012, pp. 30-34.

Idealo (2012): Indoor-Navi: OpenStreetMap für Gebäude. Online Press Release by Idealo. http://news.idealo.de/news/63233-indoor-navi-openstreetmap-fur-gebaude/. Accessed 23 September 2012.

Grüner, S. (2012): Openstreetmap auch für Innenräume möglich. Online Press Release by Golem. http://www.golem.de/1201/89098.html. Accessed 23 September 2012.

Benthin, F. (2012): OpenStreetMap wendet sich Innenräumen zu. Online Press Release by Pro-Linux. http://www.pro-linux.de/news/1/17924/openstreetmap-wendet-sich-innenraeumen-zu.html. Accessed 23 September 2012.

Thurston, J. (2012): 3D Multi-Agent Indoor Evacuation Simulation with IndoorOSM. Online Blog-Post in the 3DVW Spatial Blog. http://www.3dvisworld.com/3DVW/?p=47. Accessed 23 September 2012.

2 Results and Discussion

This Chapter gives an insight into the different results of the single aspects of this cumulative thesis. In total, six different research investigations have been conducted in order to extent OSM to indoor environments and furthermore to use such data for the development of standard-based and non-standard-based (GIS) applications. As an initial situation (*cf.* publication 1, Chapter 5), the existing OSM database has been investigated regarding possibilities for automatically generating standardized CityGML building models. It has been demonstrated that OSM does not contain appropriate indoor information, thus publication two (*cf.* Chapter 6) developed an extensive indoor mapping schema for OSM. The approach presented in the third publication (*cf.* Chapter 7) utilizes such data and describes the automated generation of detailed 3D CityGML building models. Trying to demonstrate the manifoldness and opportunities arising from crowdsourced indoor geodata, this thesis furthermore investigates the development of indoor LBS. Therefore, the forth publication (*cf.* Chapter 8) defines a length-optimal and user-adaptable indoor routing graph (as for example required for indoor routing) in a formal way, namely *Weighted Indoor Routing Graph (WIRG)*. The remaining two publications combine this graph definition with crowdsourced indoor geodata and essentially demonstrate the possibilities for extracting a *WIRG* from *IndoorOSM*. Thereby, the fifth research effort (*cf.* Chapter 9) utilizes crowdsourced indoor geodata from OSM for the generation of a web-based 3D indoor routing application, while the sixth paper (*cf.* Chapter 10) evaluates the suitability of *IndoorOSM* data for complex multi-agent indoor evacuation simulations.

2.1 Crowdsourcing Indoor Information in OpenStreetMap

Applications and (Location Based) Services for indoor environments have gained more and more attention in the last years, not only in the scientific domain but also in the economy. The lately started *In-Location* Industry Alliance (*Nokia 2012*) underlines this trend. The added value gained by extending applications, such as routing or yellow-page search, to indoor environments has been realized and hence the need for detailed (3D) indoor geodata. This is also substantiated by *Kolbe et al. (2008a*), *Jensen et al. (2011)* and *Winter (2012)*. As described in Chapter 1, crowdsourcing indoor information bears an enormous potential for satisfying this demand.

However, the first publication (*cf.* Chapter 5) and especially Section 5.5.4 revealed that OSM does not contain detailed information about indoor environments. Essentially, there was no tagging schema available which enables the OSM members to contribute polygonal geometries of different rooms, to provide information about the location of doors or windows, or to arrange different rooms in a distinct level order. Therefore, the second publication (*cf.* Chapter 6) focuses on the development of a comprehensive and detailed indoor mapping schema for OSM (namely *IndoorOSM*).

As an initial situation, an extensive state-of-the-art report of existing building models is given. Thereby, the importance of not only containing geometric aspects but also semantic information is elaborated. Building upon existent models, a *3D Building Ontology* (*3DBO*) is developed and described. Thereby, the trade-off between level-of-detail and data acquisition effort on OSM side is considered, because on the one hand a scientific correctness and completeness is required for the development of applications based upon this crowdsourced data, whereas on the other hand the OSM members (typically not being professional cartographers, architects or the like) shall not be asked too much in terms of complexity. That is, the *3DBO* is designed as simple as possible, but as detailed as required. The ontology is suitable for describing both the outdoor appearance as well as the interior structure of a building. Thereby, not only geometric aspects, but also semantic information, such as room names, level usage etc., are integrated. However, being designed for the purpose of crowdsourced indoor geodata, *3DBO* does only incorporate information about the rooms and floors of a building, rather than detailed facility management information (*e.g.*, location of pipes or cables in walls etc.).

The *3DBO* describes a building as a hierarchical object (*i.e.*, a *Building*), containing several *Levels*, which consist of several *Building Parts*. A *Building Part* represents a *Room* or *Hall* (*e.g.*, an office or a lecture room), *Corridor*, *Vertical Passage* (*i.e.*, an *Elevator, Escalator* or *Stairway*), or a *Horizontal Passage* (*i.e.*, *Ramp* or *Moving Walkway*). The developed OSM indoor extension builds upon the *3DBO*. Thereby, it is important that the existing OSM data model (*i.e.*, *nodes*, *ways*, *relations*, key-value pairs) is utilized and essentially no new data types are invented, because this allows a seamless integration of the mapping schema into the existent OSM infrastructure (*e.g.*, the OSM database, the OSM editors etc.). In principle, a building is mapped as a *relation* containing one relation-member for every building level (floor). Each level is again represented as a *relation*, whereby the different building parts are added as relation-members to the corresponding level-relation. The building parts themselves are represented as polygonal structures (*i.e.*, *ways* or *relations*).

Additional information, such as the level number, names etc., is added via key-value pairs to the corresponding object. Table 6-1, Table 6-2 and Table 6-3 in publication 2 describe the different key-value pairs. Since OSM does not provide a methodology for mapping real 3D geometries, 3D information, such as the height of a room or the height of a level is added via the OSM key *height*. Doors and windows are also considered by both the *3DBO* and the OSM mapping schema, because they are important for various applications, such as routing or 3D modeling. In OSM those can be mapped by adding a single OSM *node* to one of the involved building parts (in the case of a door) or (in the case of a window) to the building shell, which represents the geometrical outline of the level. Geometric information about the door or window, such as the height, width or breast, is again added via key-value pairs.

As a proof-of-concept, the newly invented indoor mapping schema is utilized for crowdsourcing indoor geodata of a university building. For the data contribution, the OSM editor *JOSM (2012)* is utilized. However, not being explicitly designed for the purpose of crowdsourcing indoor geodata in OSM, *JOSM* did (at this point of time) not provide an easy-to-use functionality for the developed extension. Therefore, the individual building levels have been mapped in single *JOSM* files which were manually combined afterwards prior to actually uploading the data to the OSM database.

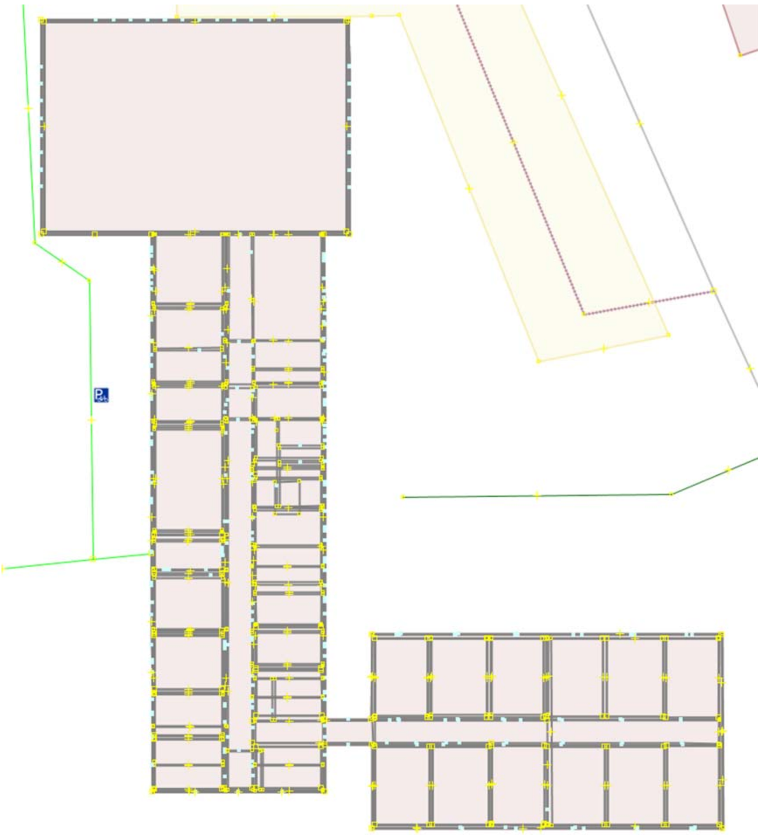

Figure 2-1. Overlapping geometries of IndoorOSM in JOSM.

One of the biggest issues (while conducting the work presented in publication 2) was that, due to the nature of a building, several features overlap each other in *JOSM*. This issue can be seen in Figure 2-1. Nevertheless, with the evolution and improvement of *JOSM*, there are now different functionalities available which ease the data contribution process. Although there is not yet an explicit indoor extension for *JOSM* available, several other functionalities enable the OSM members to contribute indoor data in a convenient manner. Essentially, newer versions of *JOSM* feature extensive filtering mechanisms which enable a user to hide distinct OSM features according to its ID, tags, role etc. In *IndoorOSM* every building level contains information about the corresponding level number (*e.g.*, *level = 1*, *level = 3* etc.) which can be perfectly used for filtering. That is, by creating a filter *child level=1* all childs (*i.e.*, relation-members) of a relation with the tag *level=1*, can be explicitly displayed or hided by the user. In other words, a user can hide or display the first floor (level 1) of a building. Since windows and doors are part of a building part geometry (*i.e.*, a child of this feature), those can be controlled via the filter *child child level=1*, *i.e.*, all doors and windows of the first floor of a building are selected. Those two mentioned rules can be furthermore combined via a logical *OR* to one filtering rule. By creating several of such rules (one for each building floor), OSM members can explicitly display a distinct building floor in *JOSM*, allowing a very convenient mapping process. Those filter rules are exemplarily visualized in Figure 2-2, whereby currently only the second floor (level 2) is visualized in *JOSM*.

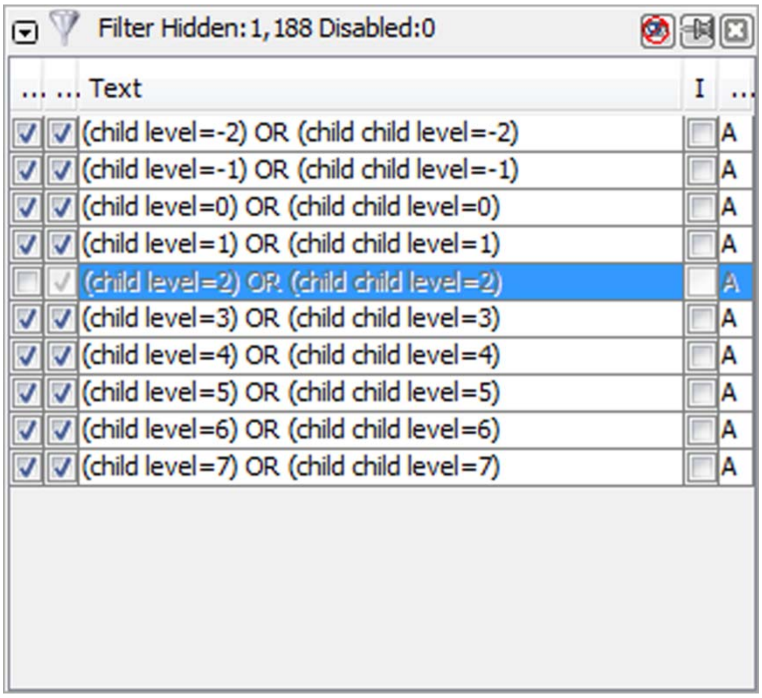

Figure 2-2. Various filters in JOSM for displaying or hiding the levels -2 to 7 of a building.

While utilizing *IndoorOSM* data for the development of various applications (which will be described in publication 3, 5 and 6), as well as presenting (*OSM 2012e*) and discussing (*OSM 2012f*) the *IndoorOSM* mapping schema with the community, several limitations, restrictions and open questions of *IndoorOSM* became apparent. For example it is not yet clear how to deal with mezzanines in a building, because *IndoorOSM* does only consider full levels. Furthermore, it needs to be stated that the ground floor is not always level 0 (as for example in the United States), which might cause some confusion to foreign mappers. Also, overhanging roofs, such as an understory, cannot be explicitly represented in *IndoorOSM*. A work-around is to map the roof as the corresponding level shell and the understory as a buildingpart with openings (*i.e.*, surface low windows) around it. However, this is not an adequate solution, thus understories leave space for improvements. Vertical connections and especially ramps, are also not yet integrated in a satisfying manner, thus should be investigated in the near future. Regarding the geometry of the building, it furthermore needs to be stated that *IndoorOSM* assumes that ceilings and grounds are always parallel and walls are always vertical. Essentially, beveled or round walls (from a vertical perspective) cannot be mapped with *IndoorOSM*.

To conclude, it can be said (as demonstrated by publication 2) that it is possible to crowdsource detailed indoor geodata in OSM by only using existent OSM methodologies. Essentially, *IndoorOSM* allows OSM members to contribute detailed information about the polygonal shape of a building and its interiors, 3D information, as well as additional (semantic) information. Although there are several limitations, it can be argued that *IndoorOSM* represents a big step towards crowdsourcing indoor geodata for various kinds of buildings, being the first mapping schema for this purpose. Furthermore, it seems likely that there will never be a schema which can represent every arbitrary shape or building. This is also the reason and motivation for researchers trying to crowdsource real 3D building models, as for example described by *Uden & Zipf (2012)*.

With *IndoorOSM*, there is a comprehensive data source for detailed indoor information available. As a next step, it will be investigated how to use *IndoorOSM* data for the generation of CityGML building models for the application within SDIs. By doing this, it will be demonstrated that detailed CityGML models with interior structures can be automatically generated.

2.2 Generating CityGML Building Models from OpenStreetMap

The first paper (*cf.* Chapter 5) introduces a framework for the automatic derivation of CityGML Models from OSM. In the very last years, it has been proven that standard-based 3D building models with semantic information are an important source or tool for various kinds of professional (GIS) applications, such as urban planning (*Shiode 2001*), mapping of environmental noise pollution (*Czerwinski et al. 2006*), city business development and tourism (*Döllner et al. 2006*), homeland security and disaster management (*Kolbe et al. 2008b*), or indoor navigation (*Mäs et al. 2006*). Furthermore, exploring indoor built environments in the context of Digital Earth (DE) becomes increasingly important, as elaborated by *Craglia et al. (2012)*.

The developed framework itself is divided into two steps: (1) a semantic mapping between key-value pairs of OSM and CityGML attributes for the automated population of CityGML attributes and (2) methodologies for the generation of CityGML geometries for the different LoDs. Regarding the semantic mapping, three different classes of relations are defined: (1) one OSM key fits to one CityGML attribute, (2) several OSM keys fit to one CityGML attribute, and (3) there is no suitable key in OSM for a CityGML attribute. By investigating the existent OSM dataset, it becomes apparent that nearly every CityGML attribute (except *bldg:yearOfDemolition*) can be populated from OSM data. The attributes *bldg:class*, *bldg:function*, *bldg:usage*, *bldg:measuredHeight*, and *bldg:roofType* have several potential counterparts in OSM, thus a careful selection of the appropriate OSM key is required. In contrast, all other CityGML attributes can be directly populated from one single OSM key. The CityGML attributes *bldg:storeysHeightsAboveGround* and *bldg:storeysHeightsBelowGround* cannot directly be populated, but approximated by considering several OSM keys (*e.g., levels:aboveground*). The generation of CityGML geometries varies with the LoD. By extruding the building footprint with the height of the building (*i.e.*, OSM key *height*) a simple blocks models (LoD1) can be generated automatically. In contrast, for the generation of LoD2 models with detailed roof structures, more information from OSM is required. By investigating different roof-related OSM keys (*e.g., building:roof:shape*, *building:roof:angle*, *building:roof:height*, *building:roof:extent* etc.), visually appealing and realistic roof geometries can be generated, for example by using skeleton computation with procedural extrusion (*Laycock & Day 2003; Kelly & Wonka 2011*). Two examples are given in Figure 2-3.

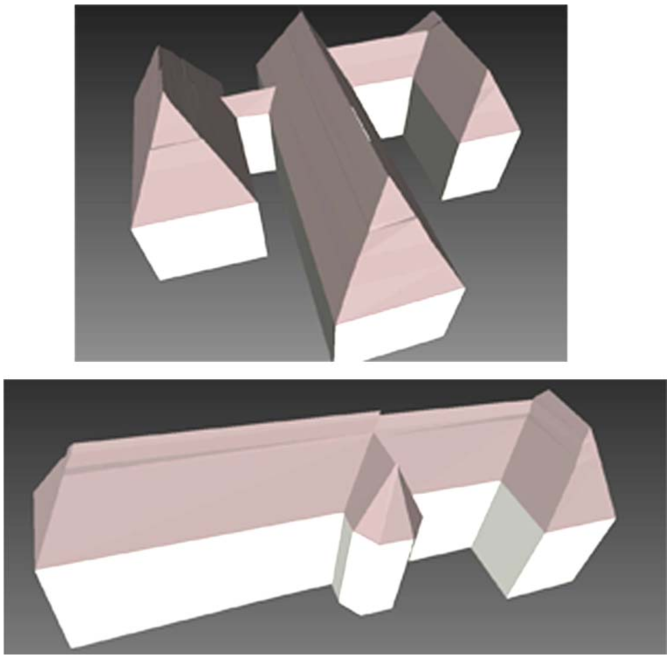

Figure 2-3. Two exemplary CityGML LoD2 models with complex roof geometries.

The generation of more detailed CityGML models and essentially LoD4 models with interior structures seemed – due to missing data (*cf.* Section 5.5.4) – impossible at that point of time, thus it is only possible to generate CityGML LoD1 and LoD2 models (*cf.* Table 5-3).

For overcoming the lack of indoor information (*Kolbe et al. 2008a; Winter 2012*) and essentially extending OSM to indoor environments, the development of *IndoorOSM* (*cf.* publication 2, Chapter 6) is an important step. With the invention and introduction of this mapping schema, very detailed information about the interior geometries and semantics of a building become freely and openly available in OSM.

The third paper (*cf.* Chapter 7) combines the before mentioned CityGML generation framework (*cf.* publication 1, Chapter 5) with *IndoorOSM* for automatically generating highly detailed CityGML LoD3 and LoD4 models. The generation process itself can be considered as a procedural building modeling approach, but in contrast to other existing approaches, such as *Wonka & Wimmer (2003)*, *Döllner & Buchholz (2005*), *Brenner & Ripperda (2006*) or *Müller et al. (2006*) – which furthermore all use proprietary data rather than crowdsourced data – also interior structures are evaluated in order to generate detailed interior models. Additionally, the approach presented in this third paper does not restrict the shape of the individual rooms, in contrast to *Gröger & Plümer (2010*) who assume a room to be representable by rectangular boxes.

Before actually describing the generation of CityGML LoD3 and LoD4 models from (Indoor)OSM, eight data constraints and requirements are defined which need to be fulfilled in order to receive reasonable results:

(1) level shells of adjacent floors overlap each other
(2) walls and their thickness are explicitly mapped
(3) building part geometries on the same floor are pairwise disjoint
(4) all building part geometries of one floor are completely covered by the corresponding shell geometry
(5) relevant measures for levels, building parts, doors and windows must be provided
(6) all provided measures are greater than zero
(7) all provided measures fit to other measures in the building
(8) all measures are not contradictory to the location of the corresponding element

Due to its novelty, there are not yet that many buildings mapped according to *IndoorOSM*. Therefore, at this point of time, quantitative and qualitative statements about the available data – in terms of how many buildings fulfill the requirements – cannot be provided, but shall be evaluated in the future. The generation of CityGML LoD3 geometries (*cf.* Figure 7-5) is realized by fetching the individual levels in ascending order of their level number, computing the CityGML *GroundSurface* element, extruding the level shell segments with the corresponding level height (resulting in various *WallSurfaces*), adding the *Openings* (*i.e.*, doors and windows) to the corresponding wall segments (thereby the height, width and breast of the window/door needs to be considered) and adding an appropriate *RoofSurface* element.

For the generation of a LoD4 model, this process is furthermore extended by the generation of the indoor features as follows: All building part geometries are stored as *FloorSurfaces*, the building part geometry is extruded with the corresponding building part height (resulting in *InteriorWallSurfaces*), *Openings* for doors and windows are added, and a *CeilingSurface* element is added on top of each room. The whole process is also visualized step-by-step in Figure 7-7.

As a proof-of-concept, the developed approach is applied to buildings which are currently available in OSM. Thereby, it becomes obvious that OSM members to not (yet) necessarily contribute 3D information, comprising a necessary prerequisite in order to be able to generated 3D CityGML models. Nevertheless, as seen in Figure 7-8, it is generally feasible to generate 3D CityGML models with the developed approach. However – as visualized in Figure 7-9 – the currently available buildings are often subject to errors or inaccuracy, such as non-congruent level shell geometries, wrong measures of windows or doors, non-parallel sides of a wall, or walls with different thickness.

This research demonstrates that – due to the development of *IndoorOSM* – it is possible to automatically generated 3D CityGML models by purely using crowdsourced (indoor) geodata. That is, it has been proven that VGI from OSM can serve as a major data source for the generation of CityGML models, whereby no manual work (despite the data contribution by the OSM members) is required in order to generate the models. Furthermore, since CityGML models are predestinated for the implementation and utilization of professional (GIS) application in SDIs, OSM can be regarded as a perfect addition for professional users in comparison to proprietary data sources.

However, not only professional (GIS) applications benefit from the large-scale availability of crowdsourced indoor geodata, but also other (non-standard-based) applications and services, such as indoor routing or indoor simulations can use *IndoorOSM* as a major data source. As a prerequisite for the development of such applications, a comprehensive routing graph needs to be formally defined beforehand.

2.3 Representing Indoor Environments with a Length-optimal Routing Graph

Today's navigation systems offer a great variety of functionality and they are often tailored to individual requirements, such as navigation for pedestrians, bicyclists, agricultural machines etc., but they are mainly designed for outdoor environments. Nevertheless, adapting well known outdoor LBS, such as routing or Point-of-Interest (POI) search, to indoor environments has gained more and more attention in the last years. This is also emphasized by the fact that global companies start to extend their well-known maps and routing services to indoors, such as *Bing (2011*), *Google (2011*) or *Navteq (2011*). The benefit and purpose of such applications has been realized and hence the need for advanced indoor applications rises.

Routing a person through an indoor environment can be generalized to finding a shortest path between two nodes in a network. Well proven algorithms, such as the Dijkstra algorithm (*Dijkstra 1959*) or the A* algorithm (*Hart et al. 1968*), can compute such shortest routes but the creation of a network (*i.e.*, a graph) is required beforehand. Thereby, specialties of indoor environments, such as the free movement of a user, vertical movement or obstacles inside room need to be considered. Several efforts towards representing indoor environments have already been conducted, such as *Raubal & Egenhofer (1998*), *Raubal & Worboys (1999*), *Gilliéron & Bertrand (2003*), *Lee (2004*), *Lorenz et al. (2006*) or *Yuan & Schneider (2010*), but they lack details and can therefore only compute coarse routes. Furthermore, none of the existent approaches tries to formally define a graph model.

The forth paper (*cf.* Chapter 8) gives an extensive state-of-the art review on existing indoor graph models and elaborates their pros and cons. Building upon this review, a user-adaptive and length-optimal routing graph for complex indoor environments is formally defined. It incorporates several building components which are relevant for indoor routing, such as obstacles inside rooms, POIs inside halls or big rooms, one-way paths inside buildings (as for example security controls at the airport), and vertical building parts (as for example staircases or elevators). In particular, none of the previously existing approaches has ever explicitly dealt with those building components, although they are very common inside buildings and heavily affect the selection of an appropriate route. In principle, the developed graph model follows the idea of the *iNav* approach (*cf. Yuan & Schneider (2010)*), thus doors are represented as nodes rather than representing the center of a room as a node. However, in contrast to *iNav*, corridors are represented in a different manner: all doors (*i.e.*, nodes in the graph) are directly connected to the centerline of the corridor. As described in Section 8.3.1 this perfectly represents human behavior while walking along a corridor. Furthermore, it has been proven (*cf.* Table 8-1) that this centerline requires less graph elements (in terms of nodes and edges) than *iNav*. Thereby, the overhead of additional travelling distance is – in the worst case – equal to the width of the corresponding corridor (*cf.* Table 8-2); however it can be argued that is overhead is negligible. The graph – namely *Weighted Indoor Routing Graph (WIRG)* – is formally defined as a 7-tupel *WIRG := (N, E, f, g, h, i, j)*. Thereby, *N* (nodes) is a set of relevant locations in the indoor environment (such as doors or turning points) and *E* (edges) is a set of connections between pairs of nodes. The functions *f*, *g*, *h*, *i* and *j* (*cf.* Section 8.4) are mathematically defined functions which serve for different purposes, such as labeling, weight distribution, one-way definition, localization, access restrictions etc. After formally defining the *WIRG*, it is discussed how to obtain and navigate it. Thereby, it is described how to define the several parameters of the *WIRG* as well as what kinds of data source can be utilized. Computing routes to a room with more than one door is achieved via computing all relevant routes and selecting the shortest one (according to a distinct requirement).

To conclude, it can be said that the *WIRG* represents indoor environments in a very detailed manner and furthermore incorporates various specialties of indoor spaces which are relevant for indoor routing. The next step is now to combine this *WIRG* with the newly invented source for crowdsourced indoor geodata (*IndoorOSM*). By developing 3D indoor routing applications based upon a *WIRG* and *IndoorOSM* data, the usability of the *WIRG* is demonstrated as well as the manifoldness and potential arising from *IndoorOSM*.

2.4 Web-based 3D Indoor Routing Applications with IndoorOSM

As already elaborated, there is an increasing demand for indoor LBS and especially indoor routing. Since indoor environments are 3D dimensional, and so are the routes inside buildings, it seems advisable to visualize computed routes in 3D. It has also been proven that 3D city models are advantageous for (mobile) routing (*Coors & Zipf 2007*) and the actual need for 3D information has also been elaborated (*Zlatanova 2008*). There are already couple of indoor routing applications available which visualize the environment and the computed routes in 3D, such as *Meijers et al. (2005*), *Kargl et al. (2007*) or *Hijazi & Ehlers (2009*), but they all use proprietary or commercial data sources. In contrast, there is also a web-based indoor map with routing capabilities available which has been developed by using *IndoorOSM* data (*Goetz & Zipf 2012b; Goetz 2012*); however – due to its pure 2D visualization – the applications lacks clarity when visualizing multi-level routes.

Therefore, the fifth paper (*cf.* Chapter 9) focuses on the development of a 3D indoor routing web application based upon *IndoorOSM* data. Following the formal definition of the *WIRG*, it has been investigated if and how such a *WIRG* can be automatically generated from *IndoorOSM* data. It has been illustrated (*cf.* Figure 9-3) that it is generally possible to automatically generate a *WIRG*. The two-dimensional coordinates (in terms of longitude and latitude) of all doors are explicitly mapped in *IndoorOSM* and the z-coordinate is implicitly provided via the corresponding level number (by accumulating the heights of the underlying levels, the z-coordinate can be computed), thus those can be automatically added to the *WIRG*. By computing the centerline for all corridors (those are tagged with *buildingpart=corridor*) additional nodes are added to the *WIRG*. The computation of the centerline itself can be achieved by computing the Skeleton of the corridor polygon (*Felkel & Obdrmalek 1998*) and pruning all Skeleton parts which are connected with the outline of the corresponding corridor polygon. Adjacent pairs of nodes are then furthermore connected via edges. Within this paper, it has been decided to use the three-dimensional Euclidian distance between two corresponding nodes as the corresponding edge weight. Since all nodes feature 3D coordinates, this computation is straight forward.

For the prototypical application, the *WIRG* is stored in a PostgreSQL database, whereby the utilized database schema is based upon *pgRouting (2012), i.e.*, a C++ implementation for PostgreSQL which adds routing capabilities to the database. Aiming at an ubiquitous accessibility of the developed 3D indoor routing application with arbitrary devices (with adequate web browsers installed), the future internet technology XML3D (*Sons et al. 2010*) is utilized. XML3D is an extension of HTML5 which allows for the creation of interactive 3D graphics and is based upon WebGL. That is, users can access and use the service without the need of installing additional software or plugins, because XML3D is already consumable in most modern desktop browsers as well as on some mobile devices (*Sons et al. 2010*). The 3D visualization is automatically generated based upon *IndoorOSM* data. In the application itself, rooms are visualized as grey boxes and a user can hide or display the different building levels via a level toggle menu (*cf.* Figure 9-6). The desired start and target point can be selected conveniently via drop-down boxes (automatically populated from *IndoorOSM*). Since all routes are already pre-computed and stored on the server, any arbitrary route can be provided within *O(1)* and visualized in the application (*cf.* Figure 9-7). With this application, a user can – either a priori before visiting a building or on-demand when actually being in the building – compute routes between distinct points, and consume and browse the route in 3D on a computer or mobile device.

To conclude this Section, it can be stated that it is feasible to develop a 3D web-application for indoor routing which follows the *WIRG* definition by only using freely available crowdsourced indoor geodata from OSM. This again demonstrates the powerful application of *IndoorOSM* data and furthermore proves the practicability of the *WIRG*. However, computing single routes inside a building can be regarded as a rather trivial task, because there is no big deal as long as the data and graph is available. For demonstrating the suitability of *IndoorOSM* for more complex applications, the next step is to discuss the utilization of crowdsourced indoor geodata for complex multi-agent evacuation simulations as a special type of multi-user routing.

2.5 Using IndoorOSM for Indoor Evacuation Simulations

Crowdsourced geodata from OSM has been proven to be a rich and major source for detailed geodata which can be utilized for environmental simulations, analyses, and the visualization of spatial phenomena – not only by the work conducted in this thesis but also by other research approaches, such as using OSM as a source for 3D SDIs (*Over et al. 2010; Goetz & Zipf 2012c*), emergency routing (*Neis et al. 2010*), or vehicle traffic simulations (*Zilske et al. 2011*). Moreover – as elaborated in the previous Section – publication 5 (*cf.* Chapter 9) demonstrated that data from OSM (and in particular the OSM indoor extension *IndoorOSM*) can be used for developing ubiquitously accessible 3D indoor routing web applications. A research field which is pretty closed related to the task of routing a single human through indoor environments is the conduction of indoor evacuation simulations. Thereby, not only one route for a single user is computed, but several routes for several users. Typically, the users are routed to building exits, as the simulation aims at evaluating the performance of evacuating a distinct building due to a disastrous incident. Thereby, parameters, such as flow capacities of corridors, population information about the building inhabitants etc., are important for revealing potential bottlenecks and blind alleys inside a building – not only for designers and architects, but also legislators. There are several approaches towards simulating mass behavior in indoor environments available, such as *Peacock & Kuligowski (2005*), *Hajibabai et al. (2007*) or *Yamashita et al. (2009*), but they all use proprietary and commercial data sources. Such data is typically hard to obtain and maintain, and there is no common standard available, thus one data provider might provide pixel images of single floors, whereas another provider facilitates detailed 3D models.

Therefore, the sixth publication (*cf.* Chapter 10) tries to investigate if, and to what extent, crowdsourced indoor geodata from OSM can be utilized for conducting complex indoor evacuation simulations, because *IndoorOSM* can be regarded as a standardized (all buildings are mapped the same way) and open data source for building indoor information. Indoor routing and indoor evacuation simulation have in common that they both use a graph-based representation of the indoor environment. In contrast to single indoor routing, the graph for indoor evacuation simulations contains more information, such as the flow capacity (*i.e.*, amount of humans which can pass an edge in the graph within a distinct period of time) or the number of permanent lanes (*i.e.*, the number of humans which can stand next to each other in a corridor). However, the principle structure of the graph, *i.e.*, what building part is represented as a node and what part as an edge, is the same. Following the definition of the *WIRG* (which has been demonstrated to perfectly represent complex indoor environments) and the procedure for automatically generating a *WIRG* from *IndoorOSM* (*cf.* Figure 9-3), it has been demonstrated that it is possible to automatically generate a graph-based representation of *IndoorOSM* buildings, suitable for indoor evacuation simulations. In contrast to an ordinary indoor routing graph, also windows are included because they can (in some cases) also serve as an emergency exit. The stepwise generation of such a graph is also visualized in Figure 10-2. Since *IndoorOSM* contains real polygonal geometries of the building interior, it is also possible to calculate the amount of permanent lanes in a corridor, as well as the flow capacities. Thereby, several computations – depending on the requirements of the simulations – can be applied. Since doors represent a crucial bottleneck inside buildings (they constrict the traffic flow), it is important to consider them in the graph representation. Therefore, two graph nodes are added with a short edge between them. The different parameters of this edge, such as capacity or permanent lanes, can be computed by using the *IndoorOSM* door information, as for example the key *width* or the type of the door (contained in the key *door*).

As a use-case scenario, an average university building is utilized, whereby two different evacuation scenarios (with different requirements) have been performed (*cf.* Sections 10.4.1 and 10.4.2). By conducting this use-case with the two scenarios, it became apparent that *IndoorOSM* contains detailed information about the interior structure (in terms of geometry and topology) of a building. However, it has also been revealed that *IndoorOSM* does only contain static information. Essentially, real population figures (with time dependencies) are not available. That is, when using *IndoorOSM*, vague estimates about population numbers must be undertaken or additional data sources need to be included. Quite obvious, *IndoorOSM* also lacks detailed information about the individual inhabitants, such as their age, sex or health condition. Another drawback of the available data is that *IndoorOSM* does not provide information about whether a window is contemplable for exiting the building. Furthermore, information about obstacles (both static and dynamic) is not (yet) available in *IndoorOSM*.

To conclude, it can be stated that crowdsourced indoor geodata from OSM contains detailed information about the geometry, topology and static aspects of a building. However, *IndoorOSM* currently lacks population information as well as dynamic aspects. It seems very likely that the latter kind of information will never be integrated or maintained in *IndoorOSM*, because this data is too specialized and detailed for the OSM contributors. That is, when conducting indoor evacuation simulations, *IndoorOSM* can be regarded as a perfect source for the geometric representation of the building, but it also has been proven that – especially for the dynamic aspects – additional data sources, such as linked geodata (*Auer et al. 2009*), live sensors (*Botts et al. 2006*) or live city information (*Resch et al. 2012*), should be integrated. It seems simply not possible for voluntarily acting OSM members to contribute such detailed or fast-changing information. This is also due to the specialties of acquiring information about indoor environments for OSM, which will be briefly described in the subsequent Section 2.6.

2.6 Data Acquisition for IndoorOSM

The here conducted research concentrates on the storage and utilization of crowdsourced indoor geodata for standard-based and non-standard-based applications. Nevertheless, an important step prior to actually contributing data to OSM is the acquisition of relevant data and information by the OSM community members. Although the actual acquisition of indoor information is not an integral part of this dissertation, it is still an important aspect which needs to be mentioned. Therefore, this Section briefly discussed different data acquisition methods which are suitable for acquiring data and information about indoor environments.

When contributing data and information about the outdoor environment, contributors typically base the information on:

(1) own personal measurements via a Global Positioning System (GPS) receiver
(2) one’s own personal (local) knowledge
(3) donated aerial imagery, such as Bing Maps (*Bing 2010*), which can be used for tracing the different map features
(4) other map data with expired copyright

That is, users do create and process their own data (option (1) and (2)), or they rely on other data sources which can be (legally) used as a basis for their mapping activities. Since GPS is scarcely working in indoor environments (*Zeimpekis et al. 2002*), and there is not yet a comparable standard for indoor localization and positioning, option (1) is not applicable for indoor spaces. Conventional measuring methods, such as the utilization of surveyor’s tape or step counters, are still suitable for indoor environments, but this can be regarded as a rather tedious and time consuming effort, which will very likely increase the barrier for users to actually acquire and contribute data. The pure usage of local knowledge might be applicable (one can estimate that a wall is four meters long), but this will result in very coarse data and therefore in a loss of information.

Being aware of this handicap, several researchers aim at developing distinct mobile mapping apps for smart phones, such as *Kerber (2011*), *Rosser et al. (2012a*) or *Rosser et al. (2012b*). Those apps use the acceleration and orientation sensors, as well as the camera of the smartphone, for calculating a distinct point inside a room. By capturing several points of a room (preferably the corners on ground or ceiling level) it is possible to derive the polygonal shape of the corresponding room. Thereby, it is important that all points are captured from the same location, which makes this approach also a bit tedious as an appropriate location from which all prominent corner points are visible, needs to be discovered prior to capturing the data. Although still in its infancy, those applications already deliver adequate and detailed data about a single room. Important to mention is, that both afore mentioned applications are motivated by the here presented *IndoorOSM* mapping proposal and therefore they are able to store the derived polygons directly as an *IndoorOSM* mapping schema. However, one major disadvantage is that those apps do not yet provide a solution for capturing locations and metrics of doors or windows. Furthermore, despite the relatively easy utilization of such apps, using them still requires extensive fieldwork of the contributors. Essentially, he or she has to enter every single room and generate the individual room polygon by capturing the prominent room corners. This is on the one hand a tedious work, which again represents an increased barrier for contribution. On the other hand, due to access restrictions or semi-public areas, in most buildings it is simply not possible to access every single room, thus important information might be lost.

Regarding option (3) – as the word already indicates – there is no aerial imagery for indoor environments. However, the basic principle (*i.e.*, tracing from an image) is also applicable for indoors: in most public or publically accessible buildings there are building floor plans available. On the one hand, several buildings voluntarily offer or post floor plans for guiding visitors inside the building. On the other hand, publishing emergency evacuation maps in predestinated places within the building is enforced by law in many countries, such as Germany (*ArbStättV 1983; HHRL M-V 2009; VStättVO 2012*) or the United States (*OSHA 2001*). In most cases, the former kind of plan is individually designed, whereas the latter kind of plan is typically based on standards, such as the *DIN ISO 23601:2010* (*ISO 2010*).

Those plans (especially the standard-based ones) contain detailed information about the shape of individual rooms or corridors, the function of a room (*i.e.*, an elevator, a staircase, an ordinary room), as well as detailed information about the location of windows and doors. That is, by taking pictures of the individual floor evacuation plans of a distinct building, an OSM user can collect all the desired information about an indoor environment in relatively short time. Essentially, one does not have to have access to every single room, which further reduces the required amount of time. Tracing from those photos can be regarded as a good possibility for contributing indoor geodata. As an example, Figure 2-4 visualizes the OSM editor *JOSM* with a photographed evacuation plan in the background.

Furthermore, with several authorities and institutions publishing such building plans openly accessible on their web pages, as for example the *Ludwig Maximilians University in Munich* (*LMU 2012*) or the *University of Nottingham (2012*), there is often no need for taking the pictures by oneself. This increases the data collection process even further.

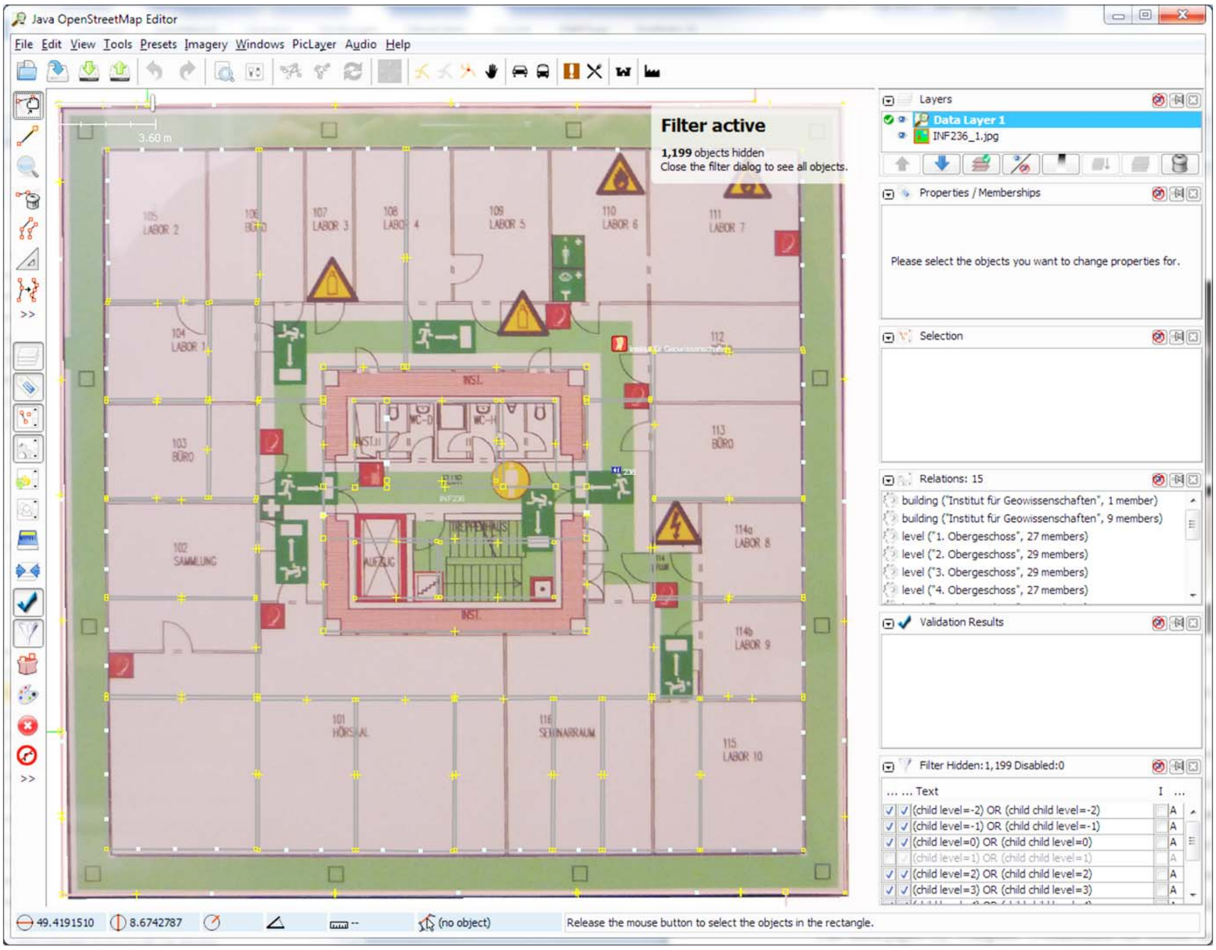

Figure 2-4. Mapping an Indoor Environment in JOSM with an underlying evacuation plan.

Option (4), *i.e.*, the utilization of data with expired copyright, is not only restricted to outdoor spaces, but also possible for indoors. That is, when discovering a non-copyrighted set of indoor data, it is eligible to use it for one’s OSM activities.

Regardless of how the data is collected, there are – due to the novelty of the idea of crowdsourcing indoor geodata – some concerns about legal aspects of collecting indoor data or using existent indoor plans. Those will be dealt with in the next Section.

2.7 Legal Issues of Crowdsourcing Indoor Geodata

While conducting the here presented research and discussing the idea of collaboratively collecting indoor geodata, people often raised doubts or concerns regarding legal aspects of the publication of detailed information about buildings. Essentially, people stated that such data might be used for illegal activities or crime, and furthermore copyright issues also seem to be relevant. Thereby, both the data providers (*i.e.*, the creators) as well as the data consumers (*i.e.*, the application developers) stated that the generation and the consumption of such data need to be confirmed from a legal perspective.

This Section tries to elaborate different perspective on legal issues. However, not being an expert in legal aspects, this Section can of course neither be complete nor generally admitted. Nevertheless, due to completeness and for demonstrating different cross-domain aspects of this dissertation, this Section aims at highlighting major concerns and aspects from a legal perspective, and furthermore tries to motivate future research within this area. All ideas, concerns and hints within this Section evolved from comprehensive and fruitful discussions with a legal expert and patent attorney (*Göpfert 2012*).

Basically, whenever an institution or a building owner grants permission to publish information about the indoor spaces of a particular building, there are no concerns regarding privacy or legal aspects. That is, whenever an OSM contributor asks for permission prior to actually contributing the data to OSM, there is no risk of future issues. However, this also means that contributors have to ask the corresponding building owner, which tends to be an exhausting effort. In particular, when comparing this approach to the current outdoor mapping activities of OSM, asking for permission prior to contributing is a tedious step which decreases the pace of the community and therefore potentially endangers one of the key advantages of crowdsourced geodata.

For the success of crowdsourced indoor geodata, it is indispensable that there are opportunities for OSM mappers to contribute data without asking for permission beforehand. So from a legal point of view, a first – yet unclearly solved – issue is, if it is legal to publish detailed information about indoor spaces without the explicit permission of the corresponding building owner. For private buildings, such as company buildings or industrial facilities, it can be argued that the broad public typically does not have access to them, and therefore acquiring data about in the interior of those buildings is hardly possible anyways. In contrast to that, public buildings, such as hospitals, shopping malls, hotels or airports, (which are often still private buildings in terms of ownership) are publically accessible. By entering such a building, one implicitly accepts the "*terms of usage*" of such a building, which typically define rules of usage or behavior, such as forbidding dogs or skateboards. However, it seems obvious that in very most cases, such *terms of usage* do not deal or discuss the acquisition of detailed information about the interior of the corresponding building. Sometimes, the building owners restrict the usage of photo cameras, but measuring or drawing plans of the interior is normally not prohibited. In accordance with the domiciliary rights (*cf. § 1004 BGB (2002)*), a building owner can prevent a third party to access or view a building. However, it can be argued that the creation of detailed indoor plans can be subsumed by the public usage, as well as by an implied consent of the building owner within the "*terms of usage*".

As described in Section 2.6, one major source for detailed indoor information comprises the publically accessible evacuation plans, which are often published in public and/or private buildings. By taking a picture of them, OSM contributors have access to all information they need for *IndoorOSM*, which make such plans to an eligible source for the mappers. Thereby, the question is, if this approach is legally harmless. At first, it needs to be stated that such plans can be subject to a license or copyright. That is, only the creator of the plan possesses the right to use and/or duplicate the plan, as long as this right is not explicitly transferred to a third party. However, considering plans and drawings as a technical and scientific work (*cf. § 2 No. 7 UrhG (1965)*), the copyright does only affect the visualization of the plan. Essentially, the content (that is the information which is visualized by the plan) cannot be protected. Furthermore, as the visualization of most evacuation plans is often restricted to topological and metric facts and furthermore typically based on standards, such as the *DIN ISO 23601:2010* (*ISO 2010*) with hardly any individual creativity, it can be argued that such plans are not protectable at all. Since OSM mappers typically do not publish the photo of the plan in OSM, but only use it as a basis for their (manual) plan digitalization efforts, this approach seems uncritical, as long as the "*terms of usage*" do not prevent one to take pictures inside the building (*cf.* above). That is, OSM contributors do only use the plan as a tool for extracting its content (which is not protectable by a copyright). The picture itself is typically taken by the OSM mapper himself, thus the copyright of the picture itself is up to the mapper and therefore not critical.

With a similar argumentation, the usage of online building plans, which are published on the Web, can be justified. Again, it can be stated that the OSM mappers use the plan as a basis for deriving the contained information rather than simply duplicating the plan. However, in contrast to pictures which have been taken by the OSM mapper himself, it is not allowed to upload the distinct plans (*i.e.*, the PDF, CAD etc.) elsewhere, because this represents a (illegal) duplication which potentially infringes the copyright of a third party. Strictly speaking, this also accounts for the storage of the plan on the local computer. However, as modern browsers typically cache browsed content (and therefore also store it on the local hard drive), this issue seems to be less critical, essentially as it is hardly verifiable of what data the final information in *IndoorOSM* is based on.

Last, the worry that indoor information in OSM could potentially be used for an illegal activity or crime can be repelled by the argument that those plans are publically accessible anyways. Essentially, the theoretical possibility of misusing the published information does not per se represent a derogation of the domiciliary rights.

To conclude this brief review on legal aspects and issues, it can be stated that publishing information about indoor spaces is not per se illegal. Essentially, when permissions are granted by the building owner, it is harmless to map indoor environments in OSM. Furthermore, from the current point of view, publically accessible evacuation plans as well as online building plans are a legal resource for indoor mapping activities. Nevertheless, it needs to be stated that the whole area potentially still represents a legal limbo, as it is brand new and not yet discussed by legal authorities. Furthermore, legal aspects typically depend on the law of the corresponding country, thus the legal situation in the United States is probably less critical as for example in Germany. However, as the whole topic is likely to receive an increasing interest and attention by both the public and economy, the legal aspects should be investigated in more detail by corresponding experts.

3 Conclusion

This Section sums up the main contributions of this dissertation, as well as novel aspects which have been revealed. Furthermore, an outlook on future research is provided.

3.1 Contributions

In this doctoral thesis a potential solution for satisfying the increasing demand of indoor information (*Kolbe et al. 2008a; Winter 2012*) has been introduced. The developed mapping schema for OSM provides the necessary basis for crowdsourcing indoor geodata and information about indoor spaces in OSM (Chapter 6). Essentially, *IndoorOSM* was the first approach towards crowdsourcing detailed information about building interiors including detailed polygonal geometries of the individual building parts. That is, with this newly invented *IndoorOSM* model users can crowdsource detailed information about the geometry and topology of a building, whereby not only point information but real polygonal geometries are provided. Due to the importance of semantics, *IndoorOSM* also contains possibilities for contributing semantic information about interior spaces.

Prior to the invention of *IndoorOSM*, crowdsourced geodata from OSM did only contain information for the generation of CityGML LoD1 and LoD2 models (Chapter 5). With the invention of *IndoorOSM* it has been demonstrated that crowdsourced indoor geodata bears an enormous potential because it is possible to automatically generate highly detailed CityGML LoD3 and LoD4 models (Chapter 7) with interior spaces and semantics attached to them. The added value of *IndoorOSM* is that it represents a globally accessible, free and open source of crowdsourced indoor geodata which can be used for the application within SDIs. Due to the developed transformation framework from OSM to CityGML for an automated generation of detailed CityGML models, it is furthermore no longer required to create LoD4 models manually. That is, a large scale and automated generation for several buildings is feasible on demand without manual work.

In order to further demonstrate the manifoldness and capabilities of *IndoorOSM*, as well as to prove the usefulness of crowdsourced indoor geodata, two practical and dedicated applications and analyses have been developed. Methodically, it has been demonstrated that a detailed graph for representing indoor environments (namely *Weighted Indoor Routing Graph*, *WIRG, cf.* Chapter 8) can be automatically generated based upon *IndoorOSM* data.

Such a graph can then be utilized for either providing a 3D web application with indoor routing functionality (Chapter 9) or as a network for complex multi-agent indoor evacuation simulations (Chapter 10). In addition to the proven generation of CityGML data based upon *IndoorOSM*, those two different applications intend to point out the flexibility and portability of *IndoorOSM* data, as well as to demonstrate the manifoldness and potentials arising from crowdsourced indoor geodata from OpenStreetMap.

The innovative findings of this thesis can be summarized as follows:

- By using the *IndoorOSM* mapping schema it is possible to contribute detailed polygonal geometries, as well as topological and semantic information about multi-level indoor environments.
- The developed mapping schema only utilizes existent OSM data structures (*i.e.*, *nodes*, *ways*, *relations* and *tags*) and therefore guarantees the seamless integration in the established OSM infrastructure and its tool chain. Hence, it is easily possible to integrate indoor crowdsourced geodata into existing applications, as well as to utilize conventional OSM editors for contributing indoor geodata.
- The crowdsourced geodata of *IndoorOSM* can be utilized for the automated generation of CityGML building models. Thereby, the Level-of-Detail varies from coarse building blocks models (LoD1) up to highly detailed models with interior structures (LoD4). That is, a large-scale and fast generation of CityGML models for standard-based SDIs is feasible. For the first time, a comprehensive framework for automatically generating CityGML based upon crowdsourced (indoor) geodata from OpenStreetMap has been developed and demonstrated. It can be concluded that *IndoorOSM* can/will represent a rich and major source for indoor information for various standard-based applications.
- The *Weighted Indoor Routing Graph* represents complex indoor environments with a length-optimal and user-adaptive routing graph. Thereby, the *WIRG* is the first graph representation with a comprehensive formal definition which additionally compensates disadvantages of former graph models.
- *IndoorOSM* data can be used for generating ubiquitously accessible 3D web applications for computing and visualizing multi-level routes in indoor environments. It can be pointed out that such services can be generated automatically with little manual work required. That is, fast provision of such services for arbitrary buildings is feasible. It has been demonstrated that the newly invented *WIRG* can be generated automatically

based upon *IndoorOSM*, which furthermore proves the practicability of the *WIRG* for computing shortest routes in indoor spaces, as well as the opportunities arising from *IndoorOSM*.

- Despite single indoor routing, it has also been demonstrated that *IndoorOSM* represents a good source for static aspects of indoor spaces, utilizable for complex indoor evacuation simulations. It can be pointed out that by fusioning *IndoorOSM* with other – either proprietary or open – data sources, the conduction of realistic and complex indoor evacuation simulations is feasible.

3.2 Outlook and Future work

With *IndoorOSM* (*cf.* publication 2, Chapter 6), an extension of OpenStreetMap for crowdsourcing detailed geometries and (semantic) information about indoor environments has been successfully invented and developed. It has been demonstrated that OSM can therefore serve as a powerful and manifold data source for various kinds of applications. The automated generation of detailed CityGML models in all LoDs from OSM data is possible and in particular, highly detailed LoD4 models with interior structures can be created automatically based upon *IndoorOSM* (*cf.* publication 3, Chapter 7). In addition, *IndoorOSM* data can also be used for the development of web-based 3D indoor routing applications (*cf.* publication 5, Chapter 9) as well as for representing static aspects in evacuation simulation scenarios (*cf.* publication 6, Chapter 10). Nevertheless, as already elaborated in the conclusions of the individual publications (*cf.* Chapter 5-10) as well as in Chapter 2, there are implementation demands as well as various fields for future research.

The major areas for future investigations which arise directly from this thesis can be summed up as follows:

- As described in Section 2.1, the current *IndoorOSM* model is only able to represent indoor spaces up to some degree of complexity. Essentially, organic shapes or artificial shapes cannot (yet) be represented due to the *Manhattan-Like* restriction (*i.e.*, vertical walls, parallel ground and ceiling). Therefore, *IndoorOSM* needs to be further improved to cope with the currently existing limitations. Thereby, important aspects which should be considered are the incorporation of non-planar grounds (*e.g.*, a ramp from one floor to another), mezzanines, semi-outside spaces (*e.g.*, balconies or arcades), roofing for understories, as well as details about the shape and appearance of windows and doors.

- According to *Uden & Zipf (2012*), OSM will – due to its limited data structure which is not explicitly designed for mapping 3D (indoor) geodata – probably never be suitable for mapping any arbitrary building shape or structure and therefore the development and improvement of ideas and possibilities for crowdsourcing real 3D geometries (*e.g.*, *OpenBuildingModels* (*Uden & Zipf 2012*), are also important. Enabling users to create, alter and enhance real 3D models (*e.g.*, created in Google Sketchup, 3DS Max or Cinema 4D etc.) will turn citizens into major data providers for various kinds of (professional) applications, such as urban planning, public participation processes, facility management and the like.
- Considering the transformation framework from *IndoorOSM* to CityGML, several geometry simplifications could be integrated, as for example merging congruent *WallSurface* elements or pruning irrelevant points of the various geometry elements. As soon as the *IndoorOSM* model itself has been improved (*cf.* above), also the CityGML generation process needs to be adapted to those new changes.
- As demonstrated by *Over et al. (2010*), *Goetz & Zipf (2012c*) and *Uden et al. (2012*), OSM contains detailed information about the outdoor environment which can be utilized for the generation of virtual 3D city models and 3D earth browsers. Building upon those approaches in combination with the developed CityGML transformation framework, a more general transformation framework from OSM to CityGML could be developed. With such a framework, large-scale CityGML datasets with various features, such as roads, buildings, landuse areas and so on, could be automatically generated. This will strengthen the importance of crowdsourced data and furthermore provide researchers, public authorities and companies, an open access to a large dataset of automatically generated CityGML models which can be utilized for various GIS applications.
- Crowdsourcing indoor geodata in OSM requires new and advanced methods for the data acquisition of the contributors. That is, distinct mapping applications for mobile devices, as for example for Android (*Rosser et al. 2012a*, *2012b*) need to developed and improved. Furthermore, low-cost devices, such as the *Microsoft Kinect*, can be utilized for capturing point clouds of indoor environments (*Budroni & Böhm 2010; Haala et al. 2011b; Haala et al. 2011a; Khoshelham & Elberink 2012*). Such point clouds can serve as a very detailed data source for indoor geometries and methodologies for automatically generating *IndoorOSM* data based upon (Kinect) point clouds are desirable. Furthermore, the possibility of automatically extracting geometries from

photographed evacuation plans has been already demonstrated (*Peter et al. 2010*) and it will be interesting to extend those methodologies in that way that they automatically generate *IndoorOSM* data.

- The derivation of comprehensible routing instructions from *IndoorOSM* for ubiquitously accessible route planning services is also an interesting field for future research. Not only limited to services based upon *IndoorOSM*, but also important for services which are based on proprietary data sources, the clear and comprehensible visualization and communication of the individual route steps and instructions is important. Thereby, different devices, such as computers, tablets or smartphones, with their individual requirements and limitations need to be considered.
- One major concern against the usage of VGI is the quality of the available data. While *Haklay (2010*) and *Neis et al. (2012*) already compared outdoor data of OSM with proprietary data sources from Ordnance Survey or Teleatlas, there is – due to its infancy – not yet such an analysis regarding crowdsourced indoor data. Nevertheless, with an increasing availability of *IndoorOSM* data, it will also be important to investigate (and hopefully prove) its quality, because this will dispel the doubts and furthermore strengthen the idea of crowdsourcing indoor geodata.
- From a legal point of view – as emphasized in Section 2.7 – there are a lot of open questions regarding the legal aspects of crowdsourcing indoor geodata. That is, the mentioned aspects (as well as probably other issues) need to be investigated in detail. It seems advisable to perform this in a cross-domain collaboration with experts from different fields, such as lawyers, patent attorneys, web experts, city planners, GIS exerts, public authorities and so on.
- *Kolbe et al. (2008a*), *Jensen et al. (2011*) and *Winter (2012*) state that there is an increasing demand for detailed indoor information, which cannot yet be satisfied in an appropriate manner. The advantages and opportunities arising from collaboratively collecting and sharing detailed indoor geodata and information in an open and globally accessible platform like OSM are clearly visible but not yet often used. Nevertheless, the transformation framework as well as the two application scenarios of this thesis showed the large potential of using crowdsourced indoor information from OSM. Future research efforts should definitely make use of this idea and its capabilities, which will lead to more potential users (from both science and economy) and result in a broader field of application. In return, new research questions and demands will arise, which furthermore stimulate new innovative ideas and developments.

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5 Publication 1: Towards Defining a Framework for the Automated Derivation of 3D CityGML Models from Volunteered Geographic Information

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Alexander Zipf

Towards Defining a Framework for the Automatic Derivation of 3D CityGML Models from Volunteered Geographic Information

Abstract

High-quality geographic data sources are eminent for urban data management and the creation of detailed 3D city models. In the past two decades, Volunteered Geographic Information (VGI) increasingly gained attractiveness to both amateur users and professionals, resulting in a broad availability of urban data within VGI communities and especially OpenStreetMap (OSM). OSM provides detailed information about urban regions and more buildings are also mapped. Existing 3D-VGI applications, e.g., KOSMOS Worldflier (*Brejc 2011*) or the OSM-3D project (*OSM-3D 2011*) only focus on visualization purposes, but a standardized usage for exchanging and sharing urban city models is not combined with VGI. Therefore, this paper presents a framework for an automatic VGI-based creation of 3D building models encoded as standardized CityGML models. The usage of VGI as a proper data source for the creation of standardized city models will be proven.

5.1 Introduction

Three-dimensional urban city models are used by the economy and public administration for different purposes, *e.g.*, environmental simulations or facility management (*Kolbe 2009*). Thereby, the field of application evolved from traditional applications such as network planning, typically requiring pure geometric models with low level-of-detail, to advanced applications in areas such as tourism. That is, the requirements of city models heavily increased, meaning that besides geometric information there is also a strong need for semantic information. However, the creation and maintenance of such detailed models is very expensive (*Benner et al. 2005*), because it is largely done manually and automatic procedures are rare, while semi-automated approaches are becoming more and more popular.

The City Geography Markup Language (CityGML) became the international standard for storing, visualizing and exchanging three-dimensional urban city models, thus allows an interoperable access to 3D city models (*Kolbe et. al. 2005*). CityGML models do not only contain geometric information, but also a variety of topologic and semantic information, *e.g.*, names, building types or addresses. The creation of CityGML models typically requires high-quality data, which is usually captured and provided by professional surveyors and cartographers, public authorities or commercial data providers. Existing standards such as Building Information Modeling (BIM) or Industry Foundation Classes (IFC) have also been shown to be transformable to CityGML (*Benner et. al. 2005*). Nevertheless, a large percentage of CityGML models are created manually by exporting the models from different CAD and 3D graphic applications (*e.g.*, Google Sketchup).

In the last couple of years, the term Volunteered Geographic Information (VGI) became popular, whereat VGI describes that an ever expanding range of users collaboratively collects geographic data (*Goodchild 2007a*). That is, hobbyists create geographic data based on personal measurements (via GPS, etc.) and share those in a Web 2.0 community, resulting in a comprehensive data source of humans acting as remote sensors (*Goodchild 2007b*). Especially in urban regions the coverage of VGI data is very good, leading to an increase of the usage of VGI in urban data management (*Song & Sun 2010*).

Nevertheless, the data in VGI communities is mostly used for creating two-dimensional maps (*e.g.*, *OSM (2011a*). However, one step towards the usage of VGI in a 3D platform has been demonstrated by *Schilling et al. (2009)*. This example also shows the potential of VGI for visualizing urban regions with 3D city models, but only focuses on the visualization of the geometry and not on semantics. Therefore, the main contribution of this paper is the development and suggestion of a framework for the automatic creation of CityGML models by purely using crowdsourced geographic information from OpenStreetMap (OSM). With such a framework, it shall be evaluated and demonstrated that VGI is capable for the creation of standardized city models which can be exchanged via Open Geospatial Consortium (OGC) standards (*e.g.*, Web Feature Service, WFS) and utilized in professional applications and analyses, *e.g.*, the mapping of environmental noise pollution (*Czerwinski et. al. 2006*), urban planning, city business development, tourism (*Döllner et. al. 2006*), homeland security (*Lapierre & Cote 2007*), disaster management (*Kolbe et. al. 2008*) or indoor navigation (*Mäs et. al. 2006*).

The remainder of this paper is organized as follows: First, the CityGML standard is described in the detail required for the subsequent work and discussion. This is followed by an introduction to OSM, providing the basics for understanding the conducted research. Afterwards, there is an overview about related work regarding 3D city model creation as well as (3D)-VGI. Thereafter, a framework for the creation of CityGML models from VGI is introduced. The last Section summarizes the presented work and discusses future research.

5.2 Interoperable Access to 3D City Models

A model for the semantic and geometric description of urban regions is the City Geography Markup Language (CityGML) (*Gröger et. al. 2008; Kolbe et. al. 2005*). CityGML became a global standard for storing and exchanging three dimensional city models, thus allows an interoperable access to 3D city models. It is based on the Geography Markup Language 3 (GML3) (*Lake et. al. 2004*), which is commonly used for exchanging data in spatial data infrastructures (SDI) (*cf. Zipf et. al. 2007*) and web environments. Additionally GML3 is the native data format of the OGC WFS (*Kolbe 2009*). CityGML does not only cover geometric aspects which are relevant for visualization, but also topologic and semantic information about urban regions such as labels or operation hours. The model "*distinguishes between buildings and other man-made artifacts, vegetation objects, waterbodies, and transportation facilities like streets and railways*" (*Kolbe et. al. 2005*).

For providing several differentially detailed city models, CityGML defines specific Level-of-Details (LoD), which vary with regard to the information resolution and generalization. The LoD concept comprises five classes: LoD0 for a 2.5 dimensional Digital Terrain Model (DTM), LoD1 for visualizing building as coarse building blocks, LoD2 for displaying roof structures and façade textures, LoD3 for denoting building details such as windows or doors and LoD4 for models with interior features.

Regarding the CityGML schema, one of the most detailed concepts of CityGML is the building model (*Gröger et. al. 2008*), which allows for the representation of thematic, spatial and semantic aspects of buildings and building parts. The class *_AbstractBuilding* describes the central class of the model, whereby entities of this class are either a *Building* or *BuildingPart*. Since an entity of *BuildingPart* is again a *_AbstractBuilding*, it is possible to aggregate a hierarchy with arbitrary depth (*Gröger, et. al. 2008*). *_AbstractBuilding* is a subclass of _CityObject and therefore it additionally inherits all properties from *_CityObject* (*e.g.*, *gml:name*, *address*, etc.). Furthermore *_AbstractBuilding* contains specific building information. These are on the one hand semantic information such as *function*, *roofType*, etc., and on the other hand quantitative or metric information, *e.g.*, *measuredHeight*, *storeysAboveGround*, etc. The spatial representation of building features is given by geometric objects, *i.e.*, *Geometries*, *MultiSurfaces* or *Solids*. A *Building* or *BuildingPart* is bounded by a *BoundarySurface*, which can be a *RoofSurface*, *WallSurface*, *GroundSurface* or *ClosureSurface*, whereby these *BoundarySurfaces* can additionally have *Openings*.

The given introduction ought to be enough for understanding the general concept of buildings in CityGML. For further information as well as UML-diagrams of the different CityGML features, please refer to *Gröger et al. (2008)*.

5.3 OpenStreetMap: One of the Most Popular Examples of VGI

During the last couple of years, diverse VGI communities such as Wikimapia, Geonames, FixMyStreet, etc. have been initiated, but somehow OpenStreetMap is the most popular example for VGI. OSM is a collaborative community which aims for the provision of free map data, which can be used and edited by the community at no charge. With currently more than 400,000 registered users (*OSM, 2011b*), OSM grew rapidly regarding the amount of data, leading to more than 1,140,000,000 geo-tagged points. What began as a free online world map, evolved very quickly to a huge source of diverse data about urban and rural areas. That is, OSM not only contains information about streets or land areas, but also different semantic information, *e.g.*, about the surface of a road or speed limits. That is, the diversity of information is beyond an ordinary map. For adding information, OSM applies a concept of free-definable key-value pairs, so that a user can add various attributes to different geo-tagged locations. There are no strict rules for the key-value pairs, but there are diverse guidelines and best-practices available, *e.g.*, for defining a street, there is the key *highway* with different values, *e.g.*, *residential*, *motorway*, etc. A list of the most commonly used keys is provided by *Tagwatch (2011a)*, as well as a list of all currently used keys by *Tagwatch (2011b)*.

From a global perspective, it is evident that different regions differ regarding data quantity and quality. Nevertheless, it has been demonstrated that, especially in urban areas, OSM is able to compete against commercial or official data sources (*Haklay, 2010; Mooney et. al. 2010; Neis et. al. 2010; Zielstra & Zipf 2010*).

Meanwhile, OSM users also started to map buildings. Therefore, users utilize closed ways for describing the ground shape of the building. A way comprises a set of points connected pair-wise with each other, and a closed way is a way whereat the first point equals the last point. Complex shaped polygons such as buildings with an atrium (*i.e.*, a hole inside the ground shape polygon, *cf.* Figure 5-5 (a)) can be mapped with relations, That is, the users map the outer bounding shape of the building with one closed way and additionally, they can provide multiple closed ways which represent the holes in the polygon (the inner polygons cut out holes of the building polygon). For tagging the shape as a building, users simply have to add the key-value *building = yes*. Currently there are more than 44.1 million tagged buildings in OSM (most of them are in Europe) and the amount steadily increases. The number of buildings between January 2007 and October 2011 is depicted in Figure 5-1. In average, currently over 375,000 new building outlines are added to OSM every week and it is likely that this trend will increase even further, due to the large availability of high resolution imagery that has been provided as source for mapping for OSM (such as Microsoft Bing Maps in December 2010, *cf. OSM (2011c)*). In contrast, the amount of streets, which are currently the major part of OSM, comprises 45.2 million instances and an per-week increase of about 200,000 (based on our internal database). Thus, it is likely that soon there will be more buildings in OSM than any other kind of spatial feature.

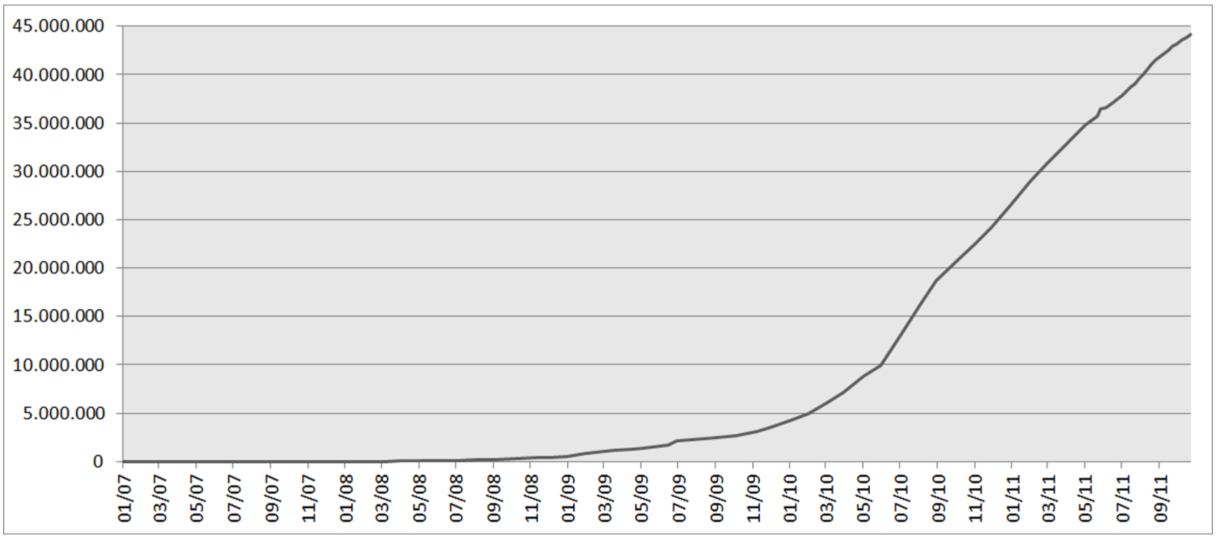

Figure 5-1. Development of the amount of tagged buildings in OSM between January 2007 and October 2011. The values are derived from our internal OSM database (updated daily).

For enriching buildings with information, there are different keys promoted in the community, *e.g.*, height, building:buildyear, etc., which can be utilized for describing the appearance and semantic characteristics. Also, address information can be added with different keys, *e.g.*, *addr:street* or *addr:housenumber*. All relevant building keys will be further discussed later in this paper.

5.4 Related Work

The problem of deriving, representing and visualizing three-dimensional building models which are close to reality (regarding both geometry and appearance) has been discussed for a while. Thereby, different approaches with different data sources were made. Research started with 2D image processing, but did soon turn towards 3D approaches (*Henricsson et. al. 1996; Lang & Förster 1996*). Also, the extraction of 3D building models from laser altimetry data is well researched (*Maas & Vosselman 1999;*

Weidner & Förster 1995). Furthermore, the utilization of shape grammars for modeling urban areas was explored in different research, *e.g.*, shape grammars (*Stiny & Gips 1971*) or split grammars (*Wonka & Wimmer 2003*). Thereby, scientists focused on different purposes such as the creation of city models for movies/games (*Müller et. al. 2006*), for reconstruction (*Brenner & Ripperda 2006*), for facades (*Müller et. al. 2007*), for detailed roofs (*Dörschlag et. al. 2008*) or for the creation of stairs (*Schmittwilken et. al. 2007*). Nevertheless, the aforementioned modeling approaches can only be used for visualization purposes, but standardized semantically enriched models cannot be derived.

Trying to generate semantic 3D building models, a new data model namely QUASY has also been presented by *Benner et al. (2005)*, whereby this new model is very similar to CityGML. Additionally, it has been described how Industry Foundation Classes (IFC), *i.e.*, a commonly used format for Business Information Modeling (BIM) (*cf. IFC (2011)*) can be transformed to this new model. However, QUASY is not a global standard, thus the massive application of the invented methodology and its benefit is questionable.

Falkowski et al. (2009) investigated how to generate full CityGML models from images. The authors utilize two stereo images and transfer them semi-automatically into a graph structure, which is then automatically transformed into a CityGML model. However, the approach requires manual work and is therefore not applicable for huge urban areas.

According to *Isikdag & Zlatanova (2009)* there are several use-cases for transferring IFC to CityGML, but literature lacks formal frameworks. Therefore, the authors present preliminary ideas, trying to semantically map both models with each other, while focusing on BIM. The presented framework describes fundamental ideas, but there is still a lot of work required for an automatic conversion. A first application of the framework concentrating on water utility networks is already presented by *Hijazi & Ehlers (2009)*.

Altogether, the beforehand described approaches have in common that they all utilize proprietary or official data, which is on the one hand hard to acquire and on the other hand often expensive. As emphasized above, publically available data from VGI communities can serve as a real alternative data source, but none of the described approaches considers VGI.

According to *Over et al. (2010)*, there is currently no literature available which describes the 3D visualization of OSM data. There are only two applications providing a real three-dimensional perspective of OSM including digital terrain models and 3D buildings: the so called KOSMOS Worldflier (*Brejc 2011*) and the OSM-3D project (*OSM-3D 2011*). Some other applications try to show also perspective scenes (with flat terrain) and sometimes even extruded buildings, *e.g.*, osm3d (*Ziegler 2011*). However, most of these applications are very limited regarding the size of the scene, the application functionality and the selected data that can be visualized in 3D. In contrast, the mentioned OSM-3D project is based on a Web3DService (W3DS) and the W3DS-Client XNavigator provides a detailed virtual globe including terrain, landuse, Point-of-Interest (POI), buildings, streets, labels, etc. Recently, realistic and detailed city models of entire Europe have been made available within OSM- 3D, whereby the building models are updated regularly. Figure 5-2 depicts an example of a building which has been mapped in OSM and rendered within the W3DS-Client XNavigator. It consists of several extruded polygons with different height, elevation and shape. This visualization already provides a coarse geometry of the building; however, currently the building generator behind OSM-3D does not yet support different roof types or other semantic aspects. The ongoing work in this project is supposed to improve this situation soon.

In general, to the authors of this paper's knowledge there is currently no work available on the (semi-)automated extraction of semantically enriched 3D models from OSM and in particular no work on the derivation of CityGML models.

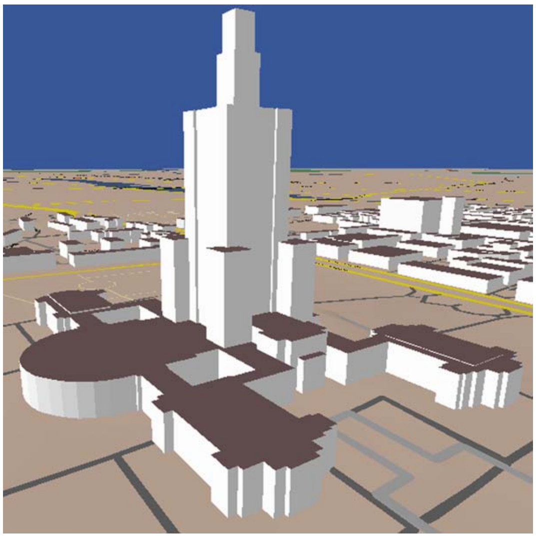

Figure 5-2. 3D Visualization within the OSM3-D project (OSM-3D 2011).

5.5 The Framework

The derivation of CityGML models from OSM data must be accomplished in a two-step approach: on the one hand semantic information transformation is required and on the other hand the generation of valid geometries must be achieved. As described above, CityGML separates the semantic aspects strictly from the geometric aspects. In OSM there is no such strict separation. The 2D geometry of the ground shape is implicitly mapped by different tagged nodes. Additional geometric information, such as the height, as well as other semantic aspects, are attached as key-value pairs to the corresponding ground shape geometry. Because of this diversity in both models, the two aforementioned conversion steps must be accomplished together.

In order to perform a successful and consistent transformation, two operations are required. First, a comprehensive set of rules for the semantic mapping between key-values in OSM and attributes in CityGML needs to be defined clearly. Secondly, methodologies for the creation of geometries for each LoD in CityGML need to be developed.

The following Sections present information transformations from OSM key-value pairs to CityGML attributes. Furthermore it is evaluated, which CityGML LoD (*i.e.*, LoD 1 - 4) geometry can be created by purely using VGI from OSM.

5.5.1 Acquisition of Semantic Information from OSM for CityGML

For populating the attributes of the *_Abstract-Building* class (*cf.* Figure 5-3 (a)) in CityGML, several keys and/or values of OSM can be utilized.

Generally, three classes of relationships can be distinguished when investigating the semantic mapping between OSM and CityGML:

(1) One key in OSM can be mapped to one attribute in CityGML (*cf.* Figure 5-3 (b)), *i.e.*, a 1:1 relationship
(2) Several keys in OSM can be mapped to a single CityGML attribute (*cf.* Figure 5-3 (c)), *i.e.*, a n:1 relationship
(3) There is no suitable key in OSM for a CityGML attribute.

The case that one key in OSM can be mapped to several CityGML attributes (*i.e.*, 1:n) does also occur. Since the developed framework focuses on unidirectional information transformation from OpenStreetMap to CityGML (*i.e.*, it is only required to populate CityGML attributes by using OSM key-value pairs and not vice-versa), a 1:n relation can be simply divided into several direct relations (*i.e.*, 1:1).

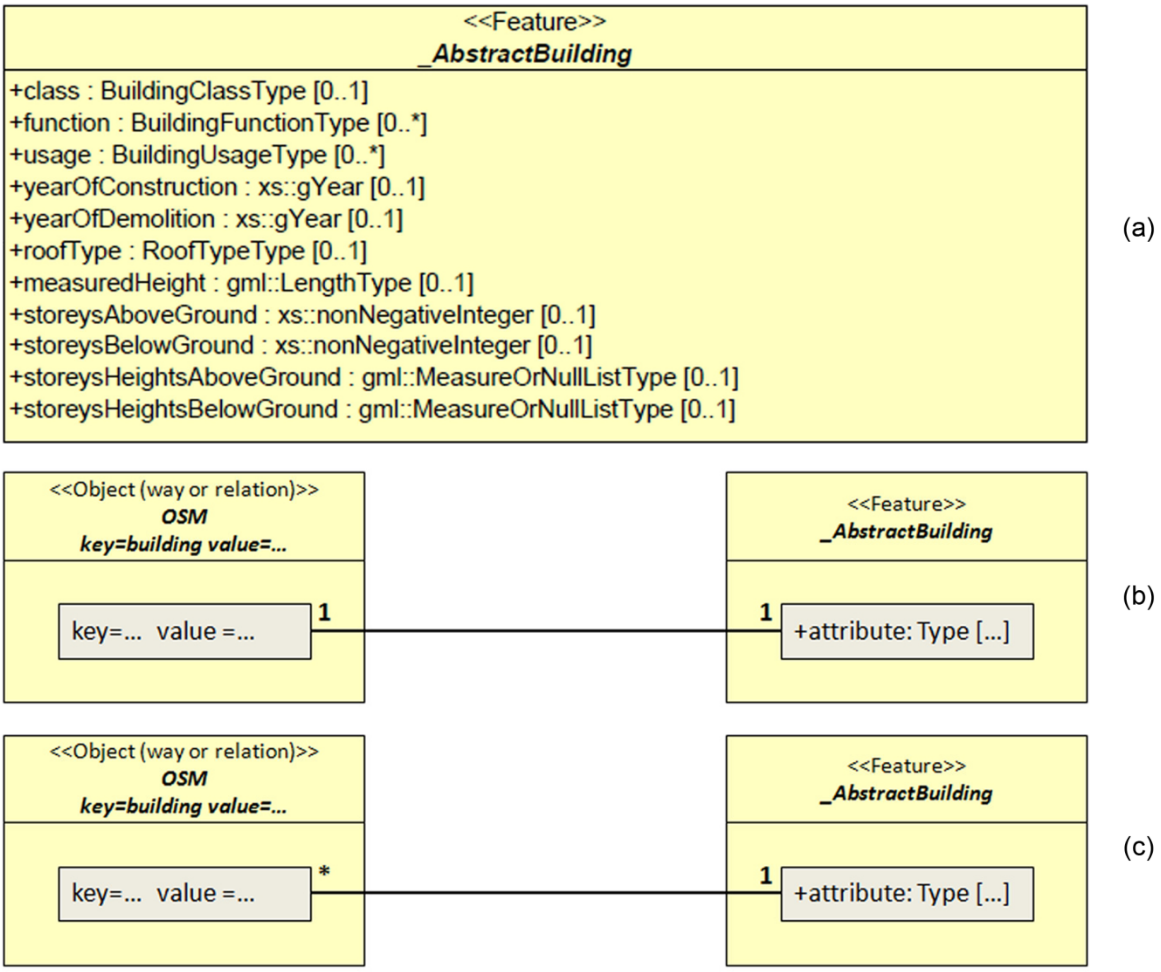

Figure 5-3. (a) Attributes of the _AbstractBuilding class (Gröger et. al. 2008), (b) OSM to CityGML relationship type 1:1, and (c) and relationship type n:1.

The examples for relationship type (i) are quite obvious. For the inherited attribute *gml:name*, the direct counterpart in OSM is the key *name* with an arbitrary value *v*. That is, using *name=v* results in *<gml:name>v</gml:name>* in CityGML. Similar to this, the attribute *bldg:yearOfConstruction* can be populated by using the value of the OSM key *building:buildyear*. The attribute *bldg:storeysAboveGround* can be populated respectively by using *building:levels:aboveground*, as well as the attribute *bldg:storeysBelowGround* by using *building:levels:underground*.

For the attribute *bldg:yearOfDemolition*, there is currently no counterpart in the OSM schema, thus this attribute belongs to the relationship type (iii). Currently, OSM does not versioning of elements, *i.e.*, whenever a building does no longer exist in real-world, it is deleted in the database. Therefore, the attribute *bldg:yearOfDemolition* cannot be populated by using VGI.

In contrast to the above mentioned attributes, the relationship type (ii) is more complicated, because different OSM keys can contain relevant information, thus a prioritization of those keys is required. One example for such an attribute is *bldg:class*. This attribute defines the class of a building, whereby the values are given as codes, representing a corresponding value. Thus, for example, a building with class code *1100* represents an academic facility such as a school or research department. Possible applicable counterparts in OSM are *amenity*, *building* or *building:use* whereby all of them can contain relevant information. Additionally, the key *building:type* can also contain relevant information, however, it has been declared as deprecated and shall no longer be used by the community (*OSM 2011d*). That is, possible values for these three OSM keys have been investigated, evaluated according to their relevance and grouped in appropriate classes which can then be linked to the different possible *BuildingClassTypes*. Populating the CityGML attributes *bldg:function* and *bldg:usage* is done respectively. This value-partitioning and grouping is a very essential task and needs to be well considered, however, due to space limitations the complete framework cannot be discussed here in detail. As an example, *amenity=school* indicates that *bldg:class* is *1100*. In contrast, the *building:type=church* indicates that *bldg:class* is *1080* (church institution), and *building:use=residential* would result in *bldg:class 1000* (habitation). For more information on the code-lists of *bldg:class, bldg:function* and *bldg:usage*, refer to *Gröger, et al. (2008)* and for the most used values of the OSM keys *amenity*, *building:type* and *building:use*, please see *Tagwatch (2011a)*.

For the CityGML attribute *bldg:measuredHeight* there are currently two potential OSM keys (namely *height* and *building:height*). Whenever both keys are available with different values, it needs to be decided which one to choose. However, this is not an easy decision, thus needs proper reasoning. A first proposal is to use the attribute with the latest value, as being most likely the most current version. Nevertheless, when investigating the data inside OSM it has been figured out that by end of October 2011 there are only few buildings available with differing height values (18 in total), whereby in most cases the height difference is less than three meters. Additionally, the key *building:height* has been declared as deprecated (*OSM 2011d*), *i.e.*, users are requested to no longer use it in the future. That is, if the community follows this request, *height* will be the only relevant key in the future, thus a one-to-one mapping between *bldg:measuredHeight* and *height* can be accomplished.

The CityGML attribute *bldg:roofType* is also defined via codes, representing specific values. Within OSM, the key *building:roof:shape* is mainly used for adding information about the roof type, although there are also two other keys (*building:roof:type* and *building:roof:style*). However, the latter two are hardly used (*Tagwatch 2011a*), *i.e.*, *building:roof:shape* is the most relevant key. Table 5-1 contains all possible codes for the

CityGML attribute *bldg:roofType*. Furthermore, a mapping with the currently existing values of the key *building:roof:shape* (*cf. Tagwatch (2011a)*) is also proposed in Table 5-1.

The two remaining CityGML attributes *bldg:storeysHeightsAboveGround* and *bldg:storeysHeightsBelowGround* do not have a direct counterpart in OSM (*i.e.*, mapping class (iii)). Nevertheless, they can be populated by approximate calculations. Both attributes contain an ordered list of the heights of the storeys, whereby those above the ground are listed in ascending order and those below the ground in descending order. The different values for the attribute list *bldg:storeysHeightsAboveGround* can be calculated by dividing the value of *bldg:measuredHeight* by the value of *bldg:storeysAboveGround*. However, this calculation is very approximative and the results can vary greatly from the real world. Due to missing information the attribute list *bldg:storeysHeightsBelowGround* cannot be provided. Nevertheless, a very coarse solution is to define all heights below ground equally to the average height of those above the ground.

Table 5-1. Mapping the values of building:roof:shape to bldg:class IDs.

OSM value for *building:roof:shape*	***bldg:class* Code**	***bldg:class* name**
flat	1000	flat roof
lean_to, lean-to, ridged, ridge	1010	monopitch roof
	1020	skip pent roof
gable, gabled, pitched	1030	gabled roof
hipped, hip	1040	hipped roof
	1050	half-hipped roof
mansard, gambrel	1060	mansard roof
crosspitched	1070	pavilion roof
cone, domical	1080	cone roof
	1090	copula roof
	1100	shed roof
catenary	1110	arch roof
pyramid, pyramidal, elongated_square_pyramid	1120	pyramidal broach roof
berlin	1130	combination of roof forms

One very important attribute of *_AbstractBuilding* is *bldg:address*, which describes the address of the building. It is provided within the feature *core::Address* and consists of several attributes. The values for these attributes can all be gathered from VGI, because there is a corresponding OSM key for all of them. That is, all attributes within *core::Address* can be populated with a direct one-to-one mapping, thus they belong to mapping class (i). The XML structure of *bldg:address* is depicted in Figure 5-4, whereby the required OSM keys are given in braces.

Concluding it can be said that all attributes of *_AbstractBuilding* (except *bldg:yearOfDemolition*) can be populated with information from OSM. The question whether it is likely or not that these values will be provided by the OSM contributors, will be discussed in the last Section.

```
<bldg:address>
  <Address>
    <xalAddress>
      <xAL:AddressDetails>
        <xAL:Country>
          <xAL:CountryName>{VALUE OF OSM KEY addr:country}</xAL:CountryName>
          <xAL:Locality Type="Town">
            <xAL:LocalityName>{VALUE OF OSM KEY addr:city}</xAL:LocalityName>
            <xAL:Thoroughfare Type="Street">
              <xAL:ThoroughfareNumber>{VALUE OF OSM KEY addr:housenumber}</xAL:ThoroughfareNumber>
              <xAL:ThoroughfareName>{VALUE OF OSM KEY addr:street}</xAL:ThoroughfareName>
            </xAL:Thoroughfare>
            <xAL:PostalCode>
              <xAL:PostalCodeNumber>{VALUE OF OSM KEY addr:postcode}</xAL:PostalCodeNumber>
            </xAL:PostalCode>
          </xAL:Locality>
        </xAL:Country>
      </xAL:AddressDetails>
    </xalAddress>
  </Address>
</bldg:address>
```

Figure 5-4. Attributes of the _AbstractBuilding class.

5.5.2 Derivation of CityGML LoD1 Building Models

In CityGML, LoD1 buildings are visualized as the "*well-known blocks model comprising buildings with flat roofs*" (*Gröger et. al. 2008*). As described in the CityGML schema (*cf. Gröger et. al. (2008)*), the geometry of a building in LoD1 can be represented in two different ways: on the one hand by utilizing *gml:_Solid* for modeling the building as a volumetric object, or on the other hand by utilizing *gml:MultiSurface* for modeling the exterior surface of the building. Generally, every wall of the building is represented as a single flat surface. However, general details, *e.g.*, edges or holes are also visualized (*cf.* Figure 5-5 (b)).

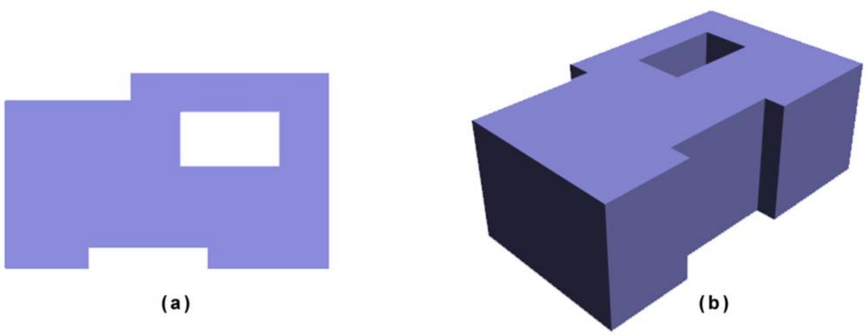

Figure 5-5. (a) Complex shaped building footprint with a hole, and (b) and corresponding geometrical representation of this building in CityGML LoD1.

A quite straight forward approach for generating LoD1 CityGML models from OSM is to acquire the ground shape of the building from the tagged nodes, ways and relations (representing the ground floor of the building) and the height of the building from the corresponding value pairs in OSM, as already described in the previous Section. That is, by extruding the building footprint with the corresponding height, a LoD1 model geometry can be easily created. Figure 5-5 (a) depicts an exemplary building footprint. By extruding this footprint, a CityGML LoD1 model is created in Figure 5-5 (b). As described beforehand in the OSM introduction, users can map buildings by either using one single closed way or by using a relation (consisting of several closed ways). In the former case, the footprint extraction is straightforward: the closed way represents the outer shell of the footprint polygon, *i.e.*, the coherent area which is enclosed by the OSM linestring represents the footprint polygon. In the latter case, it needs to be considered that there are holes inside the building footprint, which makes the building footprint creation process a bit more complicated. After creating the footprint polygon based on the outer shell, it is additionally necessary to create a polygon for each individual inner hole (also by computing the coherent area which is enclosed by the corresponding OSM linestring). The final building footprint polygon can then be gathered by subtracting the inner polygons (*i.e.*, the holes) from the outer polygon (*i.e.*, the shell).

5.5.3 Derivation of CityGML LoD2 Building Models

Compared to a CityGML LoD1 model, a LoD2 model’s façade and roof is represented in a greater detail, which is the main difference between these two LoDs. In particular, the shape of the roof is modeled as a real geometry (and not only as a flat roof). From a geometrical point of view, in LoD2 the outer walls are represented by multiple faces and curvatures in the façade are also visualized. Additionally, in LoD2 it is possible to represent outer building installations such as balconies, dormers, stairs, etc., within the *BuildingInstallation* class as an aggregation of different geometric types of *gml:Geometry*. In contrast to LoD1, in LoD2 it is furthermore possible to model different outer building parts with different classes. These classes, namely *RoofSurface*, *WallSurface*, *GroundSurface* and *ClosureSurface* are combined in the parental class *BoundarySurface* and can be utilized for a separate visualization of roof shapes, wall shapes, ground shapes and closure shapes. Furthermore LoD2 models allow the provision of textures to walls and/or roofs. That is, different outer building parts can be either differentially colored or can be wrapped by a 2D texture.

In order to generate CityGML LoD2 models, the *WallSurface* objects in the CityGML model will be generated based upon the mapped ground shape. Each segment (*i.e.*, the line between two adjacent OSM nodes) of the way which is utilized for mapping the ground shape is individually extruded with the height of the building, thus individual *WallSurface* geometries are generated. For modeling building elements which are above the ground or closures in the surface, there is additional information required. OSM provides the two keys *building:min_height* and *building:min_level*, whereby the former describes the height of the space between the ground and the building and the latter the amount of storeys which are between the ground and the building. So whenever a building (part) is enriched with one of these keys, the corresponding WallSurface geometry needs to be raised in the air. In the case that *building:min_level* is provided, general assumptions about the average height of a level need to be performed.

Additionally, the geometry of the roof (*i.e.*, the *RoofSurface* class) needs to be modeled. For that purpose, OSM provides different keys with relevant information about the roof. Table 5-2 lists the most relevant OSM keys containing information about the roof of a building, as well as potential alternative OSM keys which might contain similar information (last column). However, the keys in the first column are those which are used more regularly, so wherever applicable, the keys in the first column are to be preferred. Concluding, it can be said that by analyzing the values of these keys it should be possible to create a roof geometry which is quite similar (in the best case even equivalent) to the real roof, at least for the sake of LoD2 buildings. Since methodologies and algorithms for the creation of roof geometries are quite complex, and information about detailed (sub)structures of the roof or triangulation points are missing in OSM, it is not possible to describe the geometry creation process in detail within this paper. Generally, good results can be achieved by using skeleton computation with procedural extrusion (*Kelly & Wonka 2011; Laycock & Day 2003*), however a broad application for many buildings results in high computation costs, and there are also many special cases and exceptions which yet require manual adjustments.

The ground geometry of the roof (*i.e.*, the plane between the building and the beginning of the roof) can be generated by acquiring and elevating the geometry of the ground shape of the building. When a building roof has eaves, OSM provides the key *building:roof:extent* for describing their length. That is, whenever *building:roof:extent* is provided, it must be considered while creating the roof geometry. The *GroundSurface* object in CityGML LoD2 can be generated respectively (without considering the extent).

As stated above, CityGML LoD2 models can also be enriched with textures. Within OSM there are currently no keys proposed for providing a link to a texture for the façade or roof. Nevertheless, there are some OSM keys which contain information about the roof material and color (*cf.* Table 5-2). Additionally, there are two keys, namely *building:cladding* and *building:facade:colour* which contain information about the building façade. By analyzing these keys it should be possible to either create an appropriate but simplified synthetic texture on-the-fly (*Coors 2008*) or to select a texture from some kind of predefined textures database. For modeling details about building installations such as stairs or balconies, there are currently no appropriate keys promoted in OSM. That is, most building installations in CityGML LoD2 cannot yet be created from OSM data.

Table 5-2. OSM keys containing information about the building roof.

OSM key	**Exemplary Value**	**Alternative**
building:roof	tile, slate, flat, tile_red, reet	
building:roof:angle	30, 45, 10, 15	
building:roof:colour	grey, red, brown	building:roof:color
building:roof:material	shingles, slate, cardboard	
building:roof:orientation	along, across	
building:roof:extent	0.1, 0.3	
building:roof:ridge	yes	
building:roof:shape	pitched, hipped, flat, ridged	building:roof:style, building:roof:type

5.5.4 Derivation of CityGML LoD3/LoD4 Building Models

The main characteristics of LoD3 building models (in contrast to LoD2 models) are that outer building openings and installations such as windows, doors or chimneys are visualized. Since there are currently no examples in OSM of how to map such details and there is also no methodology presented of how to do it, the OSM database does not contain such detailed building information. That is, currently it is not possible to generate LoD3 models from OSM. The even more detailed LoD4 models do visualize inner building parts. However, until now OSM does practically not provide any detailed information about inner floor plans and footprints. There are only some very rare examples (*cf. OSM (2011e)*) of footpaths that go inside buildings and provide indoor routes on the ground floor (but not on any other floors). Therefore, at the moment it is not possible to derivate LoD4 models from the OSM database.

5.6 Conclusions and Future Work

Collaboratively and voluntarily collected geoinformation can serve as a real alternative data source for different applications. For automatically creating standardized and interoperable 3D CityGML models which can be used in professional GIS applications, information from VGI communities (especially OpenStreetMap), could be utilized, if a formal framework can be made available. Following an introduction to CityGML and the VGI community OpenStreetMap, a background literature review is provided and afterwards a general overview of information transformation (both semantic and geometric) from OSM to CityGML is proposed. The presented framework discusses which semantic attributes of CityGML can be derived and furthermore investigates how geometries in different CityGML LoDs can be extracted from OSM data. An overview about the results of the conducted investigations is summarized in Table 5-3.

Table 5-3. Summary about feasible and non-feasible transformations from OSM to CityGML.

What	**Result**	**Comment**
CityGML attributes	feasible	Nearly all CityGML attributes (except *bldg:yearOfDemolition*) can be populated by using VGI from OSM
LoD1 geometry	feasible	A blocks model can be created by extruding ground shape geometry of the building (provided as a way or relation in OSM) with the building height (provided as OSM key).
LoD2 geometry	feasible	A building model with individual surfaces (*e.g.*, *GroundSurface*, *WallSurface* etc.) as well as a roof geometry can be created by extruding the different segments of the ground shape polygon (similar to LoD1) and computing a suitable geometry for the corresponding roof type (based on provided OSM keys).
LoD3 geometry	not feasible	OSM does not yet contain information about windows or doors, thus a LoD3 geometry cannot be created by purely using VGI from OSM
LoD4 geometry	not feasible	OSM does not yet contain information about rooms inside buildings or their interior structure, thus an LoD4 geometry cannot be created by purely using VGI from OSM

With this framework, an ideally mapped building (*i.e.*, a building enriched with all required key-value pairs) can be extracted from OSM as CityGML model. However, due to missing ideas and methodologies for mapping building installations or indoor spaces in a key-value pair based way (as described beforehand), it is currently not possible to generate LoD3 or LoD4. Nevertheless, by applying the framework to an ideally tagged urban region, all buildings can be extracted as CityGML LoD1/LoD2 models, thus can be exchanged and utilized in professional applications.

As described above, for an ideal result it is crucial that all relevant data is provided. Currently, there are only a few buildings with all relevant information available and therefore the broad application of the presented framework will not lead to satisfying results. That is, the usage of the relevant keys needs to be promoted inside OSM, so that more and more buildings will be enriched with the required information. One way for such a promotion is the development and improvement of 3D applications such as OSM-3D, because these demonstrate to the OSM community, why it is useful to contribute the corresponding building data. A broad availability of high-quality mapped buildings inside OSM will result in detailed CityGML models for several areas.

Also, the quality of the available data is not yet investigated in detail. There are some investigations regarding OSM accuracy and completeness (as described in the OSM introduction at the beginning of this paper), but their focus is more on the landscape and street network and not that much on the buildings and their attributes. That is, additional investigations and comparisons (for example to official data) need to be performed. By doing so, the expected high quality of OSM can be demonstrated.

The framework presented in this paper only concentrated on unidirectional information transformation from OSM to CityGML models, as the need for such a transformation appears more eminent today. Nevertheless, bidirectional transformation also might be required to support the import of official CityGML models to OpenStreetMap. However, the authors of this paper argue that the transformation from OSM to CityGML seems to be more complex than the other way round, thus a conversion from CityGML to OSM should also feasible.

As a future step, work on the development of an algorithm which implements the presented framework and automatically creates CityGML LoD1 and LoD2 buildings from OSM will be undertaken, which is an interesting, but also challenging task. Especially an algorithm which is capable to deal with buildings that are not ideally tagged, thus generates adequate building hypotheses, is important and desirable. Also, the creation of adequate roof geometries needs to be investigated.

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6 Publication 2: Extending OpenStreetMap to Indoor Environments: Bringing Volunteered Geographic Information to the Next Level

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Marcus Goetz has developed both the 3D Building Ontology as well as the OSM Indoor Extensions himself and has written the manuscript himself. All Co-authors have supported this publication by continuing discussions about the design, methodology and the results of the developed OSM indoor mapping extension.

Alexander Zipf

Extending OpenStreetMap to Indoor Environments: Bringing Volunteered Geographic Information to the Next Level

Abstract

Extensive and high-quality geographic data sources are important for any kind of spatial analysis or application, especially in the field of urban data management. In the last couple of years, Volunteered Geographic Information (VGI) has increasingly gained attractiveness not only to amateur users, but also to professionals in the geoinformation industry. Different VGI communities evolved and especially the OpenStreetMap (OSM) community became very strong. OSM provides very detailed information about the landscape, the street network and also more and more buildings are mapped. However, until now, this building mapping is mainly related to the outer shape of the ground space of the building and there is hardly any information about the inner structure available. This paper presents an approach of extending the OSM tagging schema to indoor environments. A 3D Building Ontology targeted to VGI communities is presented for describing different information aspects about buildings and their inner structure. Based on this ontology, the OSM extension is developed and explained. A proof of concept is given by applying the developed extension in mapping a use case building.

6.1 Introduction

When dealing with spatial and geographic phenomena in urban regions and performing analysis and computations about them, it is always important to have enough high-quality data. In the past, urban data management used to be performed by professional cartographers, public authorities or commercial data providers. Nevertheless, in the last couple of years a new and different trend for data collection has evolved, describing the collaborative and volunteered collection of geographic data. According to *Elwood (2009)* there are many different terms for this trend, but one of the most popular terms is Volunteered Geographic Information (VGI). VGI comprises the effect that an ever-expanding range of users creates, assembles and disseminates geographic and spatial data in a collaborative and volunteered manner (*Goodchild 2007a*). That is, individual persons or groups collect and create geographic data based on their personal measurements (via GPS etc.) and their knowledge about their surroundings and furthermore share that information with others through open web platforms. VGI is a combination of elements of the Web 2.0 and a collective intelligence, and there is an enormous potential arising from six billion humans acting as remote sensors (*Goodchild 2007b*). That is, VGI can also be considered as a new opportunity of systems and sensors for monitoring urban and regional environments. Particularly in urban environments the coverage is very good, because many humans results in many potential sensors and therefore the usage of VGI in urban management increases (*Song & Sun 2010*). Furthermore, public participation in urban planning and data management gets increasingly important (*cf. Hansen (2004), Bugs et. al. (2010)*).

Diverse online mapping platforms such as OpenStreetMap (OSM) or Wikimapia have been initiated, allowing users to contribute and collaboratively edit spatial data. The increasing number of participants leads to a variety of different spatial data and information about geographic phenomena such as the street network, cities, POIs, buildings, landuse etc. At UDMS 2009, VGI has also been shown to be useful for urban data management by providing new sources of information that even can be integrated into a 3D platform (*Schilling et. al. 2009*).

However, most of current mapping activities are related to the outdoor environments (*e.g.*, rough building structures, information about type of businesses, playgrounds, footpaths etc.) and there is hardly any information about indoor environments available. Since there is an increasing need for mature indoor navigation solutions and other indoor location based services (*Goetz & Zipf 2010*) and data providers are hardly able to commercially capture indoor data for large areas, there is an enormous potential within VGI communities for capturing and providing information about indoor environments which are open to the public (*e.g.*, airports or shopping malls). For that purpose, it is essential to provide clear and understandable methodologies for mapping data about indoor environments. Therefore the main contribution of this paper is an extension to indoor environments for bringing VGI to the next level.

The remainder of this paper is organized as follows: First, there is an introduction to OpenStreetMap, especially focusing on its data model and data acquisition methods. Afterwards, there is a brief overview about related research. Thereafter, an extensive ontology for 3D building models with detailed information about indoor environments is presented. Subsequently, there is a description of how to extend the existing OSM tagging schema to indoor environments according to this ontology. The presented methodology is demonstrated on a use-case building and the last Section summarizes the presented research and discusses future work.

6.2 The OpenStreetMap Community

One very popular (or even the most popular) VGI community is the so called OpenStreetMap project. OSM follows the peer production model (*Haklay & Weber 2008*) that created Wikipedia and aims for the provision of free to use and editable map data. Since 2004, the project grew rapidly and by November 2010 there were more than 320.000 registered users and more than 2,000 million tracked points in the database (*OSM 2010a*). The data in OSM is created in different ways. The most important way is the acquisition of original data, manually captured by users via GPS devices. However, people can also contribute data based on aerial images (*e.g.*, by Bing or Yahoo) or by contributing their local knowledge about the region they live in.

Basically, OSM consist of differently tagged nodes, *i.e.*, a point with distinct coordinates. For defining lines or simple polygons (*i.e.*, a polygon without holes), users can create so called ways which consist of several nodes. For defining a polygon, this way needs to be closed, *i.e.*, the start point equals the end point. For mapping complex polygons or describing existing relationships between different elements, there are furthermore so called relations. These contain ways, nodes and also other relations.

In conjunction with user-generated content and collaboratively collected data, there is always a question about the accuracy and quality of the provided data. By comparing OSM data with data provided by commercial vendors like Teleatlas, it became evident that VGI is able to compete against commercial providers (*cf. Zielstra & Zipf (2010), Haklay (2010), Ludwig et. al. (2010)*). That is, data from OSM can be considered as a real alternative data source for spatial and geographic data in urban environments.

The data of OSM mainly focuses on outdoor environments and objects (*e.g.*, streets, landuse etc.). When considering buildings, some information can be available within OSM, but these do only refer to very basic things like the location, outer shape or the height of the building. The latter mentioned information can be applied in the 3D visualization of city models as within the OSM- 3D project (*Over et. al. 2010*). There are also some discussions about indoor mapping (*cf.* next Section), but until now they cannot be regarded as mature.

6.3 Related Work

When investigating new models for the built environment provided by volunteers in a crowdsourcing approach, it first needs to be assessed, what the state of art of existing and professional building models looks like. There are some basic topological data structures and models such as *Molenaar (1990)*, *Zlatanova & Tempfli (1998)*, *Coors (2003)*, *Billen & Zlatanova (2003), Holweg et. al. (2004)* or *Zlatanova et. al. (2004)*, but they do not focus on semantic aspects, thus they are not applicable for the intended purpose.

The term Building Information Modeling (BIM) describes the process of generating and managing building data (*Ashcraft 2007*), whereby typically 3D modeling approaches are utilized. A commonly used format for BIM is the Industry Foundation Classes (IFC), describing a neutral and open specification which is also registered as ISO 16739 (*IFC 2010*). IFC is an object- oriented model which consists of hierarchically organized classes (often hundreds or thousands). Examples for such classes are *ifcWall* or *ifcWindowType*, describing on the one hand a particular part of the building and on the other hand adding additional information about the type of the window. The classes in IFC can be divided into many different groups or concepts (for a detailed description refer to *IFC (2010)*), which on the one hand makes the whole framework very extensive and powerful, but on the other hand very complicated and confusing. The latter mentioned fact is also the reason why IFC is good for professional purposes, however for involving the broad public and average hobbyists, IFC is way too detailed and complex.

A closely related initiative to IFC is the City Geographic Markup Language (CityGML) which is an Open Geospatial Consortium (OGC) standard based on GML3. It is usable for describing geometric, topologic and semantic aspects of urban spaces and city models in a three-dimensional way (*Kolbe et. al. 2005*). Thereby it does not only focus on buildings, but also on other objects (*e.g.,* vegetation). Furthermore, semantic and spatial aspects are structured into five different Levels of Details (LoD), where LoD0 describes a coarse model of the city and LoD4 (*i.e.,* the most detailed one) even contains information about indoor environments. That is, CityGML can be utilized for a detailed and fine-grained description of buildings and their interiors. Nevertheless, CityGML is rather considered as a storage and exchange format for 3D city models and is mainly used by professionals. It is likely that CityGML is too complex for an application within VGI. But when new models for community based urban modeling tasks are proposed, these existing standards will provide some useful hints that shall ease the future combination of models from both worlds.

When trying to model 3D buildings, it is essential to share a common understanding of what kind of information is relevant and important. Therefore, different ontologies for buildings and indoor environments have been developed in past research efforts. *Anagnostopoulos et. al. (2005)* developed an extensive indoor navigation ontology, which is usable for path searching as well as for the presentation tasks of the navigation system. However, despite the many details about the indoor space, the presented ontology does not provide any information about the building itself. For modeling, visualization and other purposes, such information is nevertheless very important and therefore should be considered in a 3D building ontology.

A different approach is presented by *Yuan & Zizhang (2008)*. Based on BIM, the authors propose an indoor navigation ontology which captures different parts inside the building such as corridors, elevators, stairways, doors etc. However, this ontology does also not provide information about the overall building (*e.g.*, façade color, roof type etc.) and furthermore details about concrete measures and positions of the rooms etc. are also not covered by this ontology.

Dudas et. al. (2009) present ONALIN, an ontology which considers the special needs and requirements of different groups and individuals, whereby a strong focus lies on the limitations of different users (*e.g.,* visually impaired, wheelchair driver etc.). ONALIN is a "*comprehensive ontology that considers the needs of all potential people traversing in buildings based on the ADA (Americans with Disabilities Act) standards*" (*Dudas et. al. 2009*).

Other ontologies are furthermore presented by *Andersen & Vasilakis (2007)* and *Lee et. al. (2008)*. However, these are either not detailed enough for both outer appearance and inner structure, or on the other hand they are too detailed, so it is likely that the average OSM user won't be able to capture all required data.

Besides scientific work on 3D building modeling frameworks and ontologies, there is also some related work within the OSM community. In *OSM (2010b)* it is described how to map buildings. By utilizing the key-value *building = yes*, users are able to describe the ground shape of a building with a set of individual nodes. Furthermore the keys *height* and *building:height* can be utilized for adding information about the (estimated) height of the building. Currently there are almost 36 million buildings available and about 636.000 of them contain height information. Furthermore there are some discussions about how to map indoor environments (*OSM 2010c*). Thereby the key-value *indoor=yes* has been proposed, indicating that the corresponding OSM object is inside a room or building. Furthermore the key *level* shall be used for describing in which building level the corresponding OSM object is located. Currently there are about 3.000 indoor objects available, so compared to the whole dataset, the coverage of the indoor key is negligible. Nevertheless, there is a strong trend towards building and indoor mapping activities. In Germany currently over 100.000 new building outlines are added to OSM every week. The development of the usage of the keys building and indoor is depicted in Figure 6-1 (a) and Figure 6-1 (b). There is an accelerating increase of the usage and it is likely that this development will increase even further in the near future as it has been the case with other object types in OSM before. Especially when more and more outdoor spaces are completely captured, it is likely that the community will commence with buildings and indoor spaces.

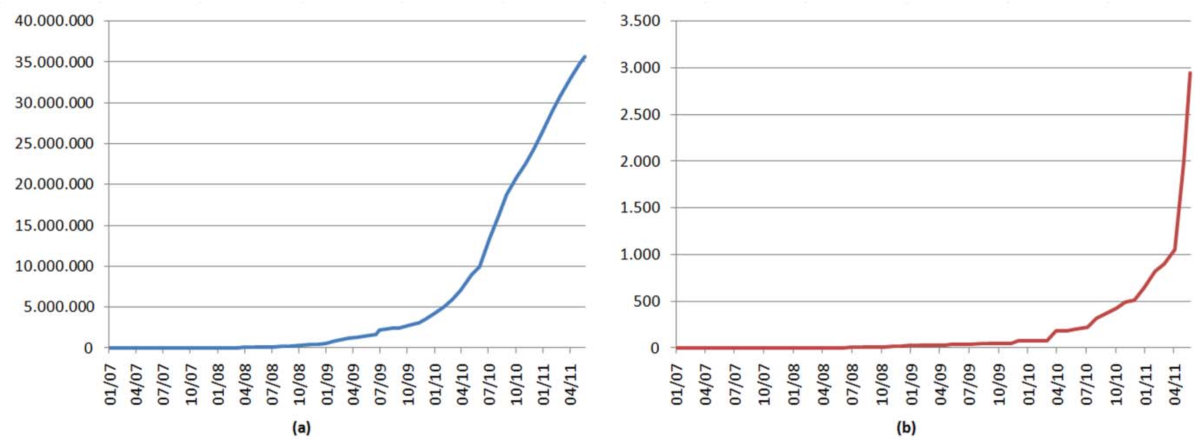

Figure 6-1. Usage of the building key (a) and the indoor key (b) between 2007 and 2010.

6.4 3D Building Ontology

Indoor spatial information and data allows transferring and extending popular existing outdoor applications and services (*e.g.*, routing, navigation or mapping) to indoor environments. In doing so, diverse indoor services (*e.g.*, navigation in a shopping mall or train station) can be provided to the public, thus assist the users in difficult situations and therefore increase their quality of life. As mentioned above, a commercial data collection for broad indoor areas is not likely and therefore it is a good opportunity to include and involve voluntarily acting hobbyists in the data acquisition process. This however leads to kind of a cleavage, because on the one hand a scientific correctness and completeness is required for proper applications, but on the other hand the OSM community is likely to not accept and utilize too complex methodologies. That is, there is a trade-off between the comprehensiveness and the usability of the invented methodology. Trying to be able to share a common understanding of building information and fulfilling a scientific correctness and completeness, a 3D Building Ontology (*3DBO*) has been developed.

Thereby, the ontology is designed as simple as possible, having in mind that not only professional users will use the extension but mainly normal users without professional skills. The ontology is suitable for describing the outer appearance and characteristics of the building as well as the inner building structure and it is likely that all relevant data can be captured by the community. So on the one hand, the ontology is kept as simple as possible, but on the other hand it contains enough information for different purposes such as a quite realistic visualization of the building or the provision of different indoor applications and services.

The ontology has been developed in OWL/RDF using Protégé. It is visualized in Figure 6-2 and a human-readable documentation is given below:

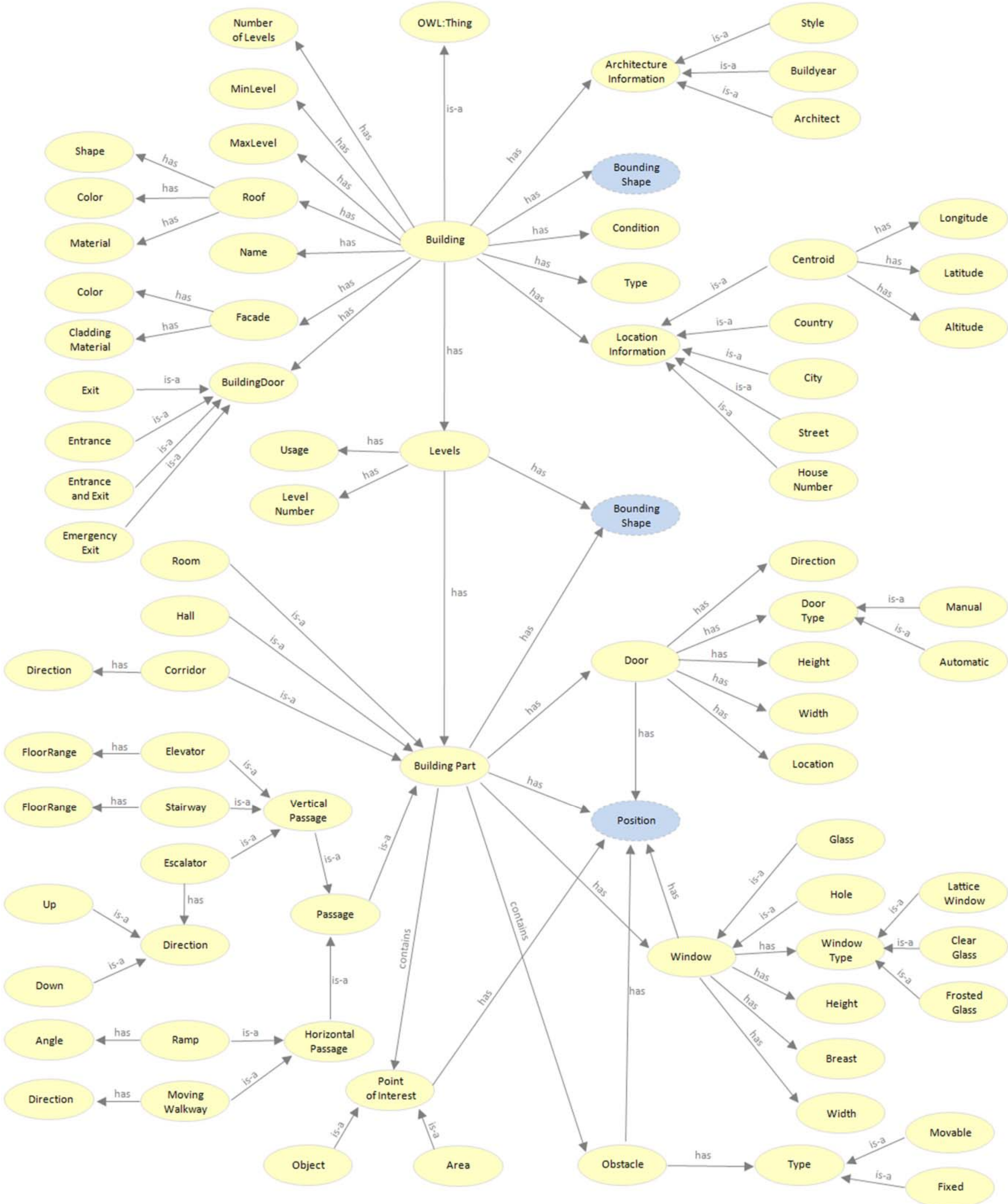

Figure 6-2. 3D Building Ontology for describing the inside and outside of a building.

Building: The concept of a building is the main part of the developed ontology. A building has diverse characteristics which describe the outer appearance of the building. One example is the roof of the building which can be described according to its shape (*e.g.,* flat, gabled etc.), color (*e.g.,* black, red etc.) or material (*e.g.,* aluminum, wood etc.). A building also has distinct shape, considering the ground area. The façade of the building can be described by a color and the cladding material (*e.g.,* glass, concrete etc.). There are also additional semantic characteristics describing the building such as its condition (*e.g.,* new, renovated etc.), its type (*e.g.,* public, academic etc.), its name (*e.g.,* "BST 48") or its total number of levels. Architectural information such as style or buildyear can also serve as additional information. Furthermore the location of the building can be described by an address and/or the exact coordinates.

BuildingDoor: A building has one or more building doors, describing a direct connection through a door from the inside of the ground floor to the outside and vice versa.

Levels: A building contains a distinct amount of levels (one or more), whereby each of them has a level number (*e.g.,* -1, 2). A level has a bounding shape which can vary from the building area and it can have a particular usage (*e.g.,* commercial, residential, etc.).

BuildingPart: A buildingpart describes any spatial element that is part of a distinct level. Those can be generally categorized as rooms, halls, vertical passages or corridors, whereby corridors can have a distinct direction. Such buildingparts can be described according to their bounding shape and they furthermore have a concrete position on the floor. They can have windows, whereby these are described by their width, height, breast (*i.e.*, height from the ground to the bottom of the window), position and type (*e.g.,* lattice window, clear glass etc.). Similar to the concept of windows, buildingparts also have doors, whereby these are described by their width, height and position. Doors have a distinct type and can be mainly categorized into automatic doors and manual doors. Additionally, doors can have a direction, describing that the door is only usable in one direction (*e.g.,* security gates at the airport).

Point of Interest: A Point of Interest (POI) describes a distinct area (*e.g.,* smoking area) or object, which might be of interest or usefulness for a user (*e.g.,* a landmark for navigation).

Obstacle: A floor element can contain an obstacle, whereby the obstacle has a distinct position. These obstacles can either be a movable (*e.g.,* an office desk) or fixed (*e.g.,* a raised stage). These groups of obstacles have in common that they are characterizing features of a floor element and furthermore it is important to be aware of them for different applications (*e.g.,* indoor navigation of the blind).

Horizontal Passages: Horizontal passages are areas or elements inside floor elements. They can be divided into ramps with a distinct angle and into moving walkways with a distinct direction. Such passages furthermore have a position inside the floor element.

Vertical Passages: The main types of vertical passages are elevators, stairways and escalators. The two former ones both have a floor range (*e.g.*, a stairway from the first floor to the sixth floor). In contrast, the escalator does not have a floor range, but a distinct direction describing that it is either going up to the next floor or down to the previous floor.

The presented ontology is a generic spatial ontology for describing generic buildings with indoor spatial environments. It is of course not complete in terms of containing all information about a building (*e.g.*, information about power cables etc.). However it represents a suitable selection of relevant building information for the described application areas (*cf.* above).

Table 6-1. Proposed relation tags for general building information.

Key	**Description**	**Exemplary Value(s)**	**Tag Count***
building	it’s a building	yes	35.670.028
building:levels	number of levels	4	305.603
building:min_level	minimum level	-1	1.504
building:max_level	maximum level	6	
building:roof	roof shape	flat, pitch, hip	21.445
building:roof:color	roof color	black	781
building:roof:material	roof material	cardboard	28
name	building name	Federal hospital	475.935
building:cladding	façade material	glass	6.876
building:facade:color	façade color	yellow	60
building:facade:image	URL to façade image	http://url.de/image.gif	
building:architecture	architecture style	modern	270
building:buildyear	buildyear	1987	14
building:architect	architect	Neumann	2
building:height	building height	25m	27.804
height	building height	25m	608.877
building:condition	building condition	renovated	46
addr:country	country	Germany	1.075.942
addr:city	city	Munich	1.396.895
addr:street	street	Luisenstraße	2.158.250
addr:housenumber	house number	5	2.298.275

* if this key is already available in OSM, the number in the column indicates the total usage amount (based on personal analysis)

6.5 Extending the OSM Tagging Schema to Indoor Environments

The fundamental basis of the OSM schema extension is the above presented *3DBO*. In most cases, buildings in OSM are mapped as a closed way or, in the case of a complex building shape, as a relation. The principle of the developed extension is to map the building as a relation. For every level inside the building there is one relation member (which also will be a relation) and one additional relation-member per building door. These doors are mapped as single nodes on the bounding shape with key *building:entrance* and values *yes*, *entrance, exit*, *emergency*, *both*. The relation itself has diverse key-value pairs for adding (semantic) information about the building (*cf. 3DBO*). The proposed keys with exemplary values are described in Table 6-1. The blue colored ovals with dashed contour in the *3DBO* (*cf.* Figure 6-2) illustrate all building parts which actually need to be mapped in *JOSM* – all other information is added as key-value pairs.

As mentioned before, each level is also defined as a relation respectively. The members of these relations are other relations, ways or single nodes, representing the different elements (rooms, halls, corridors, passages etc.) in this level. An additional relation-member (way or relation) is introduced for mapping the bounding shape of this distinct level. The relation itself again has diverse key-value pairs for adding additional information. The proposed keys for the OSM extension are depicted in Table 6-2.

Table 6-2. Proposed relation tags for general level information.

Key	**Description**	**Exemplary Value(s)**	**Tag Count***
indoor	it's inside the building	yes	2.950
name	Name of the level	Ground floor	
level:usage	Usage of the level	academic *	
level:height	Height of the level	4m	
building:level	Actual level number	1	2.884

* some values of the OSM key amenity are also reasonable for *level:usage*

The different elements of a distinct level are modeled as relations, ways or single nodes (depending on their requirements and complexity). For example, windows or doors are mapped as single nodes which are part of the corresponding element shape. That is, the bounding shape is mapped with a closed way and at every position where a window is located, there is a node with the tag *buildingpart:window*. Furthermore, there is additional information attached to them (*e.g.*, *height* or *width*). In a similar way, rooms, halls or corridors are mapped as (closed) ways and tagged with *indoor=yes*. The before described procedure is valid for any kind of level element (*cf. 3DBO*). The possible and reasonable keys for additional information are listed and described in Table 6-3. The position of the different elements is implicitly provided by their nodes. For mapping obstacles inside buildingparts (*e.g.*, a strut in a hall) there are two possibilities. If the obstacle belongs to the building and is not movable, it is the best to map it as a hole in a polygon (considering the hall shape as a polygon and the strut as a hole). In contrast, if the obstacle is not part of a building (*e.g.*, an office desk), it is possible to map it as a closed way or single node with the keys *obstacle=yes* and *obstacle:type* with value *movable* or *fixed*.

Table 6-3. Proposed tags for buildingparts (nodes, ways or relations).

Key	**Description**	**Exemplary Value(s)**
buildingpart	what type of buildingpart	room, hall, corridor
name	name of the buildingpart	Room 101
buildingpart:corridor:direction	corridor direction	one-way
buildingpart:height	height	3m
buildingpart:window	it's a window	yes, glass, hole
buildingpart:window:type	window type	lattice window, frosted glass
buildingpart:window:height	window height	1.2m
buildingpart:window:width	window width	1m
buildingpart:window:breast	breast of the window	1.3m
buildingpart:poi	point of interest	object, area
buildingpart:door	it's a door	yes, manual, automatic
buildingpart:door:height	door height	2m
buildingpart:door:width	door width	1m
buildingpart:door:direction	door direction	one-way
buildingpart:horizontalpassage	it's a horizontal passage	ramp, moving walkway
buildingpart:horizontalpassage:angle	horizontal passage angle	5 degree
buildingpart:horizontalpassage:direction	horizontal passage direction	one-way
buildingpart:verticalpassage	it's a vertical passage	elevator, stairway, escalator
buildingpart:verticalpassage:floorrange	vertical passage floor range	1-5
buildingpart:verticalpassage:direction	escalator direction	up, down

6.6 Exemplary Usage of the Proposed Schema

For demonstrating the OSM indoor extension, the building of the Chair of GIScience of the University of Heidelberg (Figure 6-3) has been mapped. It has four different levels (one basement and three above the ground) and one main entrance. It mainly contains offices and three bigger rooms for lectures. The levels are connected with two different staircases.

Figure 6-3. Use case building.

The location of the building was gathered via GPS. Information about the specific dimensions and the inner structure of the building were gathered by CAD floor plans, kindly provided by building authorities. The whole building was mapped as a relation and several keys (*e.g., building=yes, building:cladding=concrete*, *height=14.5m*, *building:roof=flat* etc.) were attached to it. There are a total of five relation-members, whereby one is a single node (indicating the building entrance) and the other four members are again relations for describing the different levels of the building. For every single level there were different keys (*e.g., level=yes, building:level=1* etc.) attached to the corresponding relation. Several closed ways (as relation-members) were utilized for mapping the bounding shape and the buildingparts of the respective level. Every buildingpart was tagged with the key *indoor=yes* and additional semantic information was added by several key-value-pairs (as described in Section 6.5). Windows were mapped by adding additional nodes to the bounding-shape ways and adding different keys *e.g., buildingpart:window=glass* or *buildingpart:window:breast=1.2m* to them. Doors were mapped in a similar way by adding additional nodes to the corresponding buildingpart ways. The two stairways inside the building were mapped as a closed ways, whereby it has been decided to model the stairs on every level (it is also possible to simply map the stairway on one level and to leave it blank for the other levels). The key *buildingpart:verticalpassage:floorrange=-1 to 2* was utilized for describing the floor range of the respective stairways.

The size and shape of the different buildingparts were gained from the CAD files and manually mapped in the OSM editor *JOSM*. Thereby, all levels have been mapped individually and afterwards manually combined by editing the OSM-XML file. This manual code-editing is required, because *JOSM* (and other OSM editors) lack visualization possibilities for multi-storage buildings with indoor environments and it is hard to distinguish between several overlapping ways. Another problem has been encountered when uploading the mapped building into the OSM database. For some reasons, the OSM renderer does not recognize buildings mapped as relations, whereby the main-relation is tagged with *building=yes*. Instead, it is required that a member of the relation (a closed way) is tagged with *building=yes* key. So at first, the use-case building was not displayed in the OSM map. For overcoming this problem, it has been decided to additionally tag the bounding-shape of the ground floor with the key *building=yes*. Utilizing the bound-shape of the ground floor was obvious, because it describes the building shape on the ground but in general also the other bounding-shapes could have been utilized. Nevertheless it must be said that these problems occur in current editors and renderers because they are not intended for this purpose, but the presented methodology shall be considered as an impulse for improvements.

6.7 Conclusion and Future Work

In this paper, an extension of the existing OSM tagging schema for mapping indoor environments has been proposed. An extensive 3D building ontology has been presented, whereby the ontology suits both the description of the outer appearance and characteristics of the building as well as the detailed description of the inner building structure. Based on this ontology, the existing OSM tagging schema has been extended and methodologies for mapping indoor spaces have been developed. By applying these extensions, members of the OSM community are now able to map indoor spaces, thus provide more detailed information about buildings and their inner structures. Both the ontology and the tagging schema extension have been kept as simple as possible, so it is realistic that the OSM community will understand and accept them.

As described above, existing OSM editors are currently not able to provide an easy-to-use functionality for the presented extensions. Therefore it is important to develop an OSM editor which provides such functionality, so it is possible to map inner building structures in an easy-to-use manner. The use-case demonstrated that existing OSM renderers need refinements, so that relations tagged with *building=yes* are also recognized in the map. Furthermore it will be interesting to see, how relevant data can be captured. Different information such as façade color or roof type can be extracted from images or visual experience, but for measuring distances or positions inside buildings, different methodologies (such as Lidar or pedometers) must be applied. Also future cell phones are likely to contain more sensors for different measurements. Moreover, importing existing standards like CAD, CityGML or IFC into OSM is wishful but a challenging idea for future research, because this would allow an integration of existing floor plans into OSM. For achieving this goal, the presented *3DBO* needs to be compared with IFC and CityGML, so possibilities for transformations can be discovered.

From a different point of view, privacy aspects for indoor spaces are also an important factor. Not every kind of information is appointed to be of interest for the public and providing those bears some kind of security risk, so this field also needs to be further investigated and explored.

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7 Publication 3: Towards Generating Highly Detailed 3D CityGML Models From OpenStreetMap

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Towards Generating Highly Detailed 3D CityGML Models From OpenStreetMap

Abstract

About one decade has passed since US vice president Al Gore articulated his vision of Digital Earth (DE). Within this decade, a global multi-resolution and three-dimensional (3D) representation of the Earth, which sums up the DE vision, increasingly gained interest in both public and science. Due to the desired high resolution of the available data, highly detailed 3D city models comprise a huge part of DE and they are becoming an essential and useful tool for a range of different applications. In the past as well as at present, 3D models normally come from a range of different sources generated by professionals, such as laser scans or photogrammetry combined with 2D cadaster data. Some models are generated with semi-automated or fully automated approaches, but in most cases manual fine tuning or even manual construction from architectural plans is required. Further beyond outdoor city models, DE additionally envisages the provision of indoor information. That is, the interior structure of public or publically accessible buildings, such as airports or shopping malls, is represented and made available in 3D; however, at the moment, such models are mostly created by hand and essentially based on professional data sources. In contrast to such professional data, which is mainly captured by surveyors or companies, the last few years revealed the phenomenon of crowdsourced geodata, which receives an increasing attractiveness as an alternative data source for many Geographic Information Systems (GIS). Former research already demonstrated the power and richness of such geodata – especially OpenStreetMap (OSM) – and it has also been proved that this non-standardized, crowdsourced geodata can be combined with international standards of the Open Geospatial Consortium (OGC). For example, CityGML Level-of-Detail 1 (LoD1) and LoD2 models have already been created automatically from OSM. The research presented in this article will further continue on the automated generation of CityGML models from OpenStreetMap. Essentially, a method for the creation of highly detailed CityGML LoD4 models with interior structures will be explained. By applying the invented approach on existing OSM data, limitations and restrictions of the IndoorOSM mapping proposal, the available data and the developed approach are revealed and discussed.

7.1 Introduction

Couple of years ago at the end of the twentieth century, US vice president Al Gore raised the term 'Digital Earth' (DE), trying to name his vision of a global multi-resolution and three-dimensional (3D) representation of the Earth enabling its users to consume a vast amount of geo-referenced information about the environment (*Gore 1999*). More than one decade later, geo-browsing applications, such as Google Earth or Digital Globe, brought different aspects of DE to the broad public, but "*they still fall short of Gore's vision of a DE*" (*Craglia et al. 2012*). Essentially, DE will not only visualize physical features of the Earth but also contain semantic and qualitative information about both the past and the present and, furthermore, exploiting the full range of information for predictions about the future (*Craglia et al. 2012*). Thereby, the scale and granularity can vary from global and coarse perspectives, up to fine-grained and detailed models. Not only limited to the context of DE, but definitely comprising a huge and important part of it, highly detailed virtual 3D city models are already utilized for various tasks in different applications, such as navigation (*Coors & Zipf 2007*), environmental simulations or facility management (*Kolbe 2009*); emergency response or rescue operations (*Kolbe et al. 2008*); noise mapping, training simulators, architecture or city planning (*Shiode 2001, Döllner et al. 2006*). Thereby, not only the geometry but also semantic aspects about the building, such as its function or type, are becoming more and more important. Currently, the creation as well as the maintenance of such models involves manual work to a considerable degree; thus, obtaining 3D models is still quite expensive. Nevertheless, in the context of DE, recent and up-to-date models are desirable because dynamic and interactive observation systems are one key feature within the vision of DE (*Craglia et al. 2012*). Therefore, automatic procedures for the generation of differently grained 3D models are required.

The above-mentioned application domains are typically related to outdoor areas; however, the idea of DE is way beyond that, additionally aiming at the possibility of consuming and exploring information about building interiors, such as the accurate description of single rooms or apartments. With the increasing size and complexity of public buildings such as airports, shopping malls or hotels, the opportunity to "*explore built environments moving from the inside of buildings to the whole metropolis*" (*Craglia et al. 2012*) becomes more important, additionally raising the need to apply the above-mentioned (outdoor) applications to indoor spaces. Not only limited to the context of DE, indoor spaces are receiving an increasing attention in science (*Jensen et al. 2011*). According to *Winter (2012)*, there are two reasons for this increase: on the one hand, a huge demand for indoor information and, on the other hand, a lack of knowledge to satisfy this demand. One of the biggest arguments for the need of indoor information is that nowadays many human activities, such as orientation or wayfinding, are related to indoors. A study about the average North American recently revealed that, due to activities such as working, living or shopping, about 90% of the time is spent inside buildings (*APS 2008*). Very likely, the amount of time spent indoors reaches similar rates in other developed countries or megacities. It is obvious that people spending so much time indoors are often confronted with foreign environments (*Winter 2012*). That is, for tasks like indoor routing or wayfinding, information about indoor environments is required and it seems apparent that the area of indoor maps and applications is an emerging market. This is underpinned by several global companies, such as *Bing (2011)*, *Google (2011)* or *Navteq (2011)*, starting to offer indoor content, yet limited to 2D, in their well-known map applications. However, 3D models are much richer concerning both geometry and semantics than 2D maps; thus it is and in the future will be even more important to obtain and maintain 3D models for indoor spaces. For complex scenarios and applications, such as 3D indoor navigation, it has been shown that a 3D visualization is beneficial for the user (*Baus et al. 2001, Coors & Zipf 2007*). Additionally, the vision of DE advocates the provision of 3D information for observing, monitoring and forecasting the environment (*Craglia et al. 2012*).

Following the idea of a ubiquitous accessibility of the DE, it is important to provide an interoperable access to 3D city models. For this purpose, the Special Interest Group 3D (SIG 3D) defined the City Geography Markup Language (CityGML), which soon became the international standard for storing, representing and exchanging 3D urban objects (*Kolbe et al. 2005*). The main difference of CityGML to other 3D formats, such as Virtual Reality Modeling Language (VRML) or Extensible 3D (X3D), is that various semantic information, such as names or detailed object types about buildings, can be stored in addition to the geometry. That is, both the visual communication of spatial information and complex analysis about built environments can be performed with CityGML (*Winter 2012*). The creation of CityGML normally requires high-quality data, which is captured by professionals such as architects, public authorities or commercial data providers. Other existing standards from other application domains, such as Industry Foundation Classes (IFC) from the Building Information Modeling (BIM) domain, can be transformed to CityGML (*Benner et al. 2005, Isikdag & Zlatanova 2009*). Nevertheless, the bigger part, especially of the highly detailed models (Level-of-Detail 4, LoD4), is created manually by using Computer Aided Design (CAD) files and 3D graphic applications.

In contrast to professional and proprietary data, in the last couple of years, a new source for geodata evolved: thousands of humans acting as remote sensors (*Goodchild 2007*) collaboratively collect crowdsourced geodata – also called Volunteered Geographic Information (VGI). That is, individuals contribute a massive amount of different (valuable) data, and a future DE should definitely exploit the new opportunities arising from this development, turning citizens into major information providers (*Craglia et al. 2012*). In particular, crowdsourced geodata bears an enormous potential of "*moving from an essentially static representation of the Earth to one that is dynamic and interactive*" (*Craglia et al. 2012*). Regarding the quantity and quality of VGI, recent investigations revealed that – especially in urban areas – VGI is able to compete against proprietary data sources (*Haklay 2010, Mooney et al. 2010, Zielstra & Zipf 2010, Neis et al. 2012*). The crowdsourcing communities (one of the most popular examples is OpenStreetMap, OSM[1]) do not only contain 2D data but also contain 3D information. The potential of VGI as a data source for the visualization of urban regions with 3D city models in a 3D Spatial Data Infrastructure (SDI) (*Zipf et al. 2007*) has already been demonstrated by *Schilling et al. (2009)*. For the application within DE and other application domains, researchers are trying to merge unstructured and non-standardized VGI with CityGML. According to *Goetz & Zipf (2012)*, it is possible to transform semantic information from OSM to CityGML, as well as to automatically generated building block models with simple roof geometries. The generation of fully detailed models with interior structure has, due to the lack of indoor tagging schemas in OSM, not been possible so far. However, with *IndoorOSM* such a schema has just recently been invented (*Goetz & Zipf 2011*) and proposed to the OSM community (*OSM 2012a*). This schema ought to contain all relevant information required for a highly detailed CityGML building model with interior structures. Therefore, the main contribution of this article is the development of a methodology for the automatic generation of highly detailed CityGML models by using VGI from OSM. In doing so, it will be shown that OSM can serve as a reasonable data source for professional applications and analyses, for example, urban planning (*Shiode 2001*), environmental noise pollution (*Czerwinski et al. 2006*) or indoor navigation (*Mäs et al. 2006*).

This article is organized as follows: following introduction, Section 7.2 provides an overview on related work. Thereby, both CityGML and OSM, as well as existing research approaches, are discussed. Section 7.3 identifies relevant constraints and requirements, which need to be fulfilled by *IndoorOSM* data, and further presents the developed approaches for an automatic CityGML model generation. Having sketched out how such a generation can be performed, Section 7.4 applies the developed approaches to current OSM data, investigates the results and provides a comprehensive discussion on the limitations and assumptions of the *IndoorOSM* mapping proposal. Section 7.5 concludes with a summary and provides an outlook on future work.

7.2 Background and Related Work

This Section elaborates required background knowledge as well as existing related work. In Section 7.2.1, an introduction to CityGML is provided. Thereafter, Section 7.2.2 briefly describes the OSM project and Section 7.2.3 gives a detailed description of a recently developed model for mapping indoor information in OSM, namely *IndoorOSM*. Section 7.2.4 provides a brief insight into related work from the field of procedural city modeling and building reconstruction.

7.2.1 Virtual 3D City Models with CityGML

CityGML has been designed with the aim of an interoperable access to 3D city models in SDIs. One main characteristic of CityGML is that the model "*distinguishes between buildings and other man-made artifacts, vegetation, waterbodies, and transportation facilities like streets and railways*" (*Kolbe et al. 2005*). Since different applications require differently detailed city models, CityGML features five LoDs, ranging from a simple 2.5-dimensional Digital Terrain Model (DTM) (LoD0) to a highly detailed model with interior structures (LoD4). Figure 7-1 depicts all the different LoDs.

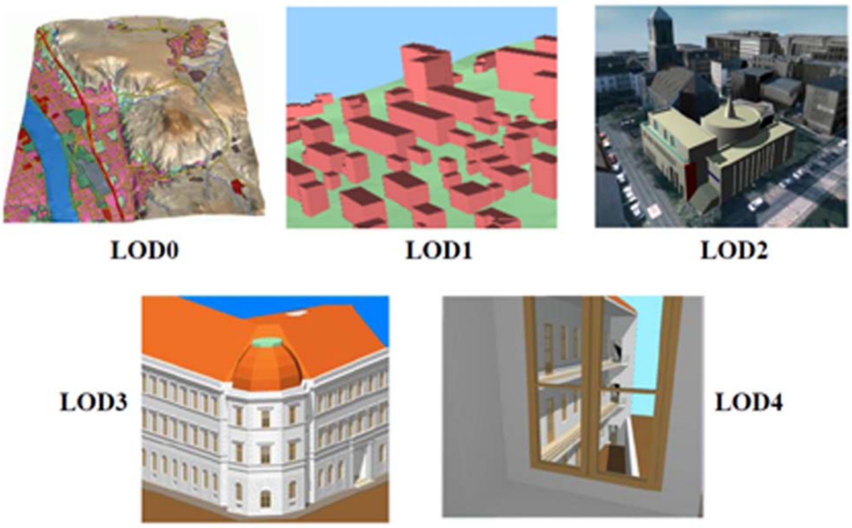

Figure 7-1. The five different Level-of-Details in CityGML (Gröger et al. 2008).

For the representation of thematic, spatial and semantic information of buildings and building parts, CityGML features a very detailed concept of a building model (*Gröger et al. 2008*). The central class of this model is the so-called *_AbstractBuilding* and instances of this class are *Buildings* or *BuildingParts*. Different entities of *_AbstractBuilding* can be organized in an arbitrarily deep hierarchy (*Gröger et al. 2008*). The class itself is derived from the more general class *_CityObject*; thus, *_AbstractBuilding* also inherits all the properties of *_CityObject*, such as *gml:name* or *address*. Additionally, *_AbstractBuilding* contains different semantic, quantitative or metric information, such as *function*, *roofType*, *measuredHeight* and *storeysBelowGround*. Furthermore, various geometric objects, such as *Geometries*, *MultiSurfaces* or *Solids,* represent the geometry of the corresponding entity. Thereby, the amount and type of geometric objects also depends on the respective LoD; so, for example, a complete LoD1 model is described with either *Solid* or *MultiSurface*. In contrast, a LoD2 building geometry (and also LoD3 and LoD4) is separated into a *RoofSurface*, *WallSurface*, *GroundSurface* or *ClosureSurface*. The given introduction to CityGML ought to be enough for understanding the research presented in this article. For more information, please refer to the CityGML standard (*Gröger et al. 2008*).

7.2.2 Crowdsourced Geodata from OpenStreetMap

Due to projects such as Wikipedia[2] and other Web 2.0 initiatives[3], the phenomenon of collaboratively collected data became mature. With the ubiquitous availability of GPS enabled devices, such as smartphones or cameras, users also commenced to collect and share geo-referenced data, such as geo-tagged photos or GPS Exchange Format (GPX) tracks. Some examples for VGI are Flickr[4] (geo-tagged images) or Wikimapia[5] (crowdsourced map).

However, in the author’s opinion, one of the most popular and most successful projects for crowdsourced geodata is OSM. With steadily increasing amount of members – currently more than 500,000 members (*OSM 2011*) – the community aims at creating a free online world map with a great variety of data. Thereby, OSM does not only contain information about natural areas or streets but also contain various kinds of semantic information, such as addresses and building types, as well as different kinds of 3D information, such as the building height and building roof type. In early 2012, the amount of streets, typically comprising the biggest fraction of the OSM map features, has even been surpassed by the amount of buildings[6].

The users of the OSM community contribute data in two ways: on the one hand, they can create 2D geometries and, on the other hand, they can annotate the geometry with additional information. For the creation of geometries, OSM provides so-called nodes describing geo-referenced points. Several nodes can be further combined to create so-called ways, describing either linestring geometries or polygons. More complex polygons, such as those with holes, or complex relationships between OSM features, such as turn restrictions or tours, can be expressed by using relations. For adding additional information to an OSM feature, it is possible to tag the geometry with key-value pairs. Thereby, the key describes some kind of information domain or characteristic (*e.g.*, *highway*, *building*, etc.) and the value refines the information (*e.g.*, *primary*, *university*, etc.). The amount of key-value pairs is unlimited as well as the key-value pairs themselves. However, there are community-accepted key-value pairs. Those are listed on the Map Feature Wiki Page (*OSM 2012b*). In contrast, *Tagwatch (2011)* provides a list of all currently used keys.

Various applications such as OSM-WMS (*Goetz et al. 2012*), OpenRouteService (*Neis & Zipf 2008*) or OSM-3D (*Over et al. 2010*) demonstrate the richness of OSM data, as well as the possibility to combine non-standardized VGI with global standards and quasi-standards of the Open Geospatial Consortium (OGC) (*e.g.*, WebMapService or Web3DService) in SDIs. Of particular interest for this article, it has also been demonstrated that the creation of CityGML LoD1 and LoD2 models based on OSM is feasible (*Goetz & Zipf 2012*).

7.2.3 IndoorOSM – Mapping the Indoor World in OpenStreetMap

Motivated by commercial indoor maps and products, such as Bing Maps Venue Maps (*Bing 2011*), Google Maps for Indoors (*Google 2011*) or Navteq Destination Maps (*Navteq 2011*), and convinced by the increasing need for indoor maps and applications, researchers and VGI communities think about how to gather and use (open) data for indoor applications. Trying to push the OSM community toward indoors, an OSM-based indoor extension has been recently invented by *Goetz & Zipf (2011)*.

The schema follows existing OSM methodologies; thus, it only uses nodes, ways, relations and key-value pairs. That is, existing OSM editors, such as *JOSM*[7] or Potlatch[8], are suitable for mapping *IndoorOSM* data. The schema is defined as follows: a whole building is represented as one OSM relation, whereas the different relation members (the children of the relation) are the different building levels (floors). A level itself consists of one or several closed way(s) for representing the shell of the level, that is the outer boundary, and several other closed ways representing the inner building parts (*e.g.*, rooms, corridors, etc.). 3D information such as the height of a level or the height of a building part is attached as a key-value pair to the corresponding OSM feature with the key *height* and corresponding values (*e.g.*, *3*, *6 ft*, etc., the default unit is meter). That is, for each level and its inner parts, a two-dimensional (2D) footprint geometry plus additional 3D information is available. Further semantic information, such as room names, level names, level numbers and so on are attached as key-value pairs to the corresponding OSM feature. Figure 7-2 depicts an exemplary floor plan of a building, including the outer shell and the inner parts of the floor.

In *IndoorOSM*, information about windows is provided by adding nodes to the OSM features which represent the level shells. Thereby, the location of the node represents the 2D center of the window (from a bird's perspective). Information about the breast, width and height is attached via corresponding keys. Information about doors is provided in a similar way: a node represents the centric position of the door, whereby the node is attached to one of the corresponding two building part features. Information about the width and height is again provided via keys. By tagging a door node with *connector:ids*, a semantic description of a connection to other OSM features is possible. Essentially this tag is used for vertically connected doors (*e.g.*, in a staircase or elevator). The value of the key is the OSM-id of the other feature; if a door is connected to several features, then multiple IDs can be added. To conclude, the *IndoorOSM* model contains detailed information about the geometry of the interior structure of a building and essentially all required data for highly detailed CityGML models are available. *Goetz & Zipf (2011)* and *OSM (2012a)* provide more information and detailed descriptions of *IndoorOSM*.

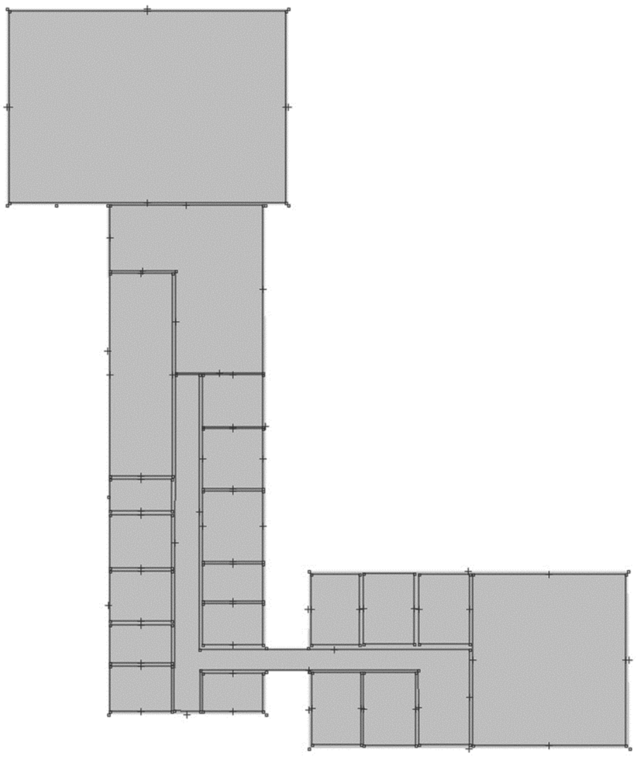

Figure 7-2. Exemplary floor plan of a building, which is mapped according to IndoorOSM in JOSM.

7.2.4 Procedural Modeling and Building Reconstruction

The creation of 3D building or city models is an important task. Instead of generating the models manually, more and more efforts are undertaken toward an automatic generation by using various kinds of data sources. For example, the extraction of 3D buildings models from airborne lidar has been researched intensively (*Weidner & Förster 1995,* *Maas & Vosselman 1999, Brenner 2005, Kada & McKinley 2009, Malambo & Hahn 2010*). Similar to that, the generation of 3D building models from aerial imagery has also been discussed (*Wefelscheid et al. 2011*). Furthermore, shape grammars (*Stiny & Gips 1971*) or split grammars (*Wonka & Wimmer 2003*) have been used for building reconstruction purposes (*Brenner & Ripperda 2006*). A comprehensive overview on existing approaches is provided by *Förstner (1999)*, *Bauer et al. (2002)*, *Ribarsky et al. (2002)* and *Hu et al. (2003)*.

An approach for procedural modeling of cities has been presented by *Parish & Müller (2001)*. The authors try to generate city models from scratch by using a comprehensive set of rules. However, the resulting model is very synthetic as both the placement and the geometry of the buildings are based on stochastic and road network geometries, rather than on real-world building data.

Wonka & Wimmer (2003) present their work toward an automatic modeling of architecture. Although they demonstrate the feasibility of their approach, they do not provide a real-world example, but state that a comprehensive amount of grammar rules would be required for such a building reconstruction. Semantic information or indoor spaces are also not considered.

A concept for modeling and representing building models is presented by *Döllner & Buchholz (2005)*. Although this approach leads to visually appealing results, the generated models lack geometric details. Essentially, windows and doors are not explicitly represented as geometry, but only visualized via textures. Furthermore, indoor spaces are not considered at all.

Müller et al. (2006) present a novel shape grammar, namely CGA shape, which produces building models with high geometric detail, but their approach has two major drawbacks: on the one hand, for reconstructing buildings by using real building footprints, a comprehensive amount of complex rules needs to be defined manually; on the other hand, their approach only reconstructs the outer appearance of the building, but neither semantics nor interior structures are considered.

Focusing more on the indoor environments, a grammar for the generation of 3D indoor models has been developed by *Gröger & Plümer (2010)*. They state that their approach generates interior models with semantic information, but a comprehensive use case based on real-world data is not provided. Additionally, their approach is quite limited regarding the shape of the different rooms and is only capable to generate box-based rooms with rectangular corners and parallel sides.

Regarding the generation of CityGML models, *Falkowski et al. (2009)* discusses the semi-automatic generation from images, and *Isikdag & Zlatanova (2009)* provide some first ideas toward the automatic generation of CityGML based on Industry Foundation Classes (IFCs), but again real-world examples are missing.

To conclude this brief review, it can be stated that there are different approaches available, but they mainly focus on the outdoor visualization. The inclusion of semantic information is often missing and most approaches lack real-world examples. Furthermore, the generation of buildings with indoor spaces is hardly discussed.

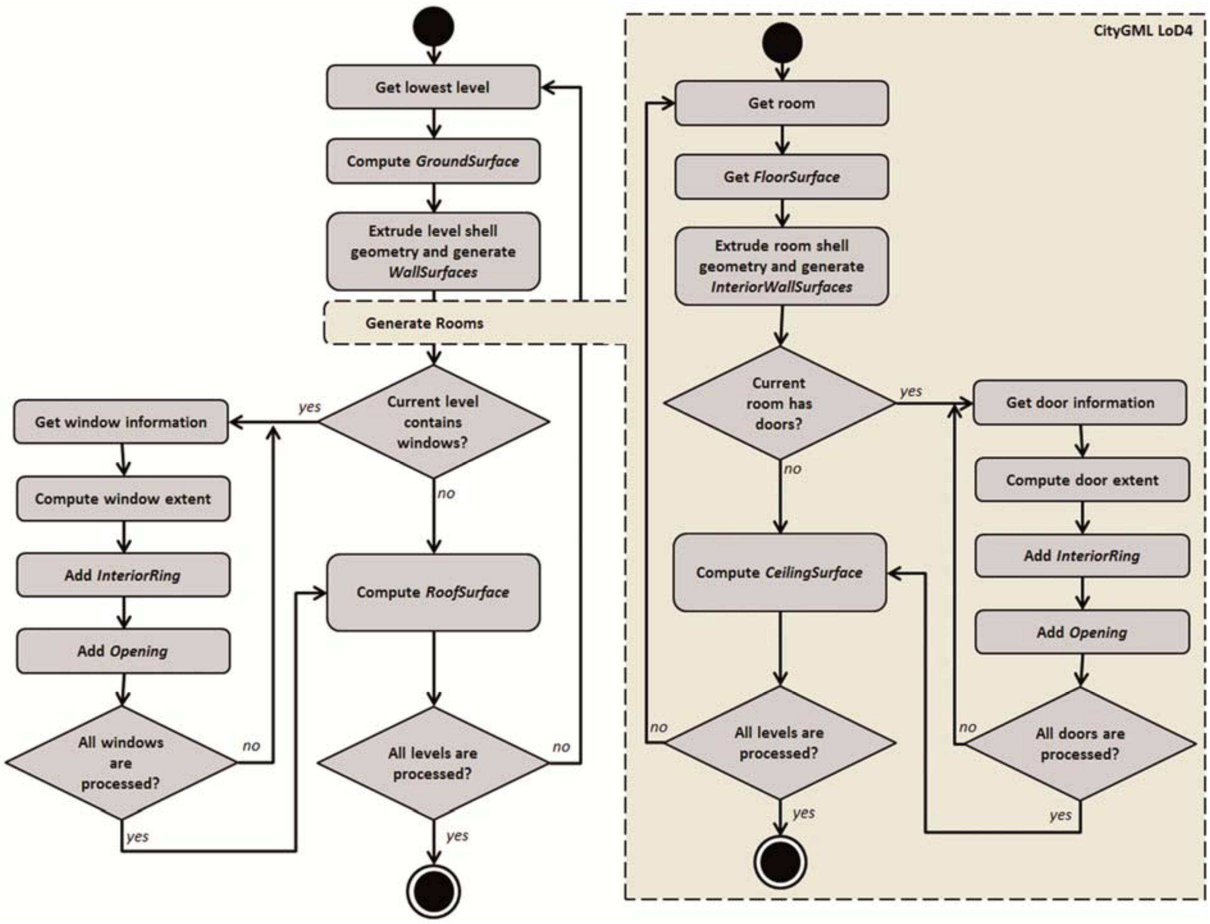

Figure 7-3. General workflow for the generation of CityGML LoD3 and LoD4 models.

7.3 Generating CityGML from OpenStreetMap

According to *Goetz & Zipf (2012)*, the generation of CityGML LoD1 and LoD2 from OSM is feasible. Building upon this work, the following Sections focus on the generation of CityGML LoD3 and LoD4 models. The next subsection elaborates the constraints and requirements, which need to be fulfilled by the OSM data. Thereafter, the generation of LoD3 and LoD4 models is described. Thereby, it is assumed that a building has been ideally mapped according to the *IndoorOSM* model, thus fulfills the described prerequisites. A proof-of-concept will be provided in a later Section. As an overview, Figure 7-3 depicts the general workflow for the generation of CityGML LoD3 and LoD4 models, whereby the former one is represented by the solid boxes and the latter one by both frameworks (the solid and the dashed one).

7.3.1 Date Constraints and Requirements

Basically, users can add any kind of data and information to OSM. Essentially, the contribution is not double-checked beforehand; thus erroneous data needs to be detected (and corrected) by other contributors. That is, the available data are potentially subject to errors and missing data. However, in order to generate CityGML LoD3 and LoD4 models, the provided data needs to satisfy and fulfill different topological constraints and metric requirements. This Section aims at formally elaborating those. Furthermore, potential solutions or reasonable assumptions, if available, are discussed.

The first requirement is that

(1) level shell of adjacent floors overlap each other

This assures that the final building model consists of one huge building feature. Essentially, single isolated floating building parts, which are independent from the rest of the building, are avoided.

(2) Walls and their thickness are explicitly mapped.

This means that there is a gap between adjacent building part geometries, representing the actual wall. In particular, adjacent walls shall not share the same OSM nodes. Otherwise, the generated model will contain walls with no thickness. However, when encountering such a circumstance, a possible solution is to automatically compute an appropriate wall thickness, by, for example, using existent wall thicknesses of other walls of the same building or by assuming an average wall thickness.

(3) The outlines of building part geometries on the same level (floor) are pairwise disjoint.

This means that two adjacent building parts shall not overlap each other. However, a building part can contain another building part, if and only if the surrounding geometry completely covers the contained geometry, such as a small room in the middle of a bigger room.

It is further required that

(4) all building part geometries of one distinct level are completely covered by the corresponding shell geometry.

That is, building part geometries do not penetrate the corresponding shell geometry and essentially no building part geometry is completely outside of the corresponding shell geometry.

(5) Relevant measures for levels, building parts, doors and windows must be provided.

That is, the OSM key height needs to be provided for each building level, building part, door and window. Furthermore, the OSM key width needs to be provided for each door and window, as well as the OSM key breast for all windows. If not available, it is possible either to assume average values (*e.g.*, 2 m for the height of a door) or to derive the missing measures from the existing ones (*e.g.*, if all building parts of a level have a height of 2.8 m or less, a total level height of 3.0 or 3.3 m could be assumed). However, these assessments need to be done rather carefully.

Closely related to this, it is furthermore required that all

(6) provided measures are greater than zero.

This constraint is relevant for all measures, because negative values make no sense. However, all values which are greater than zero shall be considered during the model generation, although it is questionable if, for example, a 0.1-m wide door is reasonable.

(7) All provided measures fit to other measure in the building complex.

This means that all provided measures are reasonable in comparison with the other building elements. Essentially, contradictions between different values, such as a 2.5-mhigh door in a room with a height of 2.2 m, are not allowed. The only exception is that a room can have a greater height than the containing level, if and only if there is no building part in the overlying level which partly or completely covers the area of the underlying building part. This is, for example, the case when mapping a huge hall which extends over two or more levels.

(8) All measures are not contradictory to the location of the corresponding element.

This means that all provided measures need to be reasonable in comparison with the location of the element. This constraint is relevant for doors and windows because it needs to be guaranteed that their extent fits to the corresponding building part geometry. For example, a door with a width of 1.5 m does not make sense on a 1-m-wide wall. For the successful generation of CityGML LoD3 and LoD4 models, the data need to fulfill those eight before-mentioned requirements and constraints. Since they are related to either simple completeness evaluations or computational geometry, such a validation can be performed automatically. That is, the feasibility of generating a model can be checked automatically beforehand. Furthermore, even if the data are not complete or ideal, some automated adjustments are possible (*cf.* above). However, these make the models coarser. It also needs to be stated that – even if the data are ideal – the output always relies on the contributors' knowledge. Essentially, broader considerations, such as architectural feasibility or theory of structures, can neither be validated nor be disproved.

7.3.2 Generating CityGML LoD3 Models

One of the main differences between a LoD2 and a LoD3 building model is that the facade of the building in LoD3 is represented in a greater detail, because openings, such as doors or windows, are explicitly represented. In CityGML, the classes *Door* and *Window* (both derived from the abstract class *Opening*) are used for this purpose. The opening itself is represented with a *gml:MultiSurface* geometry.

In order to generate LoD3 models with *IndoorOSM* data, it is required to gather all the corresponding level shell geometries (*i.e.*, the closed way(s) representing the outer shell of a level) in the sequential arrangement of their occurrence in the building (*e.g.*, level –1, level 0, level 1, etc.). The total number of levels can be gathered from the OSM key *building:levels*. Information about the minimum and maximum levels is also available with the tags *building:min_level* and *building:max_level*. Starting with the minimum level, each level shell geometry is extruded with the height of the corresponding level (OSM key height). Since each additional level must be computed on top of the previous level geometry, an individual level shell geometry z-offset needs to be calculated. The *IndoorOSM* model assumes that level 0 is always the ground level; thus, the elevation of underground levels (level number is less than zero) needs to be reduced according to the height of all levels between the current level and the ground level. Accordingly, for overground levels (level number is greater than or equal to zero), the elevation is computed by accumulating the heights of all previous overground levels.

For the incorporation of doors and windows, the corresponding opening geometries also need to be considered. Firstly, these geometries must be included as *InteriorRings* (representing holes) while generating the different *WallSurface* elements. Secondly, the opening geometries are required for the representation of the *Opening* element in CityGML. The geometry of an opening is computed as follows: the center of the opening is represented by the corresponding OSM key node. By bisecting the width of the opening (OSM key *width*), the lower left and lower right bounds can be computed. Thereby, the direction of the wall which contains the opening needs to be considered; thus, the 2D direction vector in the x-y direction of the wall needs to be calculated.

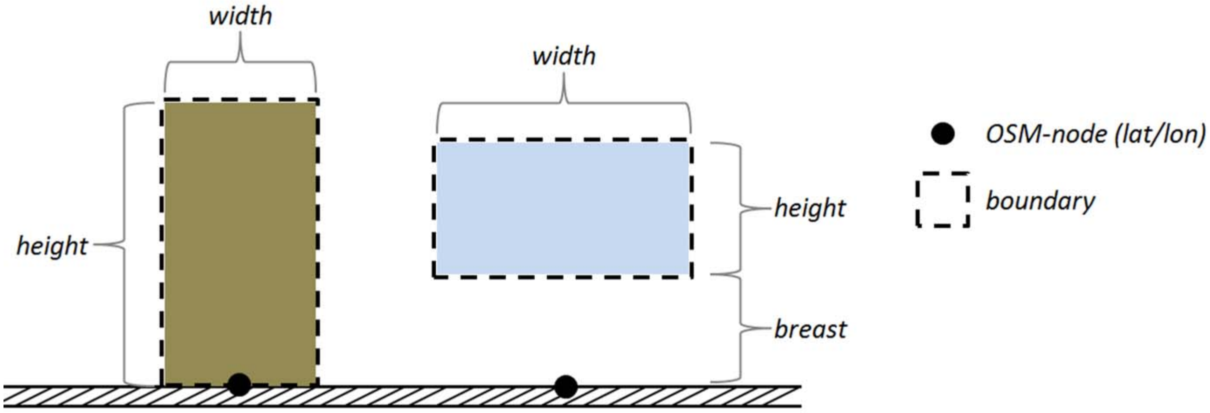

Figure 7-4. Relevant IndoorOSM information for the computation of Opening geometries.

With the usage of the height of the opening, the upper bounds can also be computed. The opening geometry is represented via these four bounds (lower left, lower right, upper right and upper left). When computing the geometry of a door, the z-values of the lower bounds equal the z-offset of the corresponding floor. In contrast, the OSM key *breast* must also be considered for the z-values of the bounds of a window. Figure 7-4 depicts a schematic visualization of the required *IndoorOSM* information.

Following the above-described approaches and methodologies, it is possible to generate a detailed CityGML LoD3 model by using *IndoorOSM* data. The basic principle of generating a LoD3 model from *IndoorOSM* data is exemplified step by step in Figure 7-5.

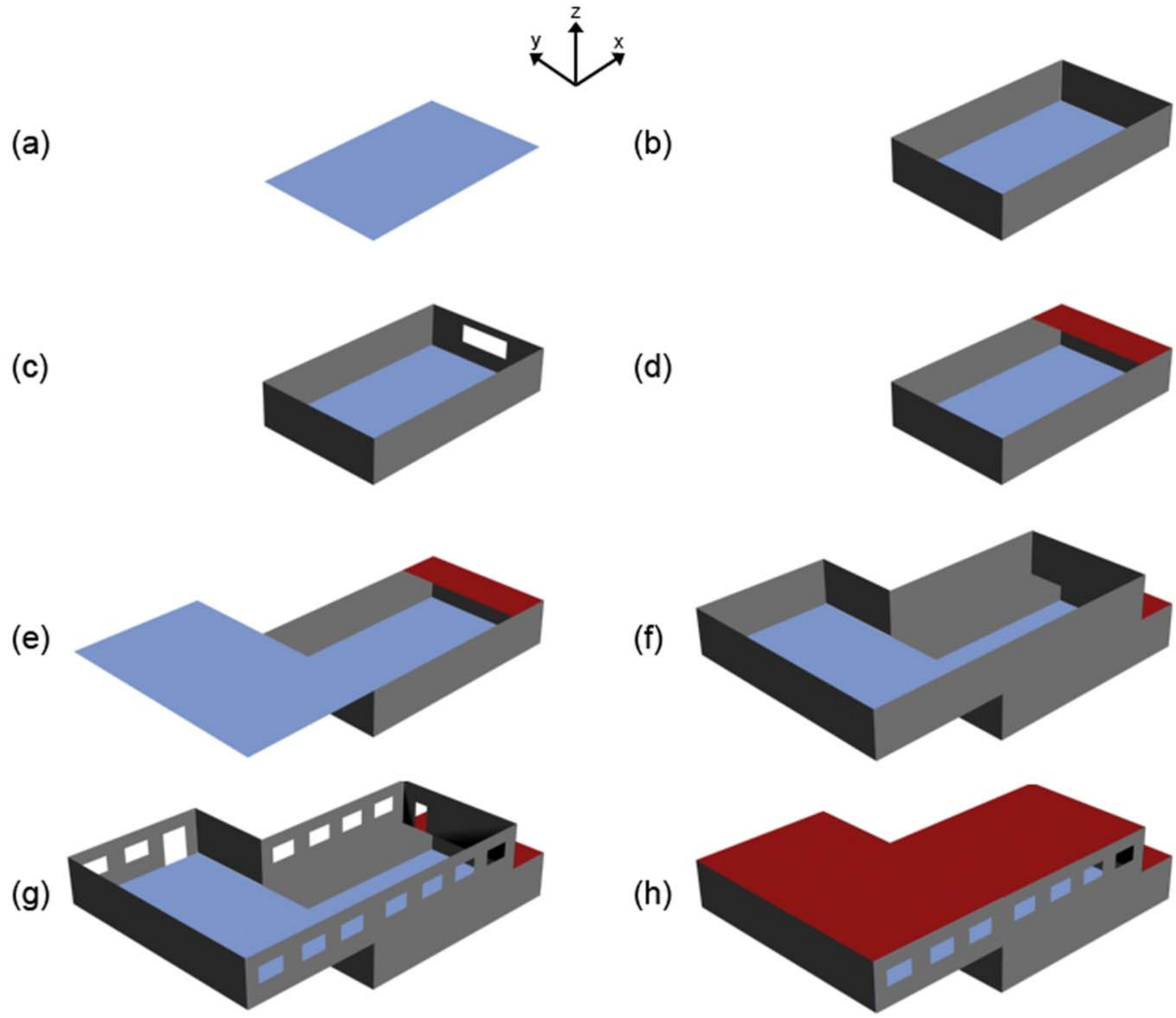

Figure 7-5. Stepwise generation of a CityGML LoD3 building model with IndoorOSM data.

By gathering the level shell geometry of the lowermost building level, a CityGML *GroundSurface* element is generated (Figure 7-5 a). Afterward, each segment of the shell geometry (*i.e.*, each pair of adjacent nodes) is extruded with the height of the corresponding level (Figure 7-5 b). Those are represented as CityGML *WallSurfaces*. Thereafter, all windows and doors, which belong to the corresponding level shell, are gathered. Based on their attributes (*i.e.*, *width*, *height* and *breast*), a CityGML *Opening* element is generated. Furthermore, an *InteriorRing* is attached to the corresponding *WallSurface* (Figure 7-5 c). Afterward, it needs to be checked whether the current level contains a CityGML *RoofSurface*. Therefore, the level shell geometry of the next higher level is gathered and subtracted from the current level shell geometry. The remainder is then added as a *RoofSurface* on top of the current level (Figure 7-5 d).

A similar procedure is performed for computing the *GroundSurface* of the next higher level. Thereby, the level shell geometry of the lower level is subtracted from the shell geometry of the upper level and the remainder is stored as a *GroundSurface* element (Figure 7-5 e). Again, the different segments of the level shell geometry are extruded with the height of the level and stored as *WallSurface* elements (Figure 7-5 f). *Opening* and *InteriorRing* elements are generated based upon the windows and doors and are added to the corresponding *WallSurface* elements (Figure 7-5 g). Finally – if no more levels are available – the level shell geometry of the highest level is used for generating the final *RoofSurface* element (Figure 7-5 h). Thereby, different roof-related OSM keys, such as *building:roof:shape* or *building:roof:style*, need to be considered (*cf. Goetz & Zipf 2012*). For multi-story buildings with more than two levels, the processing steps (d)–(g) are repeated accordingly.

7.3.3 Generating CityGML LoD4 Models

LoD4 models in CityGML are typically the most detailed ones because they include detailed information about the interior structure of a building. This representation is mainly achieved by using the CityGML classes *Room* and *IntBuildingInstallation* (for interior installations such as stairs, railings or pipes). According to the CityGML specification, a room is a semantic object for the representation of free space inside a building and therefore the room should be closed topologically. The geometry of a room can be represented by using either *gml:Solid* or *gml:MultiSurface*. For a more detailed (semantic) description of a room, its parts can be further represented with the classes *CeilingSurface*, *InteriorWallSurface* and *FloorSurface* (all subclasses of *_BoundarySurface*).

In order to generate CityGML LoD4 models, the outer geometry is computed in the same way as for LoD3. Additionally, the representation of interior structures needs to be accomplished. This is realized as follows: besides gathering the different level shell geometries, the different interior building part geometries also need to be obtained from OSM. Similar to shell geometries, building parts are also represented with a 2D footprint with additional 3D information attached to this geometry. By extruding the different line segments of the footprint with the corresponding height, individual *InteriorWallSurfaces* can be created. The *FloorSurface* geometry and the *CeilingSurface* geometry are both represented by the footprint polygon itself. In the former case, the polygon is elevated by the corresponding level elevation and, in the latter case, the geometry is additionally elevated by the height of the corresponding building part. This allows the creation of rooms that are not as high as the level.

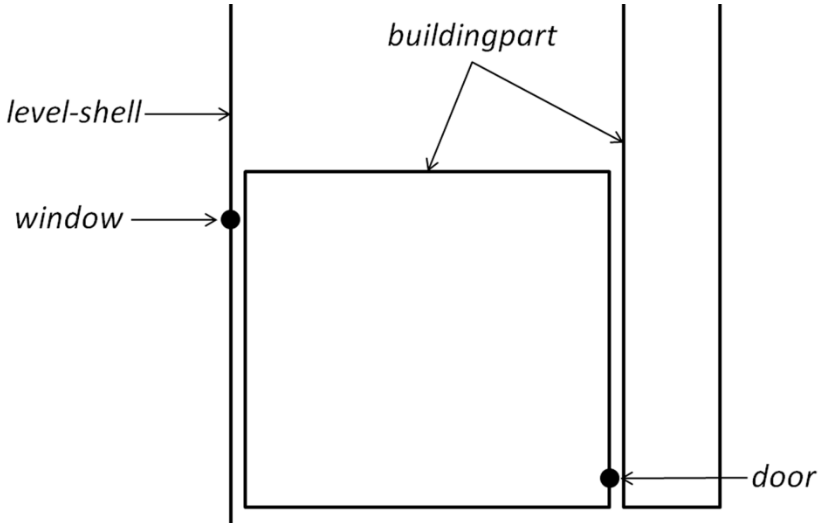

Figure 7-6. Specialties in the IndoorOSM model for windows and doors.

When generating the *InteriorWallSurfaces*, the occurrence of *Openings* must be considered. This is achieved similar to *Openings* in LoD3; however, some specifics have to be considered: when mapping an opening between two adjacent elements, such as a window between a room and the level shell or a door between two rooms, only one node for the opening is attached to one of the involved features. For example, when two building parts A and B are connected with each other through a door, only one of them will contain the corresponding door node. Figure 7-6 illustrates this issue, as well as for the case of a window. That is, when creating an opening between two OSM elements, this must be considered. General information about a *Room* (*e.g.*, *gml:name*, *function*, etc.) can be populated from several OSM keys (*e.g.*, *name*, *amenity*, *type*, etc.), which are attached to the corresponding OSM feature.

The basic principle of the generation of the interior elements is described step by step in Figure 7-7. The initial situation (Figure 7-7 a) is that the CityGML model consists of one level, including *GroundSurface*, *WallSurface* and *Opening* elements. Thereafter, all building part geometries, which are mapped as relation members of the corresponding level in OSM, are gathered and represented as *FloorSurface* elements (Figure 7-7 b). Afterward, each segment of each building part geometry is extruded with the height of the corresponding building part (Figure 7-7 c). Those are represented as *InteriorWallSurfaces* in CityGML. Similar to the outer appearance, all windows and doors of the current level are gathered. Based on their attributes, different CityGML *Opening* and *InteriorRing* elements are generated (Figure 7-7 d) for adjacent *(Interior)WallSurface* elements.

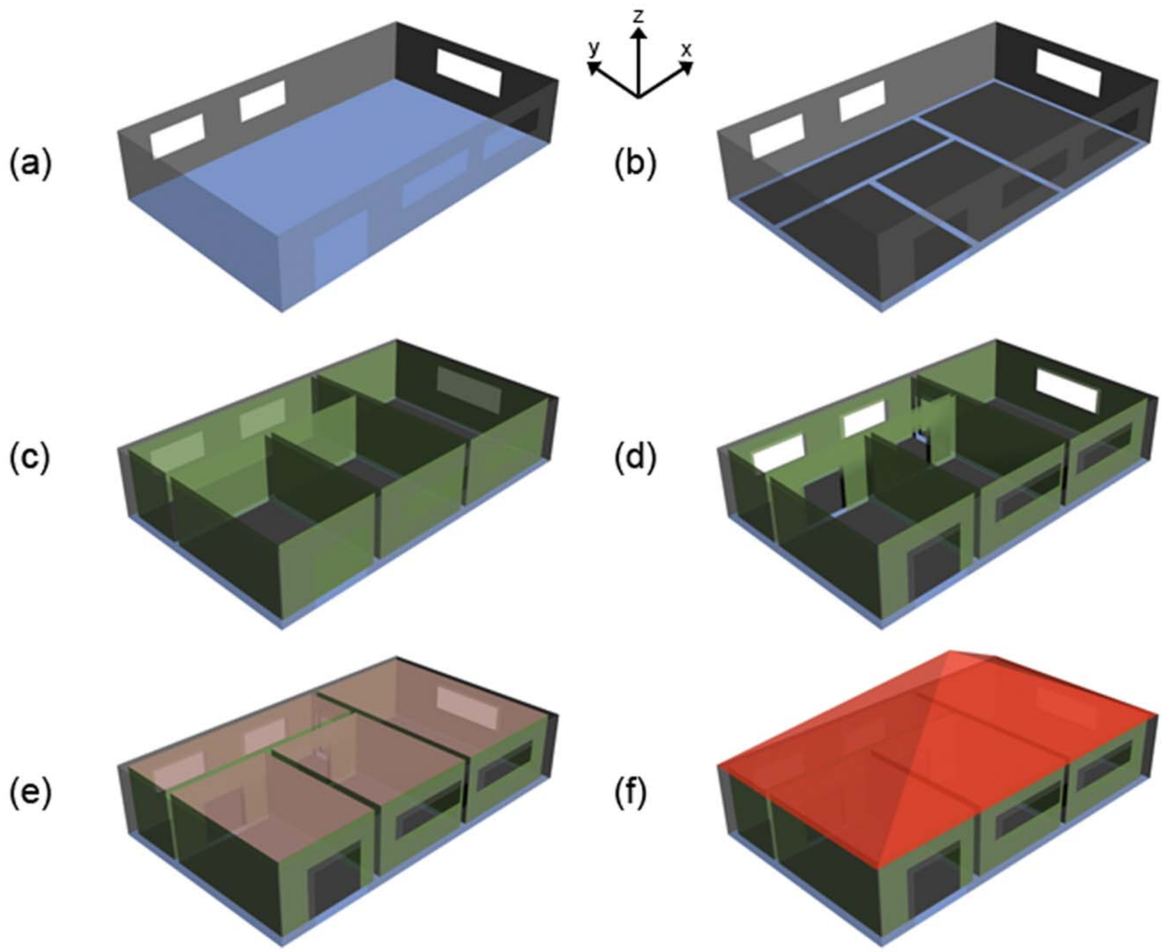

Figure 7-7. Stepwise generation of a CityGML LoD4 building model with interior structures based on IndoorOSM data.

By elevating the different building part geometries with the corresponding building part height, the different *CeilingSurface* elements can be generated (Figure 7-7 e). As already described for LoD3, the final *RoofSurface* element is then placed on the top of the building (Figure 7-7 f). For multi-story buildings, the processing steps (b)–(e) are repeated for each available building level.

As mentioned above, CityGML LoD4 models also consider building installations, such as stairs, ramps and railings. However, when talking to active members and contributors of OSM, one gets the impression that very detailed micro mapping is out of scope of OSM. That is, many OSM members are aware of the importance of indoor information, but it is likely that they are only willing to contribute such data up to some degree of granularity. Especially data about fine-grained details, such as railings or individual steps, will very likely not be mapped by the OSM community. That is, the *IndoorOSM* model does not consider such information in great detail yet, but little information is available: *IndoorOSM* provides the key-value pair *buildingpart=verticalpassage* for indicating that a building part somehow connects two levels with each other. What kind of vertical passage it is can be refined with the key *buildingpart:verticalpassage*. Possible values are, for example, elevator, escalator, stairway and so on, and the floor range can be defined with the key *buildingpart:verticalpassage:floorrange*. Additionally, *IndoorOSM* provides the key *connector:ids*, which allows the semantic description of two connected OSM features (basically doors or openings). This information is quite coarse; however, it is still useful for the generation of ramps and stairs. Due to space limitations and focus, the creation of *IntBuildingInstallations* cannot be discussed in greater detail. Nevertheless, there is already some work on the creation of different stair types (*Schmittwilken et al. 2007*), which is likely to be transferable to the domain of OSM and CityGML.

7.4 Results and Discussion

For the demonstration of the developed methodology and the detection of potential limitations of both the methodology and the available data, Section 7.4.1 describes different results, which have been gained by applying the methodology to the existing *IndoorOSM* data. While performing this case study, also some limitations of the *IndoorOSM* mapping proposal became apparent – those will be discussed in Section 7.4.2.

7.4.1 Exemplary Application of the Developed Methodologies

Since the *IndoorOSM* mapping proposal is rather new, there are not that many buildings available yet. Furthermore, it has been discovered that indoor mappers do not yet necessarily contribute 3D information. That is, although there are already a lot of buildings available, not all of them fulfill the elaborated prerequisites of the here presented approach. Nevertheless, couple of buildings are ideally mapped and the application of the here presented approach leads to satisfying results. Figure 7-8 depicts three different exemplary CityGML models (LoD1–LoD4), which are generated according to the approach presented here by using the existing OSM data.

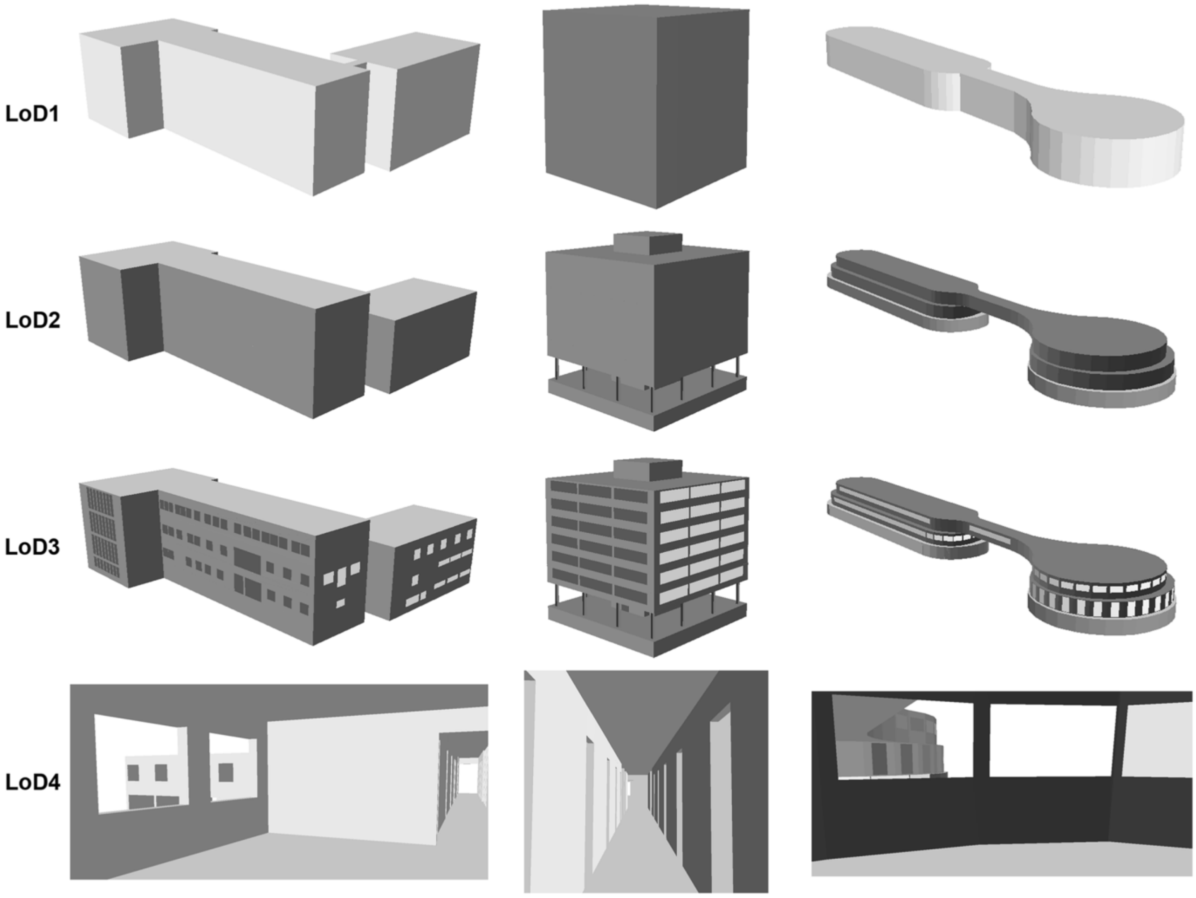

Figure 7-8. Three exemplary CityGML building models in LoD1–LoD4. All have been generated automatically by applying the presented approach to publically available OSM data.

However, by applying the developed approach to the existing OSM data, it also became apparent that there are some drawbacks of the current implementation and it seems that many buildings are subject to errors or inaccuracy. For example, some building models revealed slightly dislocated levels, resulting from non-congruent level shell geometries and impreciseness. Two examples are depicted in Figure 7-9 (a) and (b). Furthermore, in some buildings, the position of windows does not fit to the provided width. When processing such data, thus ignoring constraint (8) (*cf.* Section 7.3.1), this leads to overlapping window geometries as depicted in Figure 7-9 (c). Regarding the interior structure of the buildings and the alignment of the different rooms, it also became obvious that some building interiors lack accuracy. Different sides of a wall are sometimes not parallel. Adding an Opening to such a wall results in an imprecise 3D model (Figure 7-9 (d)). Quite often, different adjacent walls have a different thickness, for example, rooms 1 and 2 in Figure 7-9 (e) have differently thick walls on the upper side. Also, some four-sided rooms are obviously not quadrangular, as, for example, room 2 or 3 in Figure 7-9 (e)). Contrary to constraint (2) (*cf.* Section 7.3.1), many interior walls do not have a thickness (Figure 7-9 (f)), which leads to unrealistic 3D building models.

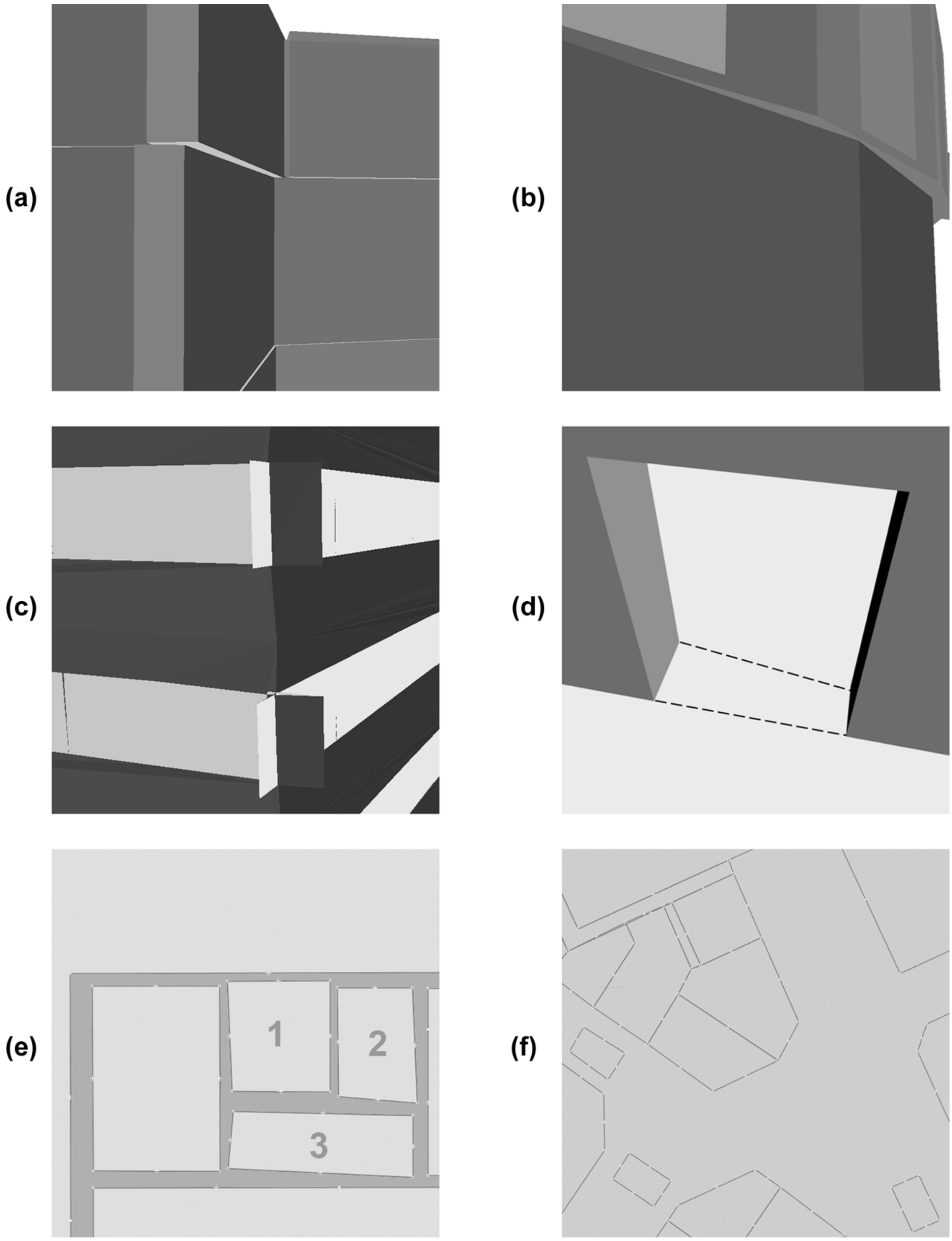

Figure 7-9. Examples for imprecise and erroneous building models (a–d) resulting from imprecise data (e.g., e–f).

7.4.2 Limitations of the *IndoorOSM* Mapping Proposal

Beside the above-described limitations, it furthermore became apparent that *IndoorOSM* is currently only suitable for describing buildings up to some degree of complexity. Essentially, the model is only capable for mapping buildings in which all walls are orthogonal to the corresponding grounds. *IndoorOSM* further assumes that ceilings and grounds are planar. There is also no information about the shape of doors and windows; thus, they are all regarded as being rectangular. That is, the *IndoorOSM* model is currently limited to some kind of Manhattan-World-like situation and it is not possible to map detailed information and to automatically compute CityGML models of buildings with organic shapes. Essentially, complex architectural elements, such as folded or beveled walls and four-centered arches, cannot be represented with this model. As an example, this Manhattan-World-like restriction becomes apparent when trying to map two adjacent floors in a building, whereby the lower level is bigger than the upper level and the facade of the lower level is beveled to the ground of the upper level (Figure 7-10 (a)). According to the *IndoorOSM* model, the shell of each individual level is mapped (Figure 7-10 (b)). Due to the assumption of a Manhattan-World, the automatically generated model differs from reality (Figure 7-10 (c)).

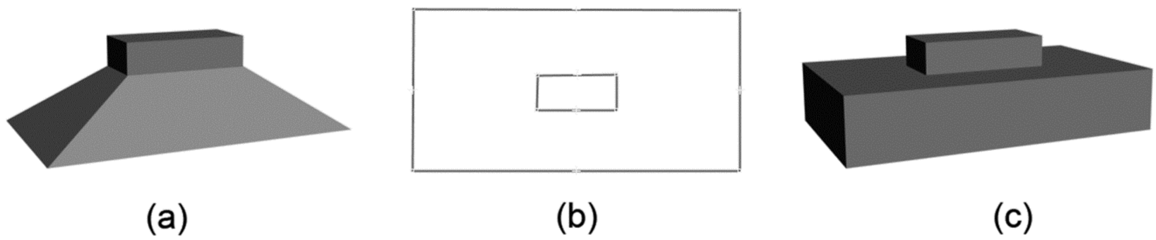

Figure 7-10. Consequences of the Manhattan-World-like restriction of IndoorOSM with the example of two adjacent levels of a building with beveled facade in between. How they really look like (a), how they are mapped in indoorOSM (b), and how the generated model looks like (c).

Regarding the provision of textural information about the facade of a building, *IndoorOSM* is also very limited. By using the tags *building:roof:color*, *building:facade:color* or *building:color* (both American and British English spelling), only a coarse description of the color of the building is possible. Although the *IndoorOSM* model proposed the key *building:facade:image* for providing one facade image for the whole building, the possibilities for mapping detailed facade information are still very limited. Especially the provision of different textures for different walls or doors is not yet possible.

Some of the above-mentioned drawbacks can be solved by introducing new OSM tags, for example, window:shape for the shape of a window. In contrast, other characteristics cannot be integrated in OSM without introducing real 3D geometries. However, such an immense change of the OSM data model is hard to realize. Also, it is questionable if the existing community members will accept it because often they are simply not able (or willing) to capture such highly detailed data.

Due to these limitations, a contrary conversion from CityGML to OSM is hardly feasible. Only simple building models that satisfy the above-described prerequisites can be mapped in *IndoorOSM*. Especially, a complete bijective mapping between OSM and CityGML is not yet (and probably never) possible. This also means that it is currently not possible to import arbitrary CityGML models into OSM.

7.5 Conclusions and Future Work

Crowdsourced geodata is an emerging trend and the data can serve as a rich (alternative or additional) data source for OGC-conform services in SDIs. Previous research investigations demonstrated that VGI and especially data from OSM can be used within SDIs and is also transformable to OGC-standard exchange formats, such as CityGML. Earlier investigations revealed that CityGML LoD1 and LoD2 models can be generated, but until then more detailed models were, due to missing data models, not feasible. With the invention and proposal of an advanced indoor mapping schema (*Goetz & Zipf 2011, OSM 2012a*), a first step toward tackling this problem has been made.

After a short discussion on the importance of 3D city models and the elaboration of the characteristics and motivation for DE, a brief introduction to CityGML has been provided. Thereafter, the OSM community has been briefly presented and a detailed overview about the newly invented *IndoorOSM* model has been provided, as well as a discussion of related work on procedural city modeling and building reconstruction. Following the transformation framework of *Goetz & Zipf (2012)*, a semantic information transformation for all LoDs is possible, as well as the generation of LoD1 and LoD2 geometries. In contrast to former investigations, the newly proposed *IndoorOSM* model also allows the generation of CityGML LoD3 models with windows and doors. The generation of highly detailed LoD4 models is also possible now. Since the presented approaches require ideally mapped buildings, the different data requirements and constraints have been elaborated. A case study on currently available *IndoorOSM* buildings not only demonstrated the feasibility of the presented approach, but also revealed the weaknesses and limitations of the available data.

A desirable extension of the presented approaches is that imprecise or incorrect mapping will be detected and (semi)-automatically solved while generating CityGML models. Furthermore, there are some possibilities for simplifying the geometries. At current stage, each wall segment is individually computed; however, due to imprecise mapping (*e.g.*, adding an additional node in the middle of a wall segment or creating angles with nearly 180°), it might be possible to prune some wall nodes. An improved algorithm could further detect congruent walls on adjacent levels and merged them to one WallSurface element. The computation of realistic roof geometries for LoD3 and LoD4 constitutes an important but challenging task. Some early results have already been gathered by using skeleton computation with procedural extrusion (Laycock & Day 2003, Kelly & Wonka 2011), but more detailed investigation is required. Developing methods, which cope with inaccurate *IndoorOSM* buildings, will lead to more realistic and less-erroneous building models.

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Notes

(1) www.openstreetmap.org
(2) www.wikipedia.org
(3) The Web 2.0 describes an open community of users who do not only consume data in the web but also create their own data and share it with the corresponding community.
(4) www.flickr.com
(5) www.wikimapia.org
(6) A global OSM dataset of 23 July 2012 contains 61,203,592 buildings and 57,941,913 streets (based on our internal OSM database).
(7) *JOSM* is a Java based OSM editor and can be downloaded on josm.openstreetmap.org.
(8) Potlatch is the integrated editor on the OSM webpage www.openstreetmap.org

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8 Publication 4: Formal Definition of a User-adaptive and Length-optimal Routing Graph for Complex Indoor Environments

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Marcus Goetz has developed the formal graph definition himself. He has also written the manuscript himself. All Co-authors have supported this publication by continuous discussions about the methodology and formalism of the developed graph definition. Furthermore, extensive proof-reading by the co-authors and two anonymous reviewers has led to substantial improvement of the manuscript.

Alexander Zipf

Formal Definition of a User-Adaptive and Length-Optimal Routing Graph For Complex Indoor Environments

Abstract

Car routing solutions are omnipresent and solutions for pedestrians also exist. Furthermore, public or commercial buildings are getting bigger and the complexity of their internal structure has increased. Consequently, the need for indoor routing solutions has emerged. Some prototypes are available, but they still lack semantically-enriched modelling (e.g., access constraints, labels, etc.) and are not suitable for providing user-adaptive length-optimal routing in complex buildings. Previous approaches consider simple rooms, concave rooms, and corridors, but important characteristics such as distinct areas in huge rooms and solid obstacles inside rooms are not considered at all, although such details can increase navigation accuracy. By formally defining a weighted indoor routing graph, it is possible to create a detailed and user-adaptive model for route computation. The defined graph also contains semantic information such as room labels, door accessibility constraints, etc. Furthermore, one-way paths inside buildings are considered, as well as three-dimensional building parts, e.g., elevators or stairways. A hierarchical structure is also possible with the presented graph model.

8.1 Introduction

With the technological improvement of mobile devices, today's navigation systems offer a variety of functionalities for nearly any kind of requirement, but they are mainly designed for outdoor environments and hardly offer any solutions for indoor routing. By comparing indoor and outdoor space, it is evident that there are objects such as rooms or distinct areas in huge halls which do not have a counterpart in the outdoor street network (*e.g.*, corridors can be compared to streets etc.), resulting in a complicated path network construction process. Nevertheless, there is an increasing need for specialized indoor solutions. Public buildings such as airports or shopping malls have become bigger and their internal structures have become more complex, resulting in a very complicated overall structure so that even familiar persons are likely to get lost when searching for a particular room or place. If the person is unfamiliar with the inner building structure, there is an even stronger need for proper guidance (*Raubal & Egenhofer 1998; Holscher et. al. 2006*). The field of application for indoor routing is very broad and there are many diverse application scenarios, *e.g.*, emergency routing or personal routing at the airport (*Goetz & Zipf 2010*).

Routing a person through space can be generalized to finding the shortest path between two nodes in a network. Well proven algorithms such as *Dijkstra (1959)*, A* (*Hart et. al. 1968*) and various specialized algorithms and heuristics, can compute shortest routes, but the creation of a network model is required beforehand. Several efforts (*cf.* next Section) have been made in creating indoor networks, but existing approaches lack details and can only provide coarse routes without considering complex interior structures. Furthermore, none of the existing approaches tries to formally define a graph model for indoor environments, although existing approaches utilize graphs.

The main contribution of this paper is the formal definition of an improved indoor routing graph that allows route computation in complex indoor environments. The presented graph allows length-optimal routing based on the (complex) geometry of indoor spaces, whereby computations can be user-adaptive. The graph elements are manually extracted from floor plans and additional semantic information is collected for different functions of the graph. By applying a shortest path algorithm on the graph, the shortest route between two distinct points can be obtained. Detailed routing information, *e.g.*, travel distances, etc., can also be obtained from the graph segments.

8.2 Related Work

According to *Pradhan (2000)* and *Brummit & Shafer (2001)* indoor space models can be separated into two different classes. The so called topological/semantic class contains models relying on abstract descriptions of spatial relations (*e.g.*, "*Office X is near the Elevator*"). In contrast, so called metrics models rely on concrete measurements of distances and angles (*e.g.*, "*The distance from Office X to Office Y is 12.3 meters*"). Early examples for such topological models are presented by *Raubal & Worboys (1999)* or *Brummit & Shafer (2001)*, but they all lack geometric aspects, thus they are not usable for computing optimal routes and predicting distances.

In contrast, *Gilliéron & Bertrand (2003)* invented an indoor space representation model based on CAD files. The files only contain metric information, *i.e.*, manual enrichment with semantic data is required. In doing so, information about locations, shapes and topological relations of spatial entities (*e.g.*, rooms, corridors, hallways, etc.) can be received. Afterwards all available data are used to derivate a so called link/node view of the building network. The authors decided to model each room as one node and corridors as a huge link with connection nodes. However, this procedure rather provides a very abstract view on the topology than a detailed perspective on the geometry. Important constraints and details such as the position of doors or obstacles inside rooms are not considered at all.

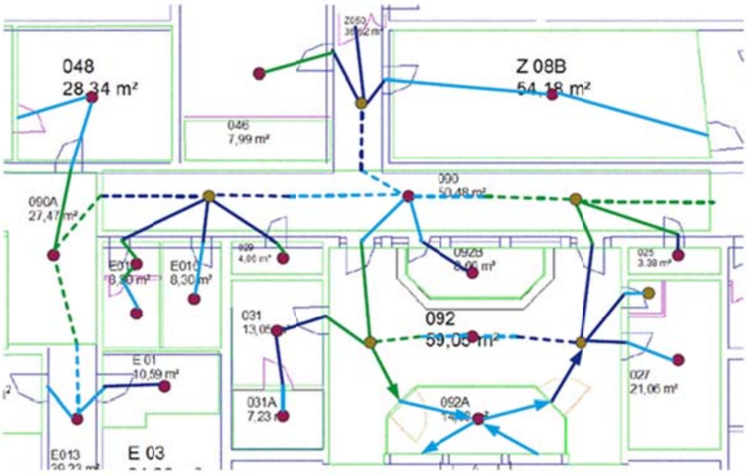

Figure 8-1. Floor plan with overlaid network graph (Lorenz et. al. 2006).

A hybrid spatial model for indoor environments, which consists of hierarchically structured paths and optional semantic information, is presented by *Lorenz et. al. (2006)*. They propose a direct mapping for small building instances (*e.g.*, small rooms, corridors) to nodes in the graph. Furthermore, pathways between rooms are described as links. For gangways, they propose decomposing cells into several non-overlapping disjoint cells (*cf.* Figure 8-1). This approach has been extended, so that also rooms with a concave shape can be modeled (*Stoffel et. al. 2007*).

A three-dimensional navigable data model is described by *Lee (2007)*. The network model is deviated via Poincaré duality combined with a graph-theoretic framework, a hierarchical representation schema and a straight-medial axis transformation (*Lee 2001; Lee 2004*). The model contains two dual graphs, where one contains topologic information and the other one geometric aspects. Thereby, the separation into two different graphs is similar to the ISO standard 19107:2003 for describing the spatial characteristics of geographic features (*ISO 2003*). Other modelling frameworks following this standard are described by *Becker et al. (2008)* and *Becker et al. (2009)* Moreover, the latter one is also utilized for defining the format IndoorML, a LOD4 CityGML based format for exchanging interior models (*Kolbe et. al. 2005*). Also the models presented by *Lee & Zlatanova (2008)* or *Kolbe et al. (2008)* are based on *Lee (2007)*.

A 3D-GIS based framework that supports BIM for topologic analysis-oriented indoor navigation is also proposed (*Yuan & Zizhang 2008*). The BIM file covers geometric and semantic information and is utilized for creating the network model. They propose to separate floor elements according to their functional aspects, but they do not provide detailed information on their graph model.

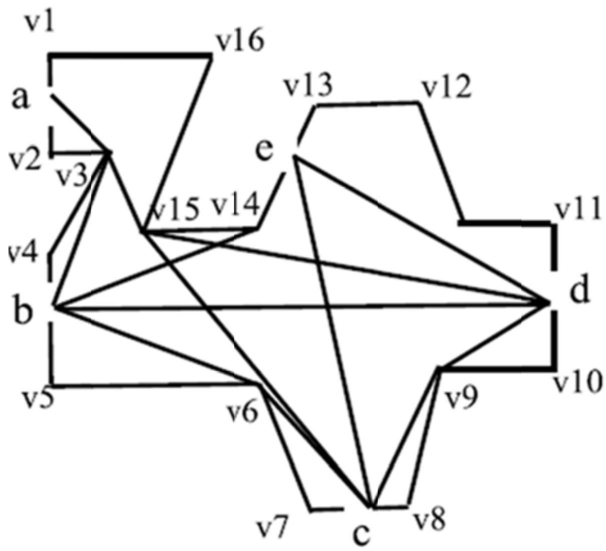

Figure 8-2. Various directly connected access points in a concave room (Yuan & Schneider 2010).

Yuan & Schneider (2010) proposed an indoor model that produces optimal non-circuitous routes. They consider all building parts as cells and separate those into simple cells, complex cells, open cells, and connectors. Furthermore, their mapping, *i.e.*, relationship between doors/rooms to nodes/edges, is different to other models. Doors are mapped to nodes and the rooms are mapped to edges. This approach is based on the assumption that doors, *i.e.*, entrances of rooms, are the destination of the user and furthermore, this allows the construction of length-dependent routes. Additionally the authors describe how to connect two doors in a concave shaped room (*cf.* Figure 8-2).

They define a *direct path graph* (DPG) *G := (V,E)* "*which reflects all possible path constructions in a given indoor space scenario*" (*Yuan & Schneider 2010*). However, this is a coarse formal definition of a routing graph. Also, the computation of length-optimal routes comes at the cost of a negative impact on the runtime. The complexity of routing algorithms strongly depends on the amount of graph elements. By following their approach and trying to model a long office corridor, this results in n nodes (n is the amount of doors) and several links between all these nodes. The *amount of required links* (*arl*) can be calculated according to Equation (1):

$$arl_n = \sum_{k=1}^{n}(n-k) = \sum_{k=1}^{n-1} k = \frac{n*(n-1)}{2} \quad (1)$$

For an exemplary corridor with 20 offices, this approach leads to 20 nodes and 190 edges. Extending this to a building with 7 levels, two elevators and one building entrance, such a graph would require 1.800 graph elements for a simple building structure, which is inacceptable for performance and storage and furthermore similar models get along with less graph elements (as will be described later).

In conclusion, it needs to be emphasized that all existing models do not discuss how to deal with obstacles or walls inside a room. The direct connection between two doors might not be navigable, due to physical constraints (*cf.* Figure 8-3), but existing models are not able to capture this. Furthermore, existing models are not capable of considering different areas inside rooms (*e.g.*, smoking area and check-in counter in an airport entrance hall), because rooms are modeled as single elements. Moreover, existing models assume that path segments do not have directions. This might be true for most buildings, but there are some scenarios (*e.g.*, airport) where the consideration of one-way paths inside a building is required. Also, none of the existing approaches tries to formally define the utilized graphs. That is, existing approaches use a graph that has never been formally defined beforehand.

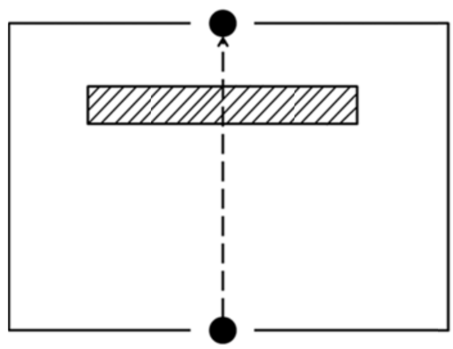

Figure 8-3. A convex shaped room with physical constraint inside.

8.3 Relevant building components for indoor routing

Routing describes the process of leading users from a starting point to a destination point in an optimal manner (according to distinct requirements). Such routes are often obtained by applying a routing algorithm onto a graph. In this Section, we discuss which inner building components are relevant for routing, and thus need to be integrated in an indoor routing model. Special constraints such as obstacles or one-way paths are also discussed. In general, small rooms (*e.g.*, offices, kitchens, etc.) are modeled as described by *Yuan & Schneider (2010)* (*cf.* Figure 8-4). We share the opinion that doors are the first targets of users, but nevertheless navigation inside rooms (as will be refined later) is also required. In contrast to previous approaches, modelling of corridors is also discussed.

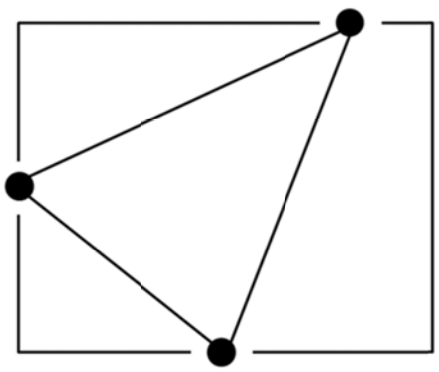

Figure 8-4. Room with three doors and corresponding route graph.

8.3.1 Corridors

From a geometric point of view, corridors are a special type of rectangular rooms in which two opposing sides are short (*i.e.*, just a few meters) and the other two sides are way much longer (*i.e.*, $0 < \frac{\text{short\_side}}{\text{long\_side}} \ll 1$). Big corridors (*i.e.*, all sides are several meters long), need to be rather considered as a hall than a corridor. In addition, from a semantic point of view, a corridor is often not a destination node, but just a connector node. There are two basic possibilities for modelling a corridor (*Meijers et. al. 2005*): just one node per corridor (not applicable) or by utilizing an adjusting line in the center of the corridor. In contrast, *Yuan & Schneider (2010)* proposed to model a corridor in the same manner as a room (*cf.* Figure 8-4). So practically there are two different methodologies for corridors, but which one is more appropriate with respect to computation performance and accuracy.

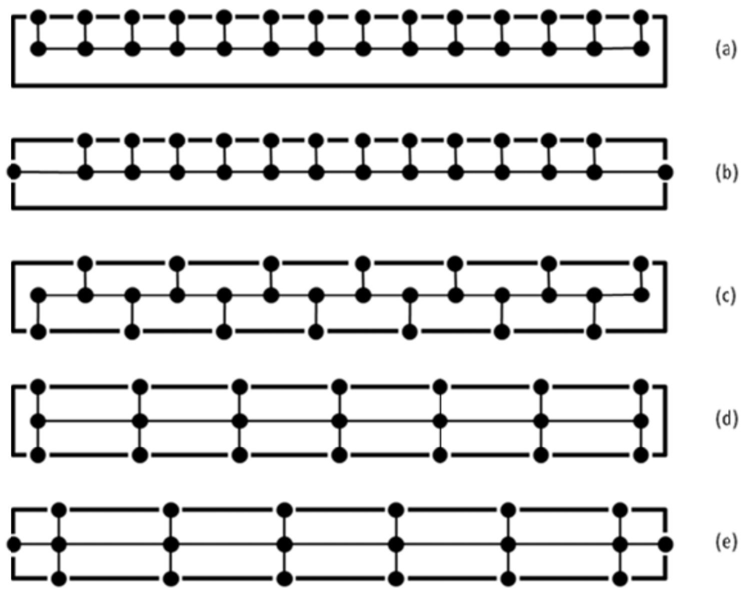

Figure 8-5. Different corridor layouts with corresponding route graphs.

When considering a corridor with 14 doors (quite common) this results in 105 graph elements for any kind of corridor layout, when modelling a corridor in the same way as a room. In contrast for the centerline approach, the total amount of required nodes depends on the corridor layout (*i.e.*, the exact location of doors) and the amount of required edges is always *#edges = #nodes – 1*. One possible corridor layout is that all doors are located at one side of the corridor (*cf.* Figure 8-5 (a)) leading to *#nodes = 2·|n|* for *n* doors and to 55 graph elements for exemplary 14 doors. Another possible layout is that two doors are at every short side and the rest of the doors are at one single side (*cf.* Figure 8-5 (b)). In general this leads to *#nodes = 2·|n| – 2* and for the example to a total of 51 graph elements. A third possible corridor layout (depicted in Figure 8-5 (c)) is that the half amount of doors is on one long side and the others on the opposed side with the constraint that there is no pair of opposed doors, resulting in *#nodes = 2·|n|*, thus in 28 nodes for the exemplary floor. Another layout is illustrated in Figure 8-5 (d), whereby opposed doors are allowed. For the exemplary corridor, the route graph has 21 nodes. Generally, such a layout requires *#nodes = 3/2·|n|*. A last possible layout (Figure 8-5 (e)) has the characteristics that there is one door on every small corridor side and the remaining ones are equally distributed on both long sides, whereby pairs of opposed doors are allowed, leading to *#nodes = 3/2·|n| – 1* (39 graph elements for the example).

Table 8-1. Comparison between different modeling approaches for a break-even analysis.

#Doors	iNav (Yuan & Schneider 2010)	Centerline (worst case)	Centerline (best case)
3	6	11	7
4	10	15	9
5	15	19	13
6	21	23	15
7	28	27	19
8	36	31	21
9	45	35	25
10	55	39	27
11	66	43	31
12	78	47	33
13	91	51	37
14	105	55	39

Of course there are other corridor layouts possible, but the described ones represent special cases. Layout a (*cf.* Figure 8-5 (a)) and layout e (*cf.* Figure 8-5 (e)) represent the upper and lower borders for the complexity and the *amount of required graph elements* (*arge*) can be approximated as follows:

$$\Omega\left(2*\left(3*\frac{|n|}{2}\right)-1\right) \leq arge \leq O(4*|n|-1) \quad (2)$$

Additionally, Table 8-1 provides an overview for different door amounts. It depicts, that the centerline approach might need less elements for more than four doors per corridor, but it definitely is advantageous for more than six doors in the corridor (which can be found very often in public or commercial buildings). Trying to reduce the complexity of the route graph, the centerline approach is preferable.

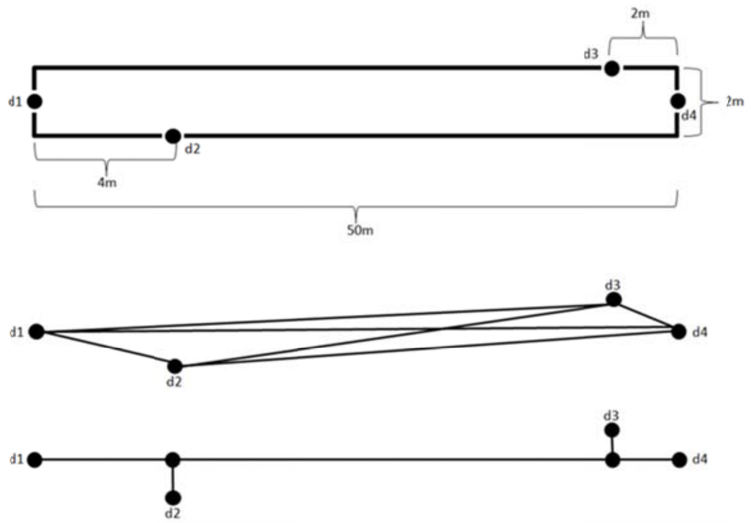

Figure 8-6. Exemplary corridor.

By adding geometric information to the model (as will be described later), it is possible to analyze travel distances and provide nearly length-optimal routes. However, distance calculations also depend on the model itself, *i.e.*, investigations on the overhead (additional travel distance) are required. A 50 m long and 2 m wide floor with 4 doors (depicted in Figure 8-6 (a)) serves as an example. The iNav approach *(Yuan & Schneider 2010*) proposes an edge between every possible pair of nodes (Figure 8-6 (b)) and the centerline approach adds additional nodes in the middle of the corridor (Figure 8-6 (c)). Table 8-2 shows the different travel distances and compares the two approaches. Thereby it becomes obvious that, the more distant two doors are, the lesser is the overhead of travel distance. So *e.g.*, for $d3 \rightarrow d4$ the overhead is 25.7%, whereas it is 2.0% for $d1 \rightarrow d3$. Furthermore, there is no additional overhead for opposed doors (*cf.* Table 8-2). In general, the resulting overhead can be approximated by $\Omega(0) \leq overhead \leq O(b)$ whereby the parameter b is the width of the corridor.

Table 8-2. Travelling distances for different modeling approaches and different pairs of doors.

#Doors	iNav (*Yuan & Schneider 2010*)	Centerline (m)	Δx $(absolute)$	Δx $(relative)$
$d1 \rightarrow d2$	4.12m	5.00m	0.88m	17.6%
$d1 \rightarrow d3$	48.01m	49.00m	0.99m	2.0%
$d1 \rightarrow d4$	50.00m	50.00m	0.00m	0.0%
$d2 \rightarrow d3$	44.05m	46.00m	1.95m	4.2%
$d2 \rightarrow d4$	46.01m	47.00m	0.99m	2.1%
$d3 \rightarrow d4$	2.23m	3.00m	0.77m	25.7%

Concluding this discussion, it becomes apparent that the centerline approach is advantageous because it reduces the amount of graph elements, and thus is likely to increase performance. The additional travel distance is rather fractional and has no serious impact on the route. Furthermore, the centerline model is more realistic because a user is likely to take a step in the middle of the corridor and then walk along it, rather than directly walking next to the wall.

8.3.2 Different areas and obstacles in halls and big rooms

Previous indoor model approaches do not present any work on big rooms (*i.e.*, halls) with complex inner shapes (*e.g.*, solid walls in the inner room). The main problem of such rooms is that the intended route through a room cannot be taken due to this physical constraint or the next target point cannot be seen (*cf.* Figure 8-3), *i.e.*, additional instructions are required for proper guidance. By manually adding additional nodes, it is possible to securely bypass such obstacles and computed routes will be more length-optimal (*cf.* Figure 8-7).

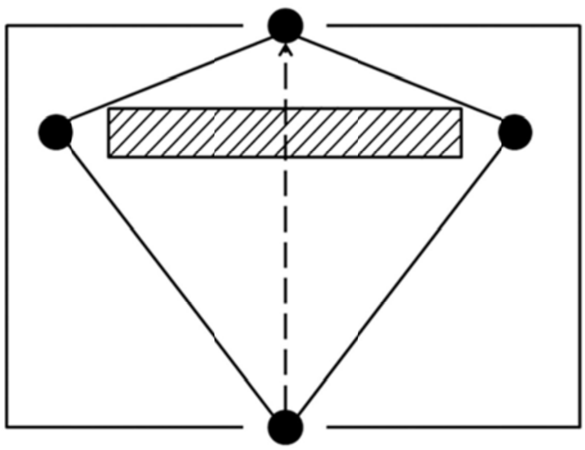

Figure 8-7. Routing graph for bypassing obstacles inside rooms.

How many and where nodes need to be added, is a question of the accuracy of navigation and not related to the routing itself. The procedure is not limited to fixed, solid obstacles, and can also be applied to other obstacles affecting the route (*e.g.*, consideration of desks or plants for navigating visually impaired). In the future it is likely that this procedure can be achieved (semi)-automatically, by utilizing intelligent space-partitioning methodologies.

Another factor not considered in previous research approaches is the consideration of special areas inside rooms. All the previous models abstract a room as a single graph element, not permitting a detailed separation of a room into different areas. For example the entrance hall of an airport is a huge room (hall) with different areas such as check-in counters or smoking areas etc., and existing solutions do not model that kind of information (*i.e.*, routing a user from the entrance to the check-in counter is not possible). Another example is a huge exhibition hall with many different booths inside, where the previous approaches model this hall as one single graph element. Motivated by such examples, it is advisable to have additional nodes for every point of interest and to connect them with existing nodes. Therefore, *e.g.*, in Figure 8-8 (a) the route graph for an airport entrance hall is modelled and in Figure 8-8 (b) the route graph of an exhibition hall is depicted. The decomposition of rooms into different areas can be further refined in a hierarchical manner (*cf.* Hierarchical outdoor wayfinding (*Car & Frank 1993*). In doing so, route instructions such as "*From the check-in counter go to departure A and then to gate 22*" can be realized.

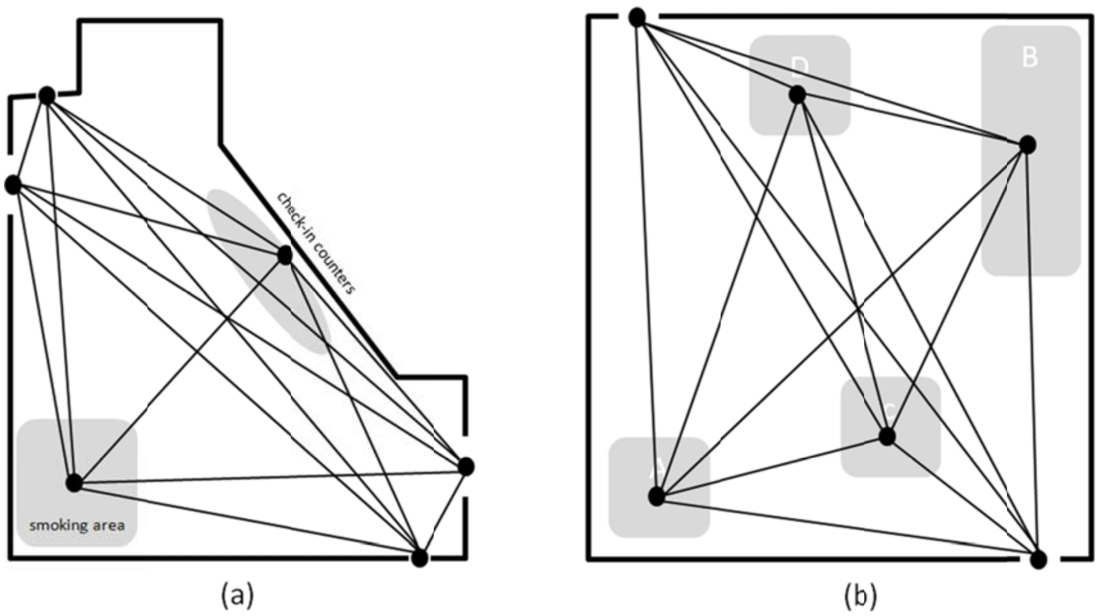

Figure 8-8. Routing graph for an airport entrance hall (a) and for an exhibition hall (b).

8.3.3 Considering the possibility of one-way paths inside a building

In the street network, one-way roads are very common and therefore routing models are often realized as directed graphs. In contrast, most “ways” or doors in indoor-environments do not have a distinct direction (*e.g.*, people can walk through a corridor in both directions). Existing approaches for indoor routing utilize non-directed graphs. However, they do not consider the possibility of one-way paths at all. There are few scenarios, *e.g.*, escalators or passport checks at the airport, which require the consideration of one-way paths or doors. Since one-way paths in buildings are rare, it is proposed to realize an undirected graph with additional semantic information, reducing the amount of graph elements significantly.

8.3.4 Vertical building parts

Most buildings have several levels that are connected via stairways, elevators, etc., and it needs to be discussed how such vertical connections should be treated. Modeling an elevator is quite intuitive: all elevator doors are already included in the network model, because they are integrated when individual floors are modeled. Furthermore, there are only edges required for directly adjacent doors, *i.e.*, door1 is connected with door2, door2 is connected with door3 etc., but there is no edge between door1 and door3. That is, an elevator connecting n levels can be modeled with n nodes and (n-1) edges (*cf.* Figure 8-9 (a)). Modeling staircases is achieved in a similar way, however it might be possible that edges are not congruent (from a bird-perspective). This is the case when stairway exits are on opposite sides of the stairway (*cf.* Figure 8-9 (b)). However, the modeling procedure is the same.

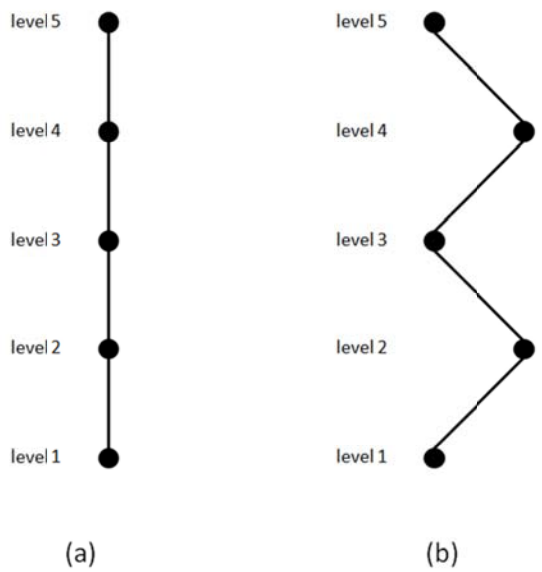

Figure 8-9. Side-face of a route graph for an elevator (a) and a stairway with opposed doors (b).

Modeling escalators is also intuitive: the start and the end of an escalator are modeled as a node inside rooms, and furthermore these nodes are connected with an edge. Since escalators cannot be strictly vertical, the edge is also not strictly vertical, but strictly horizontal edges (*cf.* moving walkway) are possible. Escalators are one-way and therefore additional information on the direction is required.

8.4 Formal definition of the Weighted Indoor Routing Graph

The most efficient way to find routes in a graph is applying a shortest path algorithm to the graph. Therefore, a graph for supporting shortest path algorithms has been developed.

Definition 1: A *weighted indoor routing graph* is a labeled graph that describes all possible path constructions in an indoor environment and furthermore contains semantic information about the different parts of the indoor environment. The *WIRG* is defined via the 7-tupel *WIRG :=(N, E, f, g, h, i, j),* where *N* (nodes) is a set of relevant points, *i.e.*, access points or doors or distinct areas in the indoor space, and *E* (edges) is a set of edges, *i.e.*, connections between relevant points in the indoor space. Additionally, *f*, *g*, *h*, *i* and *j* are mathematical functions which are responsible for labeling, weight distribution, one-way definition, localization, access restrictions, and other semantic information. For providing the above mentioned functions and for making the graph adaptable to different user requirements, the sets *L*, *TC*, *R*, *ID* and *SI* are defined below.

Definition 2.1: The set *L* (labels) as a set of all relevant labels for rooms, doors, areas etc., whereby $|L|>1$.

Definition 2.2: The set *TC* (travelling condition) describes possible different travelling conditions of the user navigating through indoor space. This set is required because different travelling conditions require different weights in the graph.

Definition 2.3: The set *R* (requirement) describes different modes for the route calculation, so a user can individually define whether to compute the shortest route according to time, distance, etc.

Definition 2.4: The set *ID* (information domain) describes different domains of additional information about the building such as accessibility of doors, corridor flow capacities, etc.

Definition 2.5: The set *SI* (semantic information) is a set of additionally available semantic information, whereby $|SI|>1$.

After defining different sets which are required for the model, the functions *f, g, h, i* and *j* are defined. The function *f* is responsible for labeling different edges in the route graph.

Definition 3: The mathematic function *f* is defined as

$$f: N \rightarrow L$$

describing a monadic, surjective and non-injective function from the set of all nodes *N* to the set of all labels L. That is, for each $l \in L$ there is a corresponding $n \in N$, but *f(n1)=f(n2)* does not automatically imply $n_1 = n_2$. This function assigns a label, *e.g.*, a room name or door name, to a node, thus adds semantic information to the model.

Next the function g, which is responsible for the weight distribution, is defined as follows.

Definition 4: The mathematic function *g* is defined as

$$g: E \ x \ TC \ x \ R \rightarrow \mathbb{R}^+$$

describing a non-surjective and non-injective function from the Cartesian product of the sets *E*, *TC* and *R* to the set $\mathbb{R}^+$. This function assigns a non-negative weight to an $e \in E$ and thereby considers different travelling conditions and different requirements.

The necessity of such a modular weight function can be illustrated by the following example, where *e* describes an edge between two stairway nodes: *g(e,'healty','shortest_route')=5.2* and *g(e,'elderly', 'shortest_route')=19.9*. Since stairways are easy to use for a healthy person, but are exhausting for an elderly person, the weight function g calculates different weights for this distinct edge e. That is, the function g is user-adaptive to individual user requirements and therefore also the *WIRG* is user-adaptive.

Furthermore, the function h is defined for considering one-way paths in indoor environments.

Definition 5: The mathematic function *h* is defined as

$$h: E \rightarrow [-1,1] \in \mathbb{Z}$$

Z describing a monadic, non-surjective and non-injective function from the set of all edges *E* to an integer in the interval between -1 and 1. The function *h* describes whether a distinct edge $e \in E$ is a one-way way inside the building or not. The function *h* is semantically defined as

$$h(e) = \begin{cases} 1 & edge\ e\ is\ oneway\ in\ the\ direction\ of\ e \\ -1 & edge\ is\ is\ oneway\ contrary\ to\ its\ direction \\ 0 & else, i.e.\ no\ oneway \end{cases}$$

That is, the function *h* can be utilized for considering one-way ways inside a building while computing a route. Also the function i is defined for retrieving the exact coordinates of a node.

Definition 6: The mathematic function *i* is defined as

$$i: N \rightarrow (\mathbb{R}, \mathbb{R}, \mathbb{R})$$

describing a monadic, non-surjective and non-injective function from the set *N* to a triple of elements $\mathbb{R}$. The function *i* returns the three-dimensional coordinates (according to a distinct coordinate system) of a node.

Additionally the function *j* is defined for adding additional semantic information, *e.g.*, accessibility constraints, to the model.

Definition 7: The mathematic function j is defined as

$$j: N\ x\ ID \rightarrow SI$$

describing a binary non-surjective and non-injective function from the Cartesian product of the sets *N* and *ID* to the set *SI*. This function adds additional information from a distinct information domain $i \epsilon ID$ to a distinct $n \epsilon N$.

The function j is utilized for adding additional information to the model, *e.g.*, *j(n1,'accessibility')='08:00 am – 06:00 pm'* or *j(n2,'flowcapacity') = '20'*. For the possibility of a hierarchical structure inside the building, *i.e.*, transition points and transition parts (*e.g.*, corridors) are described as nodes and important parts are modelled in a more detailed perspective, it is furthermore possible to replace a single node with an additional graph, so that there are one or more *WIRGs* included in a *WIRG*. In doing so, it is possible to efficiently compute routes from room *A* to an area in room *B*.

8.5 Obtaining and Navigating the WIRG

In Section 8.3, the building components relevant for the routing network were discussed, and in Section 8.4 the *WIRG* was formally defined. Obviously, the combination of all relevant nodes equals the set *N* and the combination of all relevant edges between these nodes equals the set *E*. These sets can be (manually) obtained from 3D building models. For the functions *f, g, h, i* and *j*, the sets *L, TC, R, ID* and *SI* also need to be defined. The items of set *L* describe labels of distinct nodes inside the building (*e.g.*, 'room 103') and such information can be gathered from diverse data source (*e.g.*, 3D building models, facility management systems etc.). The items of the set *TC* vary from graph to graph and therefore need to be individually figured out. One example for sounding items of *TC* is {*healthy, elderly, blind, wheelchair, crutches*}. In most cases, the items of the set *R* are always the same, because *R* describes the different requirements for the route computation. That is, *R* can be defined as *R* = {*shortest route, quickest route, most interesting, …*}. The items of the set *ID* vary from graph to graph and therefore need to be individually decided upon. When creating the graph, it has to be decided what additional information is available and from which distinct information domain it comes from. Therefore, *e.g.*, *ID* can be defined as *ID* = {*accessibility*, *flowcapacity*, …}. The items of the set *SI* are closely related to the different information domains described beforehand. Each element of *SI* represents a piece of information belonging to a distinct information domain, whereby these elements can be gathered from various data sources. Exemplary values for items belonging to *SI* are '*08:00 am – 04:00 pm*' (accessibility) or '*20*' (flowcapacity). With these sets, the functions *f*, *g*, *h*, *i* and *j* can be defined, whereby a manual assignment of parameters and values needs to be performed (*e.g.*, it has to be defined that *g(e,'healty','shortest_route')=5.2*).

By combining all these sets and functions, a *WIRG* is constructed which can be utilized for shortest path algorithms. Furthermore, the functions *f*, *g*, *h*, *i* and *j* allow qualitative assertions and add additional topologic and semantic information. Such a *WIRG* has the characteristic that each edge between two nodes represents the most direct and most realistic path between any two connected nodes. Also, any two edges directly connected with each other share the characteristic that they are visible from each other, meaning that a user can directly reach the other node without encountering an obstacle inside the room. The *length* (*i.e.*, travelling distance) of each edge can be calculated by using the Euclidean distance for three-dimensional spaces:

$$\sqrt{(x_1 - x_2)^2 + (y_2 - y_2)^2 + (z_1 - z_2)^2} \quad (3)$$

where the triples (x_1, y_1, z_1) and (x_2, y_2, z_2) can be obtained from the function *i*. Thereby, the value of *length* is not necessarily equal to the value calculated by the function *g*, because the *length* of the edge is always the same but the weights can vary for different users (*e.g.*, healthy vs. elderly).

Route computation is performed by applying a shortest path algorithm on the *WIRG*. The corresponding weights of the different edges can be either calculated beforehand or on-demand. Normally a user is not interested in navigating to a distinct door, but to a distinct room or area. That is, if the room has several doors, the shortest path algorithm is performed for each potential target node (door) and the door with the smallest overall weight, *i.e.*, the weight from the starting point to the potential target point, is determined as (implicit) target node.

8.6 Conclusion and Future Work

In this paper an advanced model which represents indoor environments with topologic, semantic, and metric information that allows nearly length-optimal routing in complex building structures has been presented. A description of the relevant parts of a complex indoor environment which are needed for route network construction and a discussion on how to model corridors and vertical building parts has been given. The importance of considering solid obstacles inside rooms by bypassing them has been described. Additionally, it has been discussed how to consider special areas inside rooms and how to integrate those areas into the routing graph. Based on these assumptions, a weighted indoor routing graph has been formally defined and constructed. This *WIRG* can then be used to calculate length-optimal routes between two points in a complex building structure. Since the *WIRG* offers semantic information, it is also possible to calculate different routes for different requirements (*e.g.*, disabled persons, elderly persons), thus the proposed model is adaptable to different users and circumstances.

For future research, it is intended to improve the model. By developing a prototype for a huge complex multi-level building, the usability of the model can be demonstrated and performance tests can be conducted. Conciliated with this goal, it is necessary and planned to analyze how the semantic information provided by *WIRG* can be utilized for a clear and understandable description of the routes through the building.

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9 Publication 5: Using Crowdsourced Indoor Geodata for the Creation of a Three-Dimensional Indoor Routing Web Application

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Marcus Goetz has developed the system architecture as well as the prototype for the 3D indoor routing himself. Furthermore, he has developed the algorithm for the automated extraction of a WIRG on his own. He has also written the manuscript himself. Extensive proof-reading by the co-authors and two anonymous reviewers has led to substantial improvement of the manuscript.

Alexander Zipf

Using Crowdsourced Indoor Geodata for the Creation of a Three-Dimensional Indoor Routing Web Application

Abstract

Routing services for outdoor areas are omnipresent and also three-dimensional (3D) visualization is quite common within this area. Recent research efforts are now trying to adapt well known outdoor routing services to complex indoor environments. However, most of the current indoor routing systems only focus on two-dimensional visualization, thus only one level can be depicted. Especially multi-level routes therefore lack visualization. Also, most of the (few) existing 3D indoor routing services utilize proprietary software or plugins, thus a widespread accessibility for those services by using common computers or mobile devices is not feasible. Therefore this paper describes the development of a web-based 3D routing system based on a new HTML extension. The visualization of rooms as well as the computed routes is realized with XML3D. Since this emerging technology is based on WebGL and will likely be integrated into the HTML5 standard, the developed system is already compatible with most common browsers such as Google Chrome or Firefox. Another key difference of the approach presented in this paper is that all utilized data is actually crowdsourced geodata from OpenStreetMap (OSM). Such data is collaboratively collected by both amateurs and professionals and can be used at no charge under the Open Data Commons Open Database License (ODbL). Our research combines user-generated geo content of the Web 2.0 with future Internet technology for the provision of a ubiquitously accessible 3D indoor routing application.

9.1 Introduction

With the increasing size and complexity of public buildings or institutions, such as universities, hotels, airports or office buildings, there is also an increasing need for mature indoor location based services (Indoor LBS), such as indoor maps or indoor routing (*Goetz & Zipf 2010*). Both research and economy entities recently became aware of this trend. Global companies such as Google, Navteq or Bing started to extend their well-known outdoor map applications towards indoors (*Bing 2011; Google 2011; Navteq 2011*); however until now they have mainly focused on the two-dimensional visualization of building representation. For simple indoor map visualization this approach seems to be feasible. In contrast, the visualization of three-dimensional (3D) routes between several floors in a building with a two-dimensional representation can always only provide a brief overview, but not properly visualize vertical parts (*i.e.*, transferring from one floor to another) of a route. Essentially, 2D environments have revealed serious limitations when considering multi-level structures (*Meijers et. al. 2005*). In contrast, a 3D map or model allows a better presentation of the provided information. It has been proven that 3D city models are advantageous for (mobile) navigation (*Coors & Zipf 2007*) and the actual need for 3D information has been elaborated (*Zlatanova 2008*).

Widespread outdoor applications and newly developed indoor applications are typically based on commercially provided data, which has been collected by professionals such as surveyors, architects or commercial data providers. However, in most cases this data is proprietary and licensed by the corresponding data provider, thus the development of own applications with such data is limited according to the individual licenses. Also, commercially collected data can be quite expensive to acquire. In contrast, within the last years a new source for geodata, namely crowdsourced geodata or volunteered geographic information (VGI), has evolved. Thereby, a community (normally aiming for some distinct goal) collaboratively collects geodata and provides it in the Internet. That is, VGI can be regarded as a spatially enriched type of user-generated content (UGC), a typical trend of the future Internet (*Havlik et. al. 2011*). Similar to the UGC phenomenon of the Web 2.0, everybody is able to use VGI for different applications at no charge. Regarding the increasing availability of GPS-enabled devices, such as cameras or smart phones, there is an enormous potential arising from "*billions of humans acting as remote sensors*" (*Goodchild 2007*). Regarding the quality and quantity of the data, several evaluations of OpenStreetMap (OSM, one of the most prominent examples of VGI) have revealed that OSM is, especially in urban areas, able to compete against commercially collected geodata (*Haklay 2010; Zielstra & Zipf 2010; Neis et. al. 2012*). The usage of OSM data is free and open under the Open Data Commons Open Database License (ODbL). Trying to utilize the power of VGI, researchers have attempted to extend such communities to indoor spaces. Especially for OSM there is a very detailed *IndoorOSM* mapping proposal available (*OSM 2012a*), which initially originated from research on the demands and requirements of crowdsourced indoor geodata (*Goetz & Zipf 2011a*).

The main contribution of this paper is the development of a web-based 3D application, capable of visualization of building interiors as well as computing and depicting (multi-level) routes inside a building. Essentially, the developed application utilizes existing (and future) HTML standards; the application runs on most modern browsers as well as on some mobile devices. A method for the automatic extraction of building interiors from crowdsourced geodata of OSM is presented, whereby this information can be used for automatically creating XML3D geometries. XML3D is an emerging technology based on the

Extensible Markup Language (XML) for the declarative generation of 3D content in the browser (*Sons et. al. 2010*). The route computation itself is based on the Dijkstra algorithm (*Dijkstra 1959*), whereas the Open Source implementation *pgrouting* for PostgreSQL databases has been utilized. A detailed route graph is created and all possible routes inside the building are pre-processed and stored as individual XML3D tiles on the server. The aim of the work presented within this paper can be summarized as: (1) to demonstrate the powerful application of crowdsourced geodata from OSM for the creation of (3D) indoor LBS; and (2) to present a web-based 3D routing system and its advantages in the context of urban environments by using future Internet technology.

The paper is organized in seven Sections: after the introduction, Section 9.2 provides a brief overview about existing (3D) indoor applications and Section 9.3 then introduces the emerging technology of XML3D. Section 9.4 provides some general introduction of OSM, as well as detailed insight into crowdsourced indoor information with *IndoorOSM*. Thereafter, Section 9.5 describes the system architecture as well as the different algorithms that have been developed. Section 9.6 then describes the web front-end which allows an easy perception and understanding of indoor information as well as the functionality of indoor route computation. Section 9.7 finally concludes the conducted research and provides an outlook on future work.

9.2 Related Work

One of the first approaches towards an indoor navigation system was the so called *Cyberguide* system (*Abowd et. al. 1997*). It is designed as a tool for guiding tourists through both outdoor and indoor environments. When entering a new room inside a building, the system indicates this by displaying an arrow on a two-dimensional map.

Similarly, the *MARS* System (*Höllerer et. al. 1999*) provides information about buildings in the Columbia university campus to the users (*e.g.*, visitors, staff, students, etc.). It is a collaborative system in which users can annotate obstacles or buildings and share this information via a desktop or augmented reality. A similar system for the École Polytechnique Fédérale de Lausanne (EPFL) is presented in *Gilliéron & Bertrand (2003)*, whereas a two-dimensional map is utilized for visualization.

The user-oriented development of a nomadic exhibition guide for trade fair visitors is described in *Schmid-Belz & Hermann (2004)*. Within the *SAiMotion* project, the authors developed a system which supports planning at home as well as mobile guidance on-site – both in a 2D map. A similar prototype for an exhibition show guiding application is also presented in *Pateli et. al. (2005)*.

One of the first 3D applications is described in (*Meijers et. al. 2005*). As a prototypical system the authors utilized Oracle Spatial 10 g (with a mixed model of geometry and graph) as DBMS and the building of the Aerospace Faculty of TU Delft (with 13 floors) as a test building. The graph contains about 1200 elements.

An indoor navigation system, namely *iNAV*, is presented in *Kargl et. al. (2007)*. It uses the A* algorithm for real-time routing and navigation. The Java client is suitable for laptops or proper PDA devices. The system consists of several distributed web services. An initial trial by the authors has revealed a lack of performance due to service communication. A similar approach with client-server architecture based on PHP (*i.e.*, programming language for dynamic web applications, namely Hypertext Preprocessor) web services and KML (a XML-based markup language for Geodata, namely Keyhole Markup Language) models is also presented in *Hijazi & Ehlers (2009)*. Similar mobile solutions (mostly in 2D) are furthermore available (*Rehrl et. al. 2005; Inoue et. al. 2008; Raad 2009*).

In *Papataxiarhis et. al. (2008)* the development of an indoor navigation system which considers users' special needs and preferences, is described. It aims at the provision of universal indoor LBS for everyone and therefore tries to support several types of users by exploiting multimodal interaction. Unfortunately the path algorithm used for route calculation "*can only be applied to connected two-dimensional digraphs, which means the route can be computed only if the O and D are located on a connected single floor*" (*Karimi et. al. 2010*). Another 2D indoor navigation framework is also presented in *Lyardet et. al. (2006)* and *Lyardet et. al. (2008*).

Besides those research-motivated indoor routing systems, there are also some web-based indoor maps developed by global companies such as *Google Indoor Maps* (*Google 2011*), *NAVTEQ Destination Map* (*Navteq 2011*), or *Bing Maps Venue maps* (*Bing 2011*), but these only utilize two-dimensional data for the visualization.

To conclude this brief review, it becomes apparent that both research and economy develop different solutions for indoor maps and routing. However, existing solutions are mainly two-dimensional, although it has been demonstrated that a 3D visualization is advantageous (*Coors & Zipf 2007*). Furthermore, existing 3D applications require additional software or plugins, thus a broad application on standard browsers is not possible. That is, users have to download and install additional software, representing a barrier for the utilization of the service. However, regarding the future Internet, a ubiquitous accessibility of such standard-based services is desirable. Regarding the data of the above mentioned applications, it becomes obvious that they all utilize proprietary data. In most cases license fees have to be paid for those, because they have typically a cost recover model for the data acquisition. Essentially, as far as the author is aware, there is no 3D indoor map and routing application available, which utilizes crowdsourced geodata.

9.3 Creating 3D Web Applications with XML3D

Web technologies are omnipresent; not only for distributing digital information in the Internet, but also for forming the base of a ubiquitous application platform. Thereby, the content itself rapidly evolved from basic text data without any styling, over dynamic and attractive web pages including styling and images, to sophisticated web applications with heterogeneous data sources and multimedia elements such as videos or live communication features. Motivated by the fact that we are living in a 3D world and that more and more communication media is shifting towards 3D visualization, web developers always aimed at creating 3D content. However, the main ideas in this area mainly comprise the integration of additional 3D content which only can be visualized when additional software, such as Java3D or VRML viewers, are installed. A platform-independent and portable solution has not yet been developed so far, but in the last two years – trying to push 3D to the future Internet – different initiatives and ideas for creating a quasi-3D-standard for the web has been conducted.

One promising possibility for the creation of 3D web content is XML3D. It is an extension of HTML5 which allows for the creation of interactive 3D graphics. The specification of XML3D has been developed together by the German Research Center for Artificial Intelligence (DFKI), the Intel Visual Computing Institute (IVCI) and the Saarland University. These are furthermore the lead institutions driving the development of XML3D as well as the efforts for making XML3D an integral part of HTML5, thus the common standard for 3D web content.

XML3D is aiming at a maximum compatibility with HTML5 as well as XHTML. For the generation of graphical objects, XML3D mainly features triangles which can then be utilized for describing nearly any arbitrary shape (*XML3D 2012*). Following a declarative approach "*XML3D fully leverages existing web technologies including HTML, Cascading Style Sheets (CSS), the Document Object Model (DOM), and AJAX for dynamic content*" (*Sons et. al. 2010*). That is, all 3D elements are part of the DOM, thus common DOM scripting and events, such as deletion of objects or on-demand integration of additional content, are fully supported. In particular, XML3D aims at enabling programmers to create 3D content without actually having any specific knowledge about certain 3D technologies

(*XML3D 2012*). That is, basically every web designer who is familiar with common World Wide Web Consortium (W3C) standards such as (X)HTML, CSS, etc. is able to create and integrate 3D elements into a web application. This is also regarded as one of the main differences between XML3D and other approaches like WebGL, O3D or X3DOM (*XML3D 2012*). The possibilities and feasibility of XML3D have already been demonstrated by integrating XML3D support into WebKits and Mozilla browsers, as well as with a portable WebGL/JavaScript based version (*Sons et. al. 2010*). Most of the latest existing browsers such as Firefox or Chrome are already able to visualize XML3D content, thus applications which are based on this technology can already be utilized by the broad public. The Microsoft Internet Explorer does however not yet support any kind of 3D content. For more information on XML3D please refer to the publication (*Sons et. al. 2010*) as well as the current specification version 0.4 (*XML3D 2010*).

9.4 OSM as a Source for Crowdsourced (Indoor) Geodata

Combining the idea of user generated content (UGC) in the Web 2.0 with the ubiquitous availability of GPS-enabled devices, such as smartphones or cameras, an enormous potential of crowdsourced geodata arises. Both amateurs and professionals collect not only content, but spatially references content, such as geo-tagged Flickr photos or street information (*e.g.*, in FixMyStreet.com).

One of the most prominent and most varied source for crowdsourced geodata is OSM. Initially, OSM aimed at the creation of a free world map, but soon the project turned beyond that, becoming more like a free global database comprising different kinds of geodata. Essentially, everybody can contribute, change and improve the data in OSM and the project benefits from currently more than 500,000 registered users (*OSM 2012b*). The users can contribute two different types of data: (1) two-dimensional geometries and (2) additional (semantic) information. For the provision of geometries, users basically provide geo-tagged points (*nodes* in OSM terminology). Currently there are about 1.42 billion *nodes* inside the database (by end of March, based on our internal OSM database). Additionally, several nodes can be combined into so called *ways*. These can be utilized for either describing linestring geometries or polygons whereas in the former case the *way* is not closed and in the latter case the *way* is closed (*i.e.*, the last node equals the first node). The current OSM database contains about 131 million *ways*. Furthermore, OSM provides so called *relations* (currently about 1.35 million) which can be utilized for mapping complex polygons with holes or for describing relationships between different OSM features (*e.g.*, turn restrictions, routes, etc.).

Besides those geometries, users can furthermore tag them, thus provide additional information about them. OSM provides an open key-value pair methodology which allows the contributors to describe a wide range of information and attribution. The key describes a special kind of information domain or characteristic of the map feature (*e.g.*, *building*, *natural*, etc.) and the value refines this information (*e.g.*, *university*, *forest*, etc.). There are some community accepted tags which are listed at *Watchlist (Tagwatch 2012)*, but basically any kind of key/value can be utilized. A complete list of all currently used tags with some exemplary values is available on *Tagwatch (2012b)*. Also, the OSM wiki provides detailed descriptions about the different keys and values (*OSM 2012c*).

Convinced by the increasing demand for indoor data, OSM tries to provide information about indoor spaces, although there is no standard indoor mapping schema available yet. However, a promising and scientifically motivated mapping proposal, namely *IndoorOSM*, has been developed (*Goetz & Zipf 2011a*) and presented (*OSM 2012a*). The application of collaboratively collected *IndoorOSM* data has already been demonstrated with a web-based two-dimensional indoor map with indoor routing capabilities (*Goetz 2012*); however an application which utilizes 3D data of *IndoorOSM* has not been developed yet.

The *IndoorOSM* model can be described as follows: a building is considered as a hierarchically structured object which consists of several levels/floors. These floors are furthermore divided into elements such as rooms, corridors, stairways, doors or windows. Within OSM, a building is therefore mapped as a relation (main-relation). All the different floors are also mapped as relations (level-relation), whereby these are considered as relation members (children) of the main-relation. Furthermore, the different building parts (rooms, etc.) are also mapped as relation members of the corresponding level-relation. The *IndoorOSM* proposal aims at providing detailed floorplan information, thus all building parts are typically mapped as closed ways, representing the polygonal footprint of the corresponding building part. By tagging the different OSM-features with the key height, it is furthermore possible to provide 3D information, such as the height of a room. Information about doors is added by using OSM-nodes and the width or height of the door can be provided with the corresponding key-value pairs. The basic ideas of the *IndoorOSM* mapping schema are also depicted in Figure 9-1, whereby Figure 9-1 (a) depicts the basic hierarchical principle of a building and Figure 9-1 (b) shows the composition of a detailed floorplan for an exemplary building level (in this case level 0, *i.e.*, the ground level).

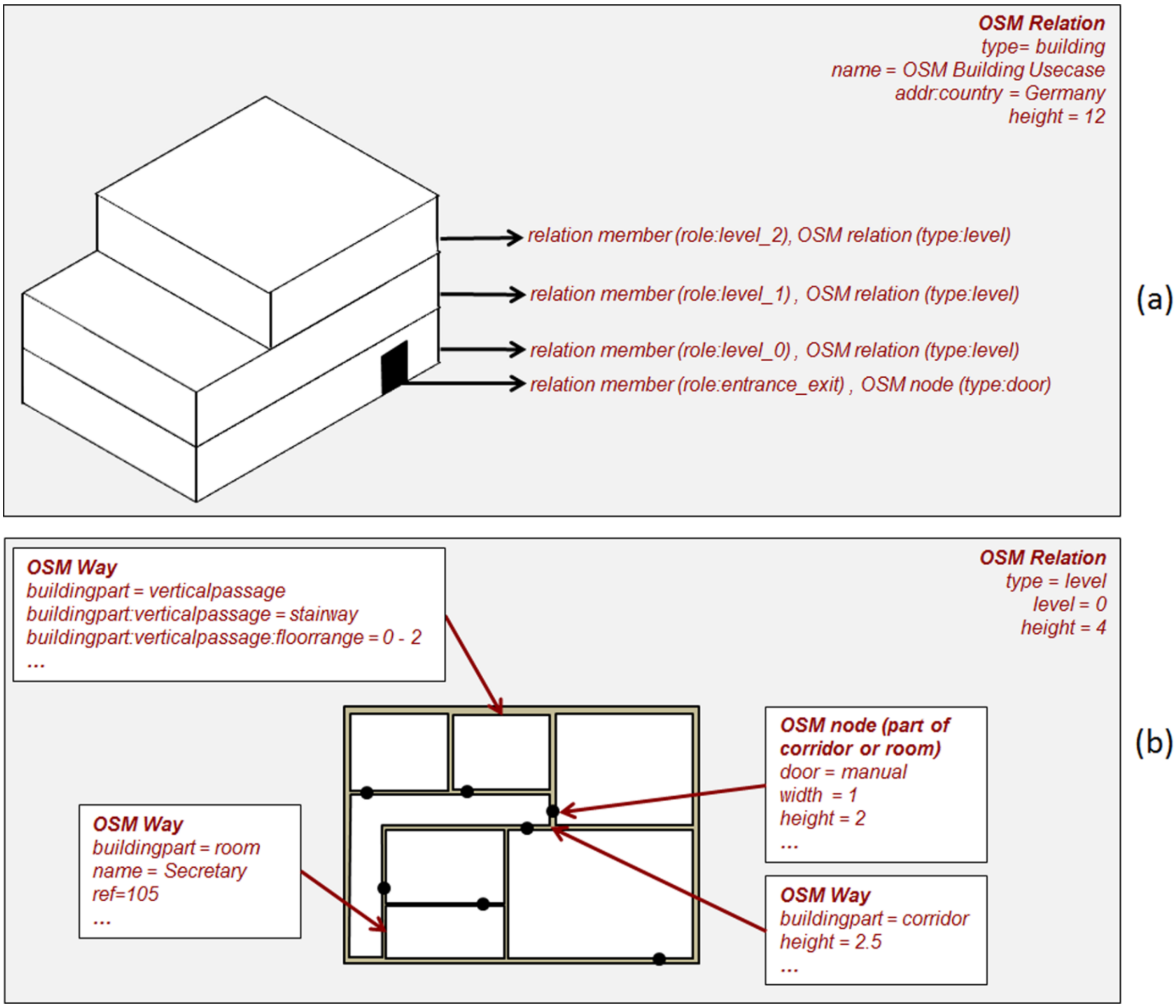


Figure 9-1. The basic hierarchical principle of a complete building (a) and the detailed floorplan information for an exemplary building floor/level (b) in IndoorOSM.

Since it is only possible to map two-dimensional geometries in OSM, vertical connections, such as stairways, escalators or elevators, need to be expressed semantically with keys and values. In general, every vertical passage is mapped as a polygon (*i.e.*, a closed way) and tagged with *buildingpart=verticalpassage*. That is, for each elevator funnel, stairway area or escalator platform, there is a polygon on the corresponding floor. Furthermore, *IndoorOSM* provides the key *buildingpart:verticalpassage* for refining the corresponding type. Exemplary values are stairway, escalator, elevator, ramp, etc. The general floor range of a vertical passage is provided by using *buildingpart:verticalpassage:floorrange*, so a user can describe for example that an elevator ranges from the ground level to the second level (value 0–2). Since all of these vertical passage polygons are accessible via another building part (*e.g.*, a corridor next to the elevator), the *IndoorOSM* model provides a corresponding door (or opening) node between the two adjacent elements. By adding the key *connector:ids* to these nodes, it is possible to semantically describe the connectivity between vertically connected elements. The value of this key is the *OSM-ID* of the element to which a vertical connection exists. For a one-way connector (*e.g.*, an escalator), only the starting node is tagged with *connector:ids*, whereas for multi-way connectors (*e.g.*, stairways or escalators), both adjacent nodes are tagged accordingly. However, the key *connector:ids* only contains information about the directly adjacent neighbors. For more information on *IndoorOSM* please refer to the underlying research publication (*Goetz & Zipf 2011a*) or the *IndoorOSM* wiki page (*OSM 2012a*).

9.5 System Architecture for the Generation and Utilization of the 3D Indoor Routing Service

The system architecture of the web application is divided into the server side and the client side (depicted in Figure 9-2). On the server side, a PostgreSQL database with PostGIS extension serves as a data container for the *IndoorOSM* data. Therefore, the raw OSM data, which can be obtained from either the OSM web page or on several OSM data pages like *Geofabrik (2012)*, is imported by using the Open Source command line tool *OSMOSIS* (*OSM 2012d*). Furthermore, the server side consists of the C++ pgrouting libraries. Pgrouting provides shortest route computation capabilities, whereas the computation is based on the wide-known Dijkstra algorithm (*Dijkstra 1959*).

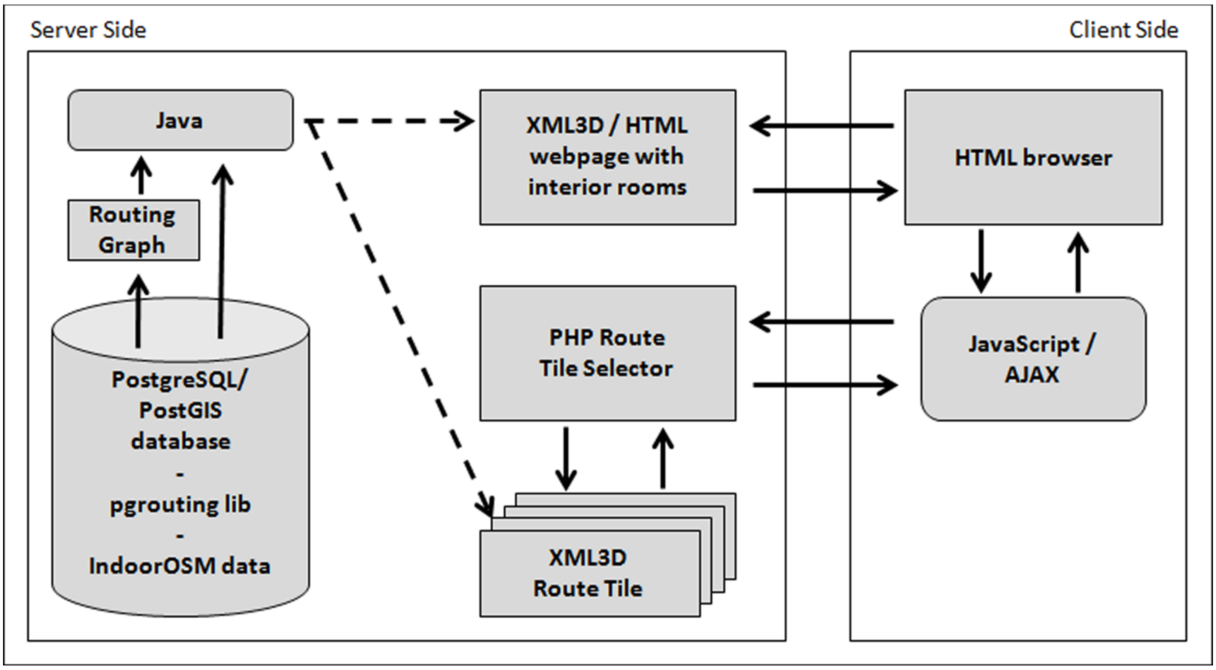


Figure 9-2. System architecture and processing workflow of the 3D indoor routing service.

Additionally, the system architecture consists of some other algorithms for the automated creation of a XML3D/HTML webpage which visualizes the interior rooms of the desired buildings and additionally allows for the control of the visibility of different floors as well as the computation and visualization of routes. Those algorithms are based on Java. The different routes inside the desired building are pre-computed and stored as individual route tiles on the web server. On the client side, the web application can be visualized in any XML3D-capable web browsers. By using JavaScript and AJAX technology, it is possible to load and visualize the pre-computed route tiles. The server side of the developed application and the required algorithms are described in great detail in the following sub-sections, whereas the client application (from a user's perspective) is elaborated in Section 9.6.

```
Algorithm createWIRG(DB, bID)

Input: DB = Database connection to a database with IndoorOSM data
Input: bID = the unique identifier for the desired building
WIRG ← empty
building ← getBuilding(DB, bID)
num_levels ← getNumLevels(building)
levels[num_levels] ← getLevels(building)
for each levels as level
   num_doors ← getNumDoors(level)
   doors[num_doors] ← getDoors(level)
   for each doors as door
      addNode(WIRG, door)
   num_edges ← getNumEdgesOfAdjacentRooms(level)          // edges between adjacent rooms
   edges[num_edges] ← getEdgesOfAdjacentRooms(level)
   for each edges as edge
      weight ← computeWeight(edge)
      addEdge (WIRG, edge, weight)
   num_corridors ← getNumCorridors(level)
   corridors[num_corridors] ← getCorridors(level)
   for each corridors as corridor
      centerline ← computeCenterLine(corridor, doors)
      centerlineNodes ← getNodes(centerline)
      centerlineEdges ← geEdges(centerline)
      for each centerlineNodes as centerlineNode
         addNode(WIRG, centerlineNode)
      for each centerlineEdges as centerlineEdge
         weight ← computeWeight(edge)
         addEdge(WIRG, centerlineEdge, weight)
num_verticalConns ← getNumVerticalConns(building)
verticalConns[num_verticalConns] ← getVerticalConns(building)
for each verticalConns as verticalConn
   addEdge(WIRG, verticalConns)

Output: Weighted Indoor Routing Graph (WIRG)
```

Figure 9-3. Pseudo-code algorithm for the automated generation of a WIRG from IndoorOSM.

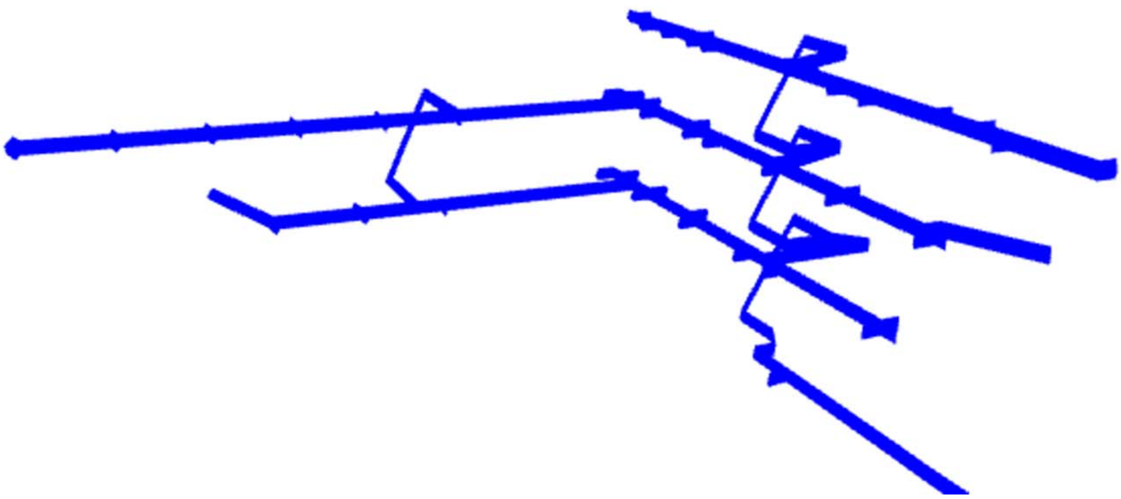
9.5.1 Generating the Routing Graph

For the computation of meaningful shortest routes within the building, different building elements such as rooms, corridors and doors have to be modeled. For this purpose, a comprehensive route graph has been automatically created. Thereby, the methodology of the graph is based on the *Weighted Indoor Routing Graph (WIRG)* (*Goetz & Zipf 2011b*), thus all doors are represented as nodes in the graph and edges represent connections between adjacent doors. The doors of the building can be automatically retrieved from OSM, because they are mapped as OSM-nodes.

Vertical connections, such as stairways or elevators, are represented as edges in the graph and can be automatically retrieved from different OSM keys, such as *connector:ids* or *buildingpart:verticalpassage*, etc. (*cf.* Section 9.4). By computing the centerline of a corridor and adding vertical edges from the doors to this centerline, it is possible to model corridors (*cf. Goetz & Zipf (2011b)*). The complete algorithm for the automated routing graph generation is briefly described in Figure 9-3 as pseudo-code.

	id serial	source integer	target integer	cost double precis	reverse_cost double precis	oneway text	x1 double precis	y1 double precis	z1 dou	x2 double precis	y2 double precis	z2 dou	gid [PK]	the_geom geometry	length double precis
49	49	224311	68	6.947277037	6.947277037	N	8.6771015	49.4185436	-4	8.677101111	49.41855053	-4	49	010500002	6.947277037
50	50	68	224613	6.970561306	6.970561306	N	8.677101111	49.41855053	-4	8.6771008	49.4185575	-4	50	010500002	6.970561306
51	51	68	69	5.134246619	5.134246619	N	8.677101111	49.41855053	-4	8.677152453	49.41855043	-4	51	010500002	5.134246619
52	52	225563	69	6.878086266	6.878086266	N	8.6771532	49.4185436	-4	8.677152453	49.41855043	-4	52	010500002	6.878086266
53	53	69	228595	7.156125461	7.156125461	N	8.677152453	49.41855043	-4	8.6771513	49.4185575	-4	53	010500002	7.156125461
54	54	73	226822	2.094211873	2.094211873	N	8.676757347	49.41861475	-4	8.6767572	49.4186357	-4	54	010500002	2.094211873
55	55	224568	49	1.104752449	1.104752449	N	8.6767691	49.4187554	-4	8.676780147	49.41875531	-4	55	010500002	1.104752449
56	56	225818	226369	5.397795846	5.397795846	N	8.6767699	49.4187137	0	8.676767	49.4187676	0	56	010500002	5.397795846
57	57	226369	227132	4.874935897	4.874935897	N	8.676767	49.4187676	0	8.6767803	49.4187207	0	57	010500002	4.874935897
58	58	227132	35	6.936567049	6.936567049	N	8.6767803	49.4187207	0	8.676780345	49.41871376	0	58	010500002	6.936567049
59	59	225818	35	1.044522120	1.044522120	N	8.6767699	49.4187137	0	8.676780345	49.41871376	0	59	010500002	1.044522120
60	60	35	226756	1.186300263	1.186300263	N	8.676780345	49.41871376	0	8.6767922	49.4187142	0	60	010500002	1.186300263
61	61	35	36	5.497793566	5.497793566	N	8.676780345	49.41871376	0	8.676780419	49.41865878	0	61	010500002	5.497793566
62	62	36	227063	1.168812334	1.168812334	N	8.676780419	49.41865878	0	8.6767921	49.4186592	0	62	010500002	1.168812334
63	63	36	37	9.794131010	9.794131010	N	8.676780419	49.41865878	0	8.676780518	49.41864899	0	63	010500002	9.794131010
64	64	37	226685	1.411814968	1.411814968	N	8.676780518	49.41864899	0	8.6767664	49.418649	0	64	010500002	1.411814968

(a)



(b)

Figure 9-4. Route graph with x, y, z coordinates of the source and target nodes with connectivity and oneway information (a) and a complete 3D route graph for a sample building (b).

After the extraction and generation of the routing graph, it is transferred to the PostgreSQL/PostGIS database. The network is stored in one physical database table. It consists of link IDs, source and target of the corresponding edges, the 3D coordinates (both combined and separated into x, y, z) and the 3D length of the edge which is used as the cost parameter for Dijkstra. An excerpt of the route graph database table is provided in Figure 9-4 (a) and the complete 3D route graph is visualized in Figure 9-4 (b).

9.5.2 Automated Generation of an 3D Indoor Model for XML3D

Aiming at an easy and fast generation of 3D indoor models for different buildings from *IndoorOSM* information, an automatic generation is required. Therefore, information from OSM about the desired building (which is mapped according to the *IndoorOSM* mapping proposal) needs to be gathered. Thereby, the real world coordinates of OSM with latitude and longitude information must be transformed into some kind of local reference system (*e.g.*, based on the building bounding box), because XML3D is currently not able to handle double precision coordinate values.

The algorithm is depicted as pseudo-code in Figure 9-5 and a human-readable explanation is given in the following: The algorithm sequentially retrieves all the different levels (floors) of the building. For each room on the corresponding floor, a XML3D geometry is created in that way that all corresponding walls are created as well as the floor and ceiling geometry. These faces are then triangulated, because XML3D is currently only capable of dealing with triangle geometries. The respective room elevation is based on the current level elevation, which can be calculated from all the other levels. For example, when computing the level elevation of floor 2, the elevations of level 0 and level 1 are accumulated (based on the OSM key height). The elevation of the ceiling of a room is the level elevation plus the height of the corresponding room. After computing all the room geometries, they are added to the XML3D indoor model. Being able to hide different levels in the web application (*cf.* also next Section), all rooms are grouped, according to their level, in the DOM of the web application. In doing so, it is possible to set the visibility of the different groups in the DOM via JavaScript and CSS on-demand during runtime.

```
Algorithm createIndoorModel(DB, bID)

Input: DB = Database connection to a database with IndoorOSM data
Input: bID = the unique identifier for the desired building
3DIM ← empty
addHeaderInfo(3DIM)
building ← getBuilding(DB, bID)
bounds ← computeBounds(building)
num_levels ← getNumLevels(building)
levels[num_levels] ← getLevels(building)
for each levels as level
   num_rooms ← getNumRooms(level)
   rooms[num_rooms] ← getRooms(level)
   level_height ← getLevelHeight(level)
   level_elevation ← getLevelElevation(level)
   for each rooms as room
      num_walls ← getNumWalls(room)
      walls[num_walls] ← getWalls(room)
      room_height ← getHeight(room)
      for each walls as wall
         wall ← computeAndTriangulateWall(wall, room _height)
      wall ← computeAndTriangulateFloor(room, room _elevation)
      ceiling ← computeAndTriangulateCeiling(room, room _elevation, room_height)
      transformCoordinatesForXML3D(walls,  bounds)
      transformCoordinatesForXML3D  (floor, bounds)
      transformCoordinatesForXML3D  (ceiling, bounds)
      add(3DIM, walls)
      add(3DIM, floor)
      add(3DIM, ceiling)
addControls(3DIM)

Output: XML3D Indoor Model (3DIM)
```

Figure 9-5. Figure 5. Pseudo-code algorithm for the generation of a XML3D indoor model from IndoorOSM.

9.6 The XML3D-based Web Application

To allow for the routing analysis and the 3D visualization of both the interior building parts as well as the routes, a web site which can be accessed from any XML3D-capable computer or mobile device, is created (Figure 9-6). A predefined list enables the user to select the source and target of the desired route. The level overview on the right-hand side (*cf.* Figure 9-6) can be utilized for displaying or hiding the different floors. This enables the user to only visualize the desired floors, thus the visualization can be adapted to the user's requirements. By clicking on Computer Route, the optimal path between the user defined entities is selected from the pre-computed XML3D route tiles and visualized in 3D in the routing application. Essentially, the pre-computation of all routes allows an efficient provision of any desired route in O(1) on the user's device. Figure 9-7 depicts an exemplary 3D route from the entrance of a building to an office on the second floor. For visualization purposes, the other floors (the basement and level 1) are hidden. By clicking on Clear Route the visualized route is removed from the DOM.

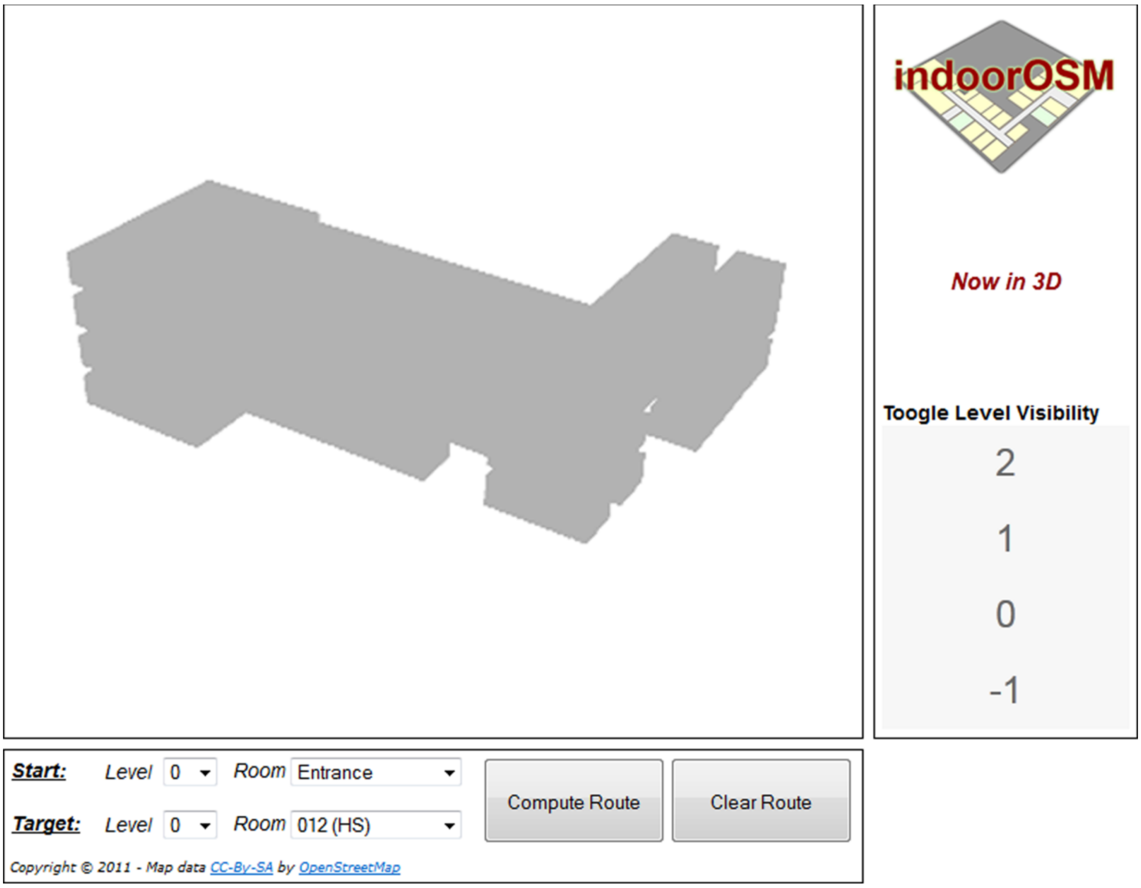


Figure 9-6. Indoor routing web application with XML3D scene graph.

For realizing the on-demand loading and removing of the corresponding route tile, Asynchronous JavaScript and XML (AJAX) technology is utilized (*cf.* Figure 9-2). When clicking the Compute Route button, an AJAX script retrieves the desired start and target node and sends them via HTTP-GET to a PHP application. This then checks if there is a shortest path between the desired nodes and if so, returns the XML3D code from the corresponding route tile file. The AJAX script parses the PHP response and, in the case of an existing route, appends the XML3D to the DOM. In contrast, when clicking the Clear Route button, a different AJAX script searches for every existing route tile in the scene graph and removes them from the DOM.

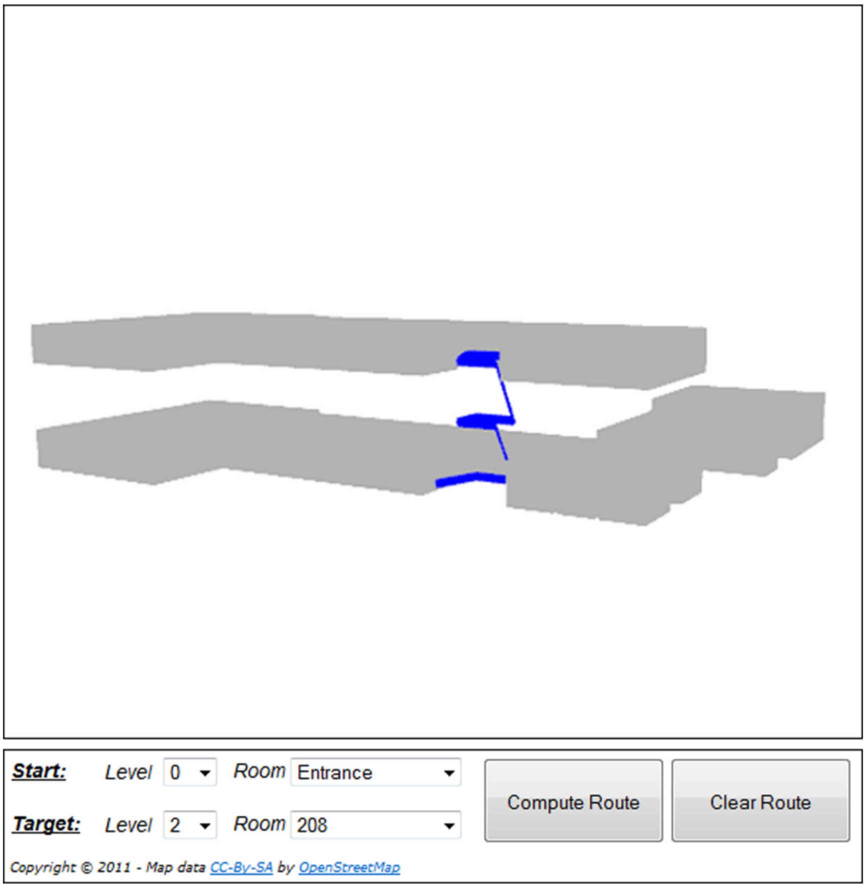


Figure 9-7. 3D visualization for a computed route between user-defined start and target inside the building.

9.7 Conclusion and Future Work

Indoor LBS and especially indoor routing are gaining attraction in research efforts as well as commercial application. Contrary to existing approaches, a 3D visualization is desirable, because it allows a better perception and understanding of the provided information (*e.g.*, the computed route) for the users. When developing 3D indoor applications, it is furthermore important that they are broadly accessible, thus that common browsers can visualize 3D indoor information. That is, for reducing the barrier of using the application, no additional software or plugin should be required. Furthermore, crowdsourced indoor geodata seems to a promising data source for detailed information about indoor spaces.

Due to the pre-computation of routes, the approach presented here suits well to static scenarios, in which routes are always available and room settings do not change. However, in its current state, it cannot be directly adapted to scenarios which are rather dynamic, such as emergency situations or simulations, etc., in which certain routings may quickly become invalid. That is, for the consideration of such dynamic scenarios, it is required to not only provide pre-computed routes, but also on-demand route computation functionality.

It can be concluded that it is already feasible to create 3D indoor routing applications which are purely based on crowdsourced indoor geodata from OSM. In particular, it has been proven that 3D indoor routing services can be implemented by using XML3D, thus that 3D indoor LBS can be used without any specific software or prerequisite (except the XML3D-enabled browser). Essentially, this allows the provision of 3D applications in the context of future Internet by utilizing cutting edge Internet technology. As described beforehand, the conducted research has been based on crowdsourced geodata. However, the general architecture as well as the client itself is also suitable for other data sources. In general, any other (proprietary) data source, such as CAD plans, evacuation plans, Industry Foundation Classes (IFC) models from the Building Information Modeling (BIM) domain or 3D modelling software (*e.g.*, Cinema 4D or 3D Studio Max), can be utilized for the generation of the here presented XML3D based indoor routing application. In this research we have shown the potential of a crowdsourcing approach through OSM, because the authors believe that this is an important and rich source for open and free geodata.

Future work will include the incorporation of several buildings. This will allow queries like "*What is the shortest route between office 321 on the 3rd floor of building A to the lecture room in the basement of building B*". Also, different usage modes such as examination or walk-around shall be included, because this is likely to increase the user experience. Additionally, the inclusion of access restrictions and different states of spaces and doors has to be considered in both the *IndoorOSM* model and the presented application. Furthermore, the XML3D technology needs to be developed further; essentially it is desirable that XML3D will become a part of HTML5, thus a standard which is accessible in every browser on any device. The utilization of the generated routing graph for complex analysis, such as emergency evacuation simulations, is also a desirable, but challenging task, and will be investigated in the near future. Regarding the data acquisition by OSM contributors, there is fertile ground for future research. Due to missing GPS signals inside buildings, other methodologies, techniques and devices must be utilized for indoor mapping activities. Some existing examples are step counters, images of publically accessible evacuation plans, or distinct indoor mapping apps, but easy to use and cost effective solutions are required. Research on indoor LBS applications, not necessarily 3D but also 2D, based on indoor VGI will increase the application presented here further.

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10 Publication 6: Using Crowdsourced Geodata for Agent-Based Indoor Evacuation Simulations

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Marcus Goetz has conducted all simulation developments for this publication himself, as well as all use-case scenarios. He has also written the manuscript himself. All Co-authors have supported this publication by continuing discussions about the design and execution of the evacuation simulations. Furthermore, extensive proof-reading by the co-authors and four anonymous reviewers and the editors has led to substantial improvement of the manuscript.

Alexander Zipf

Using Crowdsourced Geodata for Agent-Based Indoor Evacuation Simulations

Abstract

Crowdsourced geodata has been proven to be a rich and major data source for environmental simulations and analysis, as well as the visualization of spatial phenomena. With the increasing size and complexity of public buildings, such as universities or hotels, there is also an increasing demand for information about indoor spaces. Trying to stimulate this growing demand, both researchers and Volunteered Geographic Information (VGI) communities envision to extend established communities towards indoors. It has already been showcased that VGI from OpenStreetMap (OSM) can be utilized for different applications in Spatial Data Infrastructures (SDIs) as well as for simple shortest path computations inside buildings. The here presented research now tries to utilize crowdsourced indoor geodata for more complex indoor routing scenarios of multiple users. Essentially, it will be investigated if, and to what extent, the available data can be utilized for performing indoor evacuation simulations with the simulation framework *MATSim*. That is, this paper investigates the suitability of crowdsourced indoor information from OSM (*IndoorOSM*) for evacuation simulations. Additionally, the applicability of *MATSim* for agent-based indoor evacuation simulations is conducted. The paper discusses the automatic generation simulation-related data, and provides experimental results for two different evacuation scenarios. Furthermore, limitations of the *IndoorOSM* data and the *MATSim* framework for indoor evacuation simulations are elaborated and discussed.

10.1 Introduction

The last couple of years yielded the phenomenon of crowdsourced geodata (also known as Volunteered Geographic Information, VGI). Thereby, geographic data is collaboratively collected by users (both amateurs and professionals) and shared on an online community platform. VGI comprises a special kind of user-generated content (UGC), whereby the spatial component, *i.e.*, the geo-location of a distinct feature, is an integral part of the collected data. It has already been demonstrated that VGI can be used for various kinds of applications and analysis, such as vehicle routing (*Schmitz et. al. 2008; Neis & Zipf 2008*), emergency routing (*Neis et. al. 2010*), or traffic simulation studies (*Dallmeyer et. al. 2011*; *Zilske et. al. 2011*). Furthermore, it has been demonstrated that VGI, especially from OpenStreetMap (OSM), can (potentially) serve as a major dataset (*Zielstra & Zipf 2010; Haklay 2010; Neis et. al. 2012*) for urban areas.

With the increasing size and complexity of the interior structure of public buildings, institutions and facilities, such as universities, hotels, or airports, there is also an increasing demand on data – and particularly information – about indoor environments (*Jensen et. al. 2011; Winter 2012*). Trying to stimulate this demand and furthermore to use the momentum of the crowd intelligence of VGI, there are efforts to extend OSM to indoor spaces. Originating from research on the requirements of crowdsourced indoor geodata (*Goetz & Zipf 2011a*), there is a detailed *IndoorOSM* mapping proposal available (*OSM 2012a*). It has already been demonstrated that *IndoorOSM* contains very detailed information about indoor environments, which can be utilized for automatically generating standardized 3D city models (*Goetz 2012*). Essentially, this means that OSM can be regarded as a rich and powerful (additional) data source for Spatial Data Infrastructures (SDI) (*cf. Zipf et. al. (2007*)), as well as professional applications and analysis for built environments, such as environmental simulations and facility management (Kolbe 2009), or emergency response and rescue operations (*Kolbe et. al. 2008*). Furthermore, it has already been showcased that crowdsourced geodata can be utilized for developing and providing indoor routing services with shortest path computation functionality in 2D (*Goetz & Zipf 2012a; Goetz 2012b*) and 3D client applications (*Goetz 2012c*).

In urban built environments and their interior spaces, it seems obvious that, especially during rush-hours, there are a lot of people inside a building at the same time. Once an incident or emergency occurs, people typically start to search for their nearest exit, thus to leave the ‘unsecure’ building. However, in such emergency situations the collective human behavior is rather unstructured, thus a fast and secure evacuation is not realizable in an easy manner. Additionally, such situations often lead to (mass) panic and crowd stampede which might cause serious injury to humans as people are crushed or trampled. To avoid such harm, it is important to identify potential bottlenecks or blind alleys in the building layout prior to constructing a new building or planning an event in an existing building, not only from the perspective of the designers and architects, but also from the perspective of the legislators. However, “*it is not an easy task to predict evacuation performances for large buildings with complex layouts*” (*Shi et. al. 2008*). Since the costs (both monetary and temporally) of practical simulations cannot be easily afforded, evacuation simulations with computers became popular within the last years (*Shi et. al. 2008*). Some exemplary scenarios for such simulations are: (1) a planned and structured site clearing of a hospital due to a predicted flood, (2) a fast but safe site clearing of a building due to a hostage crisis on a distinct building floor or (3) a rapid and unplanned evacuation due to a fire. It becomes apparent that there are different requirements for the evacuation as well as different stress-levels of the individual humans. By incorporating different parameters and requirements, it is assumed to create decision support for rescue operations or to mitigate disaster situations (*Okaya et. al. 2009*). However, it needs to be stated that evacuation simulations always depend on the simulation models, agents and assumptions. That is, simulations are subject to impreciseness which needs to be considered while evaluating the simulation.

For retrieving probable and reasonable simulation results, detailed and fine grained data about the affected building is required. However, it is often difficult to obtain and maintain appropriate data. For instance, information about the different floor layouts, stairways and potential building exits need to be collected from different third parties, such as architects, building owners or public authorities. However, those 'data providers' often deliver the data in various (non-standard) formats, typically ranging from low-level pixel images, over vector-based drawings, up to (3D) Computer Aided Design (CAD) plans. Furthermore, the different data sets are usually not explicitly referenced to each other and extensive pre-processing is required. In contrast, crowdsourced (indoor) geodata probably provides a solution for the aforementioned drawbacks, because it can be regarded as a well-defined source for geodata with (potentially) global coverage and unrestricted accessibility.

Therefore, the main objective of this paper is to investigate if and to which extent *IndoorOSM* data can be used for evacuation simulations. Thereby, the available data and information will be discussed, as well as the possibilities for an automated generation of such simulations. Essentially, an automated simulation generation allow a fast application of the here presented approaches to other crowdsourced buildings in *IndoorOSM*. Furthermore, by performing two exemplary evacuation simulation scenarios, limitations and missing data of *IndoorOSM* will be revealed.

The rest of this paper is organized as follows: Section 10.2 describes related work, focusing on crowdsourced indoor geodata from OSM, as well as existing agent-based simulation frameworks in general and the *MATSim* framework (which has been used for the here presented proof-of-concept) in particular. Section 10.3 will focus on the (semi-) automatic generation of all relevant simulation data sources. As a proof-of-concept, Section 10.4 will depict experimental results of two different evacuation scenarios. Section 10.5 discusses limitations and problems of the *IndoorOSM* data as well as the *MATSim* framework. The last Section serves as conclusion and outlook on future work.

10.2 Related Work

10.2.1 Crowdsourced (Indoor) Geodata From OpenStreetMap

Trying to benefit from a crowd-intelligence and utilizing thousands of humans acting as remote sensors (*Goodchild 2007*), more and more Internet communities are aiming at the collection of not only user-generated content (UGC), but spatially-referenced user-generated content. Thereby, volunteers collaboratively collect, generate, enhance and share geodata in a Web 2.0 community platform. Contrary to proprietary data, the available data can be used for individual purposes at no charge. That is, community members benefit from a vast amount of various kinds of geodata, which they can use for their own applications. One of the most popular and most manifold sources for VGI is OSM. Initiated in 2004, OSM grew rapidly regarding the amount of contributors as well as amount of data. It has already been proven that data from OSM can be used for various kinds of applications and analysis, such as routing (*Schmitz et. al. 2008; Neis & Zipf 2008*), emergency routing (*Neis et. al. 2010*), or traffic simulation studies (*Dallmeyer et. al. 2011; Zilske et. al. 2011*). Furthermore, it has been demonstrated that (in urban areas) OSM is comparable to commercially collected geodata (*Zielstra & Zipf 2010; Haklay 2010; Neis et. al. 2012*).

Regarding the data structure, OSM is kept rather simple: the users provide two-dimensional geometries which furthermore can be enriched (*i.e.*, *tagged*) with additional (semantic) information. In general, the user contribute single geo-referenced points (*i.e.*, *nodes*), which can be combined to so called ways for representing either lines (*i.e.*, a non-closed *way*) or polygons (*i.e.*, a closed *way*). Additionally, users can utilize *relations* for describing complex relationships between objects, such as turn restrictions or holes in a polygon. The tagging is realized via an open key-value pair methodology. That is, the contributors add an arbitrary key, representing some kind of information or information class (*e.g.*, *building*, *highway* etc.) and additionally refine this information with some value (*e.g.*, *airport*, *residential* etc.). Thereby, the amount of key-value pairs, as well as the keys and values themselves are unlimited. That is, a user can basically provide any kind of information. However, the most commonly used tags, *i.e.*, the community wide accepted map features, are listed on the map features wiki page (*OSM 2012b*). In contrast, *Tagwatch (2012)* provides an overview of all currently used tags, as well as some corresponding values. Additionally, the *OSM Wiki* (*OSM 2012c*) provides detailed (user-generated) descriptions for most key-value pairs.

Trying to benefit from the crowd intelligence and to disclose new possibilities, various OSM contributors try to use OSM for collecting indoor information. However, there is currently no community wide accepted standard or schema for mapping indoor information. There are several efforts in the community, varying in both mapping granularity and documentation (*OSM 2012d*). To the authors, one of the most advanced proposals is the so called *IndoorOSM* mapping schema, because it provides detailed information about the interior structure of a building. Furthermore, *IndoorOSM* is the only proposal which originated from research on the demands and requirements of collaboratively collected indoor information (*Goetz & Zipf 2011a*). It has already been demonstrated that *IndoorOSM* contains very detailed data which is suitable for generating standardized 3D CityGML building models (*Goetz 2012a*) for the application within SDIs. Additionally, the usage of *IndoorOSM* for the development of indoor routing services with basic shortest path computation has already been demonstrate with a 2D client for both desktop computers (Goetz 2012b) and mobile devices (*Goetz & Zipf 2012*), as well as a real 3D route planning application (*Goetz 2012c*). However, *IndoorOSM* data has not yet been utilized for the conduction of more complex and advanced indoor route applications with multiple users. Essentially, *IndoorOSM* has not yet been used as a data source for indoor evacuation simulations. Nevertheless, since *IndoorOSM* does not only contain data about the shape of rooms, but also detailed information about the location and attributes of doors and windows – which is important for emergency situations – the available data of *IndoorOSM* is (potentially) suitable for indoor evacuation simulations.

For mapping indoor information in OSM, *IndoorOSM* utilizes existing OSM data types (*i.e.*, nodes, ways, relations, tags). A building is represented as a hierarchically structured object, consisting of several building floors (*i.e.*, levels). Each floor furthermore contains a distinct amount of building parts (buildingpart), such as rooms, corridors, stairways etc. That is, the complete building is represented as a relation in OSM (the main-relation). The different relation-members of this main-relation represent the different floors, whereby each of them is again represented as an OSM-relation. Each individual part of the corresponding floor is then mapped as an OSM element (typically a closed way for representing the geometry of the building part).

Additional (semantic) information, such as room names, level numbers, heights, etc., can be added with key-value pairs to the corresponding OSM features. Information about doors or windows (which are very important for evacuation purposes) can be mapped by adding a node to the corresponding building part way and tagging it as window or door.

Additionally, information about the width or height of a door/window can be tagged respectively. The basic hierarchical idea of *IndoorOSM* is also visualized in Figure 10-1 (a). The composition of a detailed floor plan for an exemplary building level with rooms, corridors, doors and windows is furthermore depicted in Figure 10-1 (b). For more information on the *IndoorOSM* mapping proposal please refer to the underlying research publication (*Goetz & Zipf 2011a*) as well as to the corresponding OSM wiki page (*OSM 2012a*).

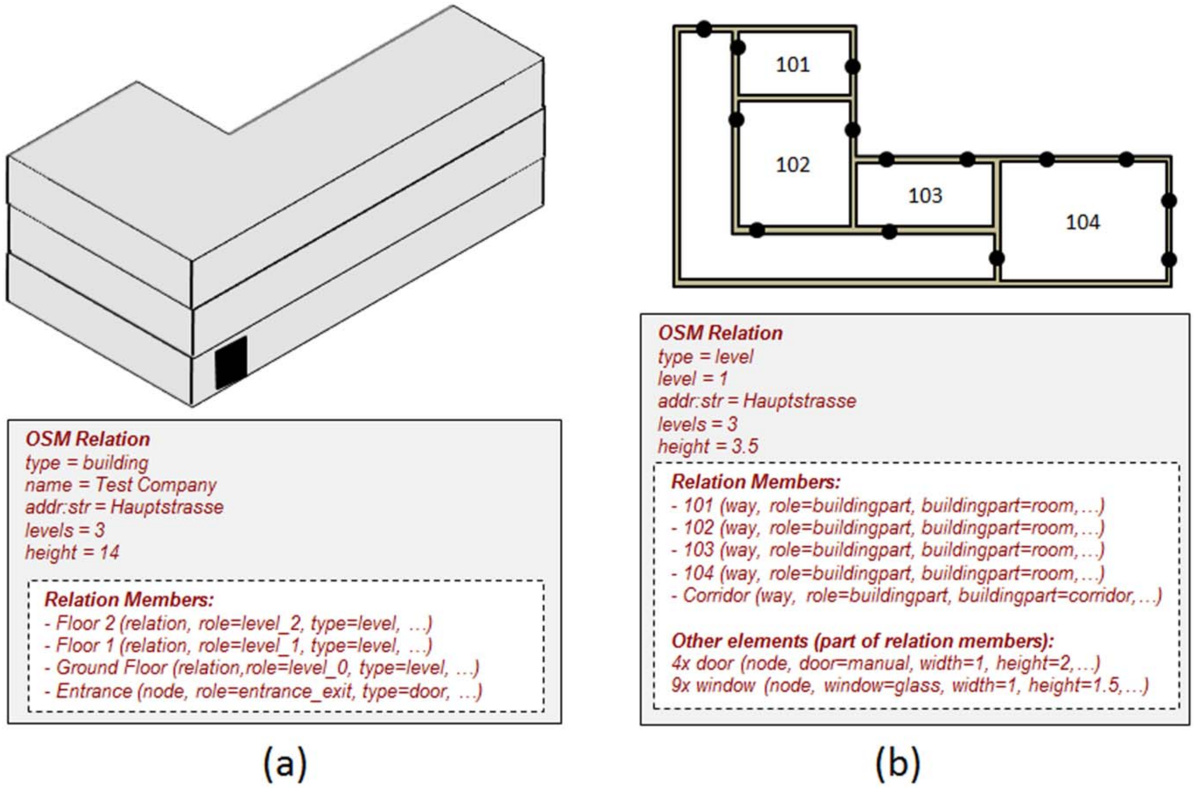

Figure 10-1. The basic hierarchy of a complete building (a) and an exemplary detailed floor plan with rooms, corridor, doors and windows (b) in IndoorOSM.

10.2.2 Agent-based Indoor Evacuation Simulation

Several disastrous emergencies in the past, such as the 9/11 terror attacks or the earthquake in Japan 2011, motivated discussions and research efforts on how to protect and evacuate persons inside a building during an emergency (*Peacock & Kuligowski 2005*). Furthermore, there are quite a lot of different research efforts on indoor (and outdoor) evacuation simulations. An agent-based simulation of spatial cognition as well as wayfinding in buildings for the scenario of a fire emergency is discussed by *Hajibabai et al. (2007)*. Quite similar, an agent-based evacuation model for large public buildings under dynamic fire conditions is also available (*Shi et. al. 2008*). A hybrid approach that is a combination of both network simulation as well as free space model has been presented (*Okaya et. al. 2009*). An assistant system based on indoor networks is described by *Yamashita et al. (2009)*. Regarding large scenarios, it has also been showcased that agent-based simulation is suitable for outdoor evacuation simulations in Hong Kong (*Wu & Lin 2012*). Besides those, there are furthermore many other evacuation models, such as *EGRESS*, *EXODUS*, *SIMULEX*, *EXITT*, *WAYOUT* (*Gwynne et. al. 1998*), available, which are all based on a network representation. Essentially, they are suitable for simulating the evacuation, as well as analyzing the evacuation efficiency for arbitrary buildings. A comprehensive overview about pedestrian evacuation simulation can be furthermore found in the book series *Pedestrian and Evacuation Dynamics* (*Schreckenberg 2001; Schreckenberg & Sharma 2002; Galea 2003; Waldau et. al. 2006; Klingsch et. al. 2010; Peacock & Kuligowski 2011*).

Obviously, there are several efforts towards agent-based indoor evacuation simulation. However, current approaches all utilize proprietary data. Essentially, none of the existing approaches utilizes crowdsourced indoor geodata. However, crowdsourced indoor geodata from OSM has the benefit that it is a non-proprietary internationally growing dataset. That is, developed applications and approaches can be used for any arbitrary building which is available in OSM. Therefore, within the remainder of this paper, possibilities for an efficient and automated provision of indoor evacuation simulations for arbitrary buildings based on crowdsourced indoor geodata will be investigated and discussed.

10.2.3 Multi-agent Transport Simulation (*MATSim*)

As described in the previous Section, there are quite lot of different simulation frameworks – all with advantages (*e.g.,* iterative learning, consideration of different agents, modular extensibility etc.) and disadvantages (*e.g.*, neglecting the third dimension, restricted to vehicle simulation etc.). However, when comparing a framework with the utilization of large multidimensional probability arrays, computational savings in favor of the framework should appear. Besides that, a large range of output options as well as explicit modeling techniques for individuals' decision making processes are desirable (*Balmer et. al. 2009*). Especially the last point is very essential, because evacuation scenarios strongly depend on the decisions of the individuals. For the here conducted research it has been decided to use the so called *Multi-Agent Transport Simulation* (*MATSim*) framework, because it fulfills all the before mentioned requirements. *MATSim* incorporates a multi-agent micro-simulation, describing that the behavior of each simulated person (*i.e.*, an agent) can be defined by individual parameters, such as age, profession, traveling plan etc. The key features of *MATSim* are a fast agent-based traffic simulation, support of large multi-level scenarios, sophisticated interactive visualizer, versatile analyses, modular approach, and active open source development (*MATSim 2012*).

MATSim is developed in Java, thus utilizable on many operation platforms. All required input files, such as the network, the population or the evacuation area (will be described later), are based on XML schemas. *MATSim* has already been used for a variety of different (evacuation) simulations, ranging from large-scale vehicle traffic simulations (*Meister et. al. 2010*), over city evacuation scenarios (*Bekhor et. al. 2011; Bakillah et. al. 2012a; Bakillah et. al. 2012b*), up to pedestrian evacuation (*Lämmel et. al. 2009*). However, up to the authors' knowledge, *MATSim* has not yet been used for simulating mass evacuation in a multi-level building. It has been proven that *MATSim* simulations produce more realistic results—especially from a temporal point of view—than other simulation frameworks (*Gao et. al. 2010*). It is based on a parallel queue model with a capacity constraint and a storage constraint (*Cetin & Nagel 2003*). The former constraint avoids that more agents leave a link in the network within a certain time than the flow capacity of this link. The latter constraint describes that a link can only contain a certain amount of agents at one point of time. That is, as soon as a link is full, a queue spill-back occurs and the amount of incoming agents is reduced (*Cetin & Nagel 2003*). More information about *MATSim* is available on the corresponding project webpage (*MATSim 2012*).

To conclude, it can be said that *MATSim* seems to be the best choice for the aim of the here presented research. On the one hand, it has already been demonstrated that *MATSim* can be used with OSM data (*Zilske et. al. 2011*) and on the other hand it provides many possibilities for adapting the simulations to individual requirements. Therefore, *MATSim* has been selected as the evacuation simulation framework for the here conducted research. That is, the remainder of this paper will discuss the possibilities of using crowdsourced indoor geodata from OSM for indoor evacuation simulations with *MATSim*.

10.3 Evacuation Simulations with *IndoorOSM*

This Section focusses on the possibilities of automatically deploying indoor evacuation simulations with *IndoorOSM* data. In particular, it will be discussed what kind of evacuation related information is available and how this can be used for the simulation. As described in the previous Section, the framework *MATSim* has been selected for the here conducted research. Furthermore, the different required input files and parameters as well as necessary assumptions are elaborated.

10.3.1 Generating the Network

When computing (shortest) paths inside buildings, the indoor environment is typically represented with a routing graph which is capable for applying a shortest path algorithm (*e.g.*, *Dijkstra (1959)* or *Hart et. al. (1968)*) to it. Thereby, nodes in the graph typically represent decision-points and links represent connections between different decision-points. In outdoor environments, a decision-point typically comprises a street crossing. However, since the work within this paper focusses on indoor traffic simulations, a decision-point represents indoor transitions, such as doors or intermediate turning points in a corridor. In principle, there are different graph models available, such as (*Lee 2004; Lorenz et. al. 2006; Zlatanova 2008; Yuan & Schneider 2010*), which mainly vary in granularity and formalism. It has been demonstrated that some of those can be automatically extracted from official data sources, but the extraction of such graphs from VGI has not yet been discussed. In contrast, the so called *Weighted Indoor Routing Graph* (*WIRG*) (*Goetz & Zipf 2011b*)—representing a formally defined and reasoned graph model for length-optimal indoor routing—can be automatically generated by purely using crowdsourced indoor geodata from *IndoorOSM* (*Goetz 2012c*). That is, it is feasible to generate an indoor routing graph from *IndoorOSM*. However, it needs yet to be proven, that *IndoorOSM* data is also suitable for generating a graph which can be used for complex indoor evacuation simulations. In particular, such a graph should not only contain information about doors and rooms, but also about windows, because those are important for evacuation purposes. However, the selection of contemplable windows is not always an easy task, because it might require local knowledge about the building structure as well as the surrounding terrain, to define which windows can serve as emergency exits and which ones not. This problem will also be discussed in Section 10.5.1.

Figure 10-2 (a–f) visualizes the general principle of the generation of a detailed indoor routing graph step-by-step. Thereby, not only doors are considered and integrated in the graph, but also the different windows of the rooms. All the required information is available in *IndoorOSM* and the graph can be automatically generated by purely using this data. As an initial situation (Figure 10-2 (a)), all building part footprints, *i.e.*, the polygonal shapes of all rooms or corridors of a distinct building floor, are mapped according to the *IndoorOSM* mapping proposal (*cf.* Section 10.2.1).

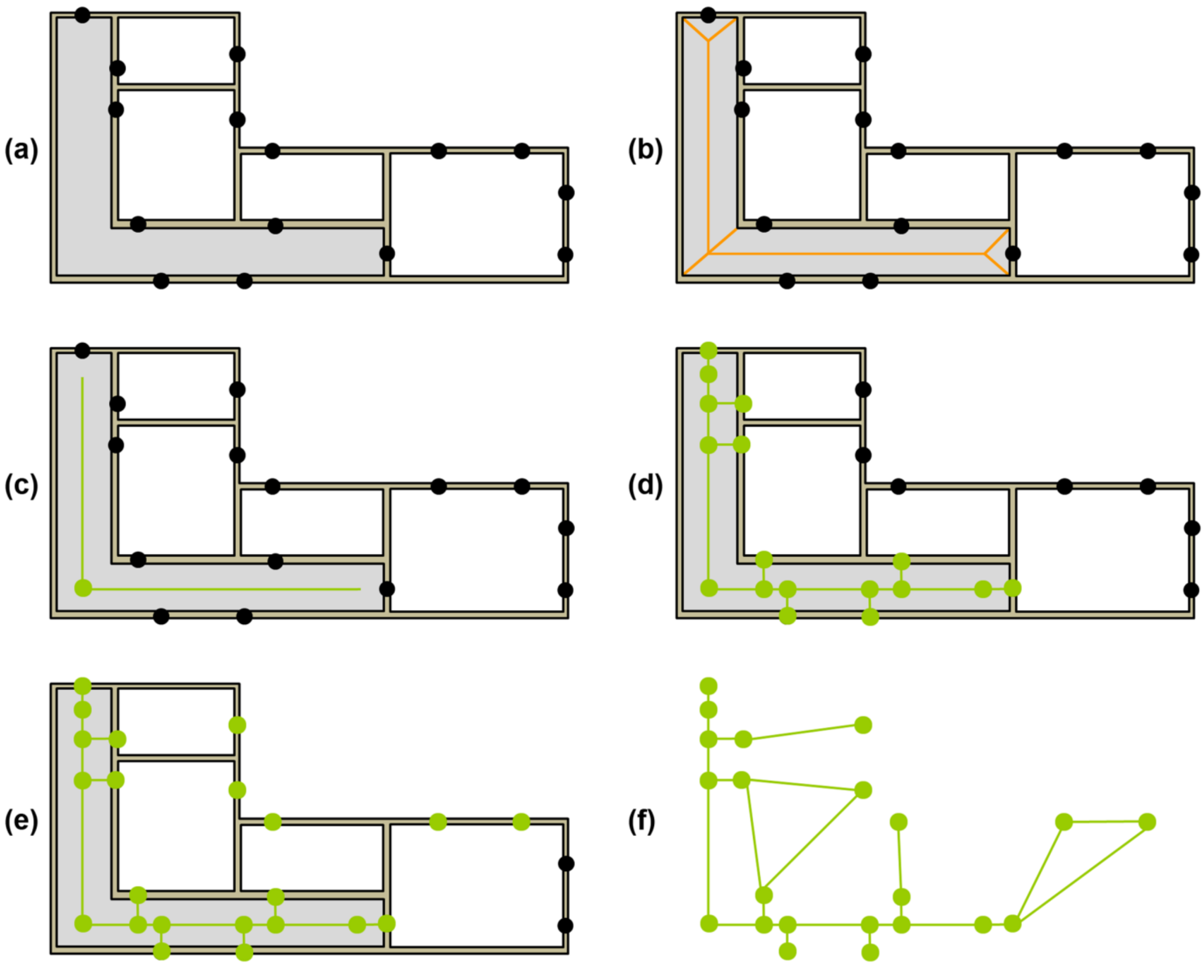

Figure 10-2. Stepwise generation of an indoor routing graph (according to the Weighted Indoor Routing Graph (WIRG) definition (Goetz & Zipf 2011b)) with a selection of contemplable windows for emergency evacuation simulations.

For each corridor (those are explicitly tagged in *IndoorOSM* as *buildingpart=corridor*) the centerline is computed by generating the skeleton (*Felkel & Obdrmalek 1998*) of the underlying corridor polygon (orange line in Figure 10-2 (b)) and pruning all lines of the skeleton which are connected to the outline of the corresponding corridor. The remainder constitutes the centerline of the corridor (green line and nodes in Figure 10-2 (c)), which on the one hand have been proven to represent the geometry of the corridor very detailed and on the other hand also represents human behavior when walking along a corridor (*Goetz & Zipf 2011b*). Thereafter, all doors (OSM key door) which are related to the corridor (those are either part of the corridor geometry or part of an adjacent building part) are added to the routing graph and vertically connected with the corresponding corridor (Figure 10-2 (d)). Afterwards, contemplable windows, *i.e.*, those which are suitable for emergency evacuation (*cf.* also the discussion in Section 10.5.1) are added as nodes to the graph. Finally – as stated in the *WIRG* definition (*Goetz & Zipf 2011b*) – all nodes (*i.e.*, doors and windows) of a single room are connected pairwise with each other via an edge in the graph, resulting in the final routing graph (Figure 10-2 (f)). Fore multi-level buildings, the steps (a) to (f) are repeated accordingly for every building floor. Furthermore, vertical connections, such as stairways or escalators, are included by evaluating the available data of *IndoorOSM* (*e.g.*, the keys *buildingpart=verticalpassage*, *connector:ids* etc., *cf.* Section 10.2.1).

In *MATSim*, the network inside the building is represented with a directed graph, *i.e.*, the graph contains two directed links rather than one non-directed link. The nodes are represented via a unique ID, as well as a two-dimensional coordinates (*i.e.*, x and y) from a bird's perspective. The height (*i.e.*, the z-value) however is not explicitly required. The different links are represented via a unique ID, information about the start (*from*) and end (*to*), the *length* of the link, the *freespeed* (*i.e.*, the maximum traveling speed) and the *capacity* (*i.e.*, the flow capacity in terms of how many agents can pass this link in a given time). Furthermore, all links contain information about the amount of permanent lanes (*permlanes*). Regarding outdoor simulations, this parameter is basically used for describing the number of car lanes for a distinct road. Considering indoor spaces (and especially corridors), this parameter represents the number of agents which are able to stand next to each other in a given space (*e.g.*, corridor). *Weidmann (1993)* defined the average agent's width as *0.71 m*, so for example a corridor with a width of 2.13 m is represented as a link with three *permlanes*. In the *MATSim* specification, the value of *permlanes* is a double, thus values like *permlanes=1.46* are also possible. Important to mention is that the value of *capacity* is related to the value of the parameter *capperiod*. This parameter is globally defined for the whole simulation scenario and describes the time period for which the different *capacity* values are valid. That is, when *capperiod* is set to *00:01:00* (*i.e.*, one hour), the value of *capacity* is interpreted as flow capacity for one hour. As already described in Section 10.2.2, *MATSim* applies a cell-based queue model. Therefore, the cell-size needs to be globally defined for the simulation via the two parameters *effectivecellsize* and *effectivelanewidth*. For pedestrian simulation, reasonable values are *0.26 m* and *0.71 m* (*Weidmann 1993*). However, due to the static definition of these values, this causes some impreciseness. This issue will be further discussed in Section 10.5.2.

The *length* of the links is the distance between the two involved nodes in meters which can be easily populated by computing the Euclidean distance between the two nodes. The parameter freespeed defines the upper boundary for the maximum travel speed of an agent, thus the traveling speed of an agent in a free space. There are different research efforts and investigations on travel speeds of pedestrians in indoor spaces, typically also depending on the agents themselves as well as the investigated scenario. *Weidmann (1993*) evaluated 52 different investigations on the traveling speed of pedestrians. He discovered a range between *0.97 m/s* and *1.65 m/s,* whereby most of the values are between *1.25 m/s* and *1.45 m/s*. The general average traveling speed for pedestrians can be assumed to be *1.34 m/s* (*Weidmann 1993*). Depending on the individual situation of the agent, these values can vary, so for example a 70 years old person is likely to achieve approximately 72% of this average speed (*Weidmann 1993*). Regarding movements on stairs, pedestrians are approximately 50% slower (*Weidmann 1993*). The amount of permanent lines also needs to be provided for each link. Thereby, the average agent's width of *0.71 m* (*Weidmann 1993*) can be utilized. For an automated population of this value, there are basically three possible approaches, as described in the equations below. Thereby, the variable width represents a list of all corridor widths in increasing order and length represents the length of the corridor.

$$permlanes = \frac{\min widths}{0.71} \qquad (1)$$

$$permlanes = \frac{\sum_{i=1}^{n} widths_i}{n * 0.71} \qquad (2)$$

$$permlanes = \frac{\sum widths}{length * 0.71} \qquad (3)$$

Equation (1) does only incorporate the minimum width, thus represents the most pessimistic parameter (worst case). In contrast, computation Equation (3) is the most optimistic approach (best case). Usually a worst case and a best case approach are used for demonstrating the bandwidth of the expected evacuation performance to the decision makers. The individual *capacity* of a link can be defined by considering the agent's average width, the traveling speed and the corridor width.

Since doors in indoor environments reduce the flow capacity of the mass (less people can simultaneously pass a one meter wide door than a three meter wide gateway), the incorporating of the size of a door or window (especially its width) is important. This information is explicitly mapped in OSM with the key *width* (as well as *height* or *breast*) and can therefore be used when generating routing graphs. As described in Section 10.2.1, in *IndoorOSM* a door or window is added to one of the two involved building part geometries (Figure 10-3 (a)). Therefore, the single node (door or window) needs to be projected to the other involved geometry, resulting in an additional node in the graph (Figure 10-3 (b)). Those two nodes are then furthermore connected via a (very short) edge, whereby the width is utilized for calculating the different link parameters, such as *permlanes* or *capacity*.

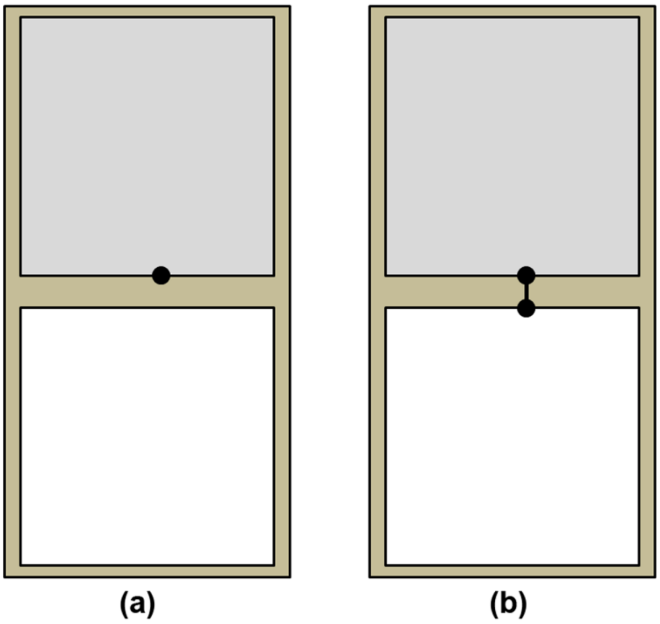

Figure 10-3. An OSM node (black circle) representing a door between to rooms (a) and the additional node (projected to the adjacent polygon) with an additional edge connecting them (b).

10.3.2 Generating the Synthetic Population

MATSim requires information about the different agents. This information is called population and is described in the *population.xml* file. Basically, a population consists of a (non-limited) amount of persons. Each person element contains a unique *id* (mandatory), as well as some other (optional) parameters, such as the agent's *sex* or *age*. Furthermore, each person has a plan, thus a sequence of at least one planed activity (*act*). Thereby, an activity represents the physical location (defined via the network link *id*) of the corresponding agent for some distinct time or interval. The movement of an agent within the network over time can be represented by adding several activities to an agent.

Currently, *IndoorOSM* does not consider population information for indoor spaces. This issue will be further discussed in Section 10.5.1. That is, when performing indoor evacuation simulations, there are basically two possibilities: (1) a manual creation of the population with real-world figures or (2) an automated creation with a random distribution of the agents to the different rooms (probably based on estimations according to room size or function).

Depending on the amount of agents and the distinct scenario, both possibilities have their advantages and disadvantages. However, more realistic results can be achieved with manually added real world figures (if available).

10.3.3 Defining the Evacuation Area

Basically, the two input files mentioned beforehand would be enough for a *MATSim* traffic simulation. However, as the intention of this paper is the conduction of evacuation simulations, there is a third input file required: the *evacuationarea.xml* file. The sake of this input file is (as the name might indicate) to define which area of the scenario (the network) needs to be evacuated. In other words, the *evacuationarea.xml* file describes which parts of the network are safe and which are endangered (by some threat). The file structure itself is rather simple, as it only contains the *ids* of the endangered links in the network. In addition, it is possible to define a deadline for the individual links, *i.e.*, the point of time at which the link is accessible at the latest.

Basically, this file can be easily generated automatically from *IndoorOSM* data. Typically, an indoor evacuation aims at evacuating all inhabitants to the outside of the building. That is, the evacuation area consists of all links of the network which are inside the building. All other links (*i.e.*, the outdoor features of OSM) are not part of the evacuation area (at least for a basic indoor evacuation simulation). For incorporating some kind of safety area around the building (*e.g.*, in the scenario of a fire), it is also possible to add all features (essentially streets or paths) to the evacuation area, which are within a distinct distance around the building.

10.4 Demonstration and Experimental Results

As a demonstration and proof-of-concept, two exemplary evacuation simulations have been performed. By doing this, several limitations of both the *IndoorOSM* data and the *MATSim* framework became apparent. Those will be discussed in Section 10.5. The two simulation scenarios are as follows: (1) a planned site clearing, *i.e.*, a structured, organized and safe evacuation as it is for example required in the case of a forecasted flood, and (2) an unpredicted evacuation simulation for a sudden disastrous incident. The main difference between those two scenarios is that in the first scenario all persons are safely evacuated trough the main building exits. In contrast, in the latter scenario all possible (emergency) exits are considered. Essentially, also windows, garage doors etc., can serve as an exit for the affected population in Scenario 2. For simplification purposes, in both scenarios an average travelling speed of 1.0 m/s has been defined. This seems to be an adequate (simplified) average value which incorporates different agent's conditions, different movements (*i.e.*, plane vs. stairs), and different stress levels. For simplification, a distinction between different kinds of agents has not been performed. That is, all agents have the same average travelling speed, as well as the same sex or age. As another simplification, in both scenarios it is assumed that all agents start their movement instantly at the same time. In particular, no individual reaction time has been included. In reality this behavior is rather unlikely, because people have different reaction times as well as behavior, *e.g.*, some will instantly escape the building, others will get their belongings and then leave the building, and probably some will not even notice the emergency alert. It needs to be mentioned that all these simplifications are made because of the focus of this paper. The main aim of this paper is to demonstrate and discuss the utilization of *IndoorOSM* for evacuation simulations, rather than performing highly realistic simulations for a distinct building and discussing those afterwards.

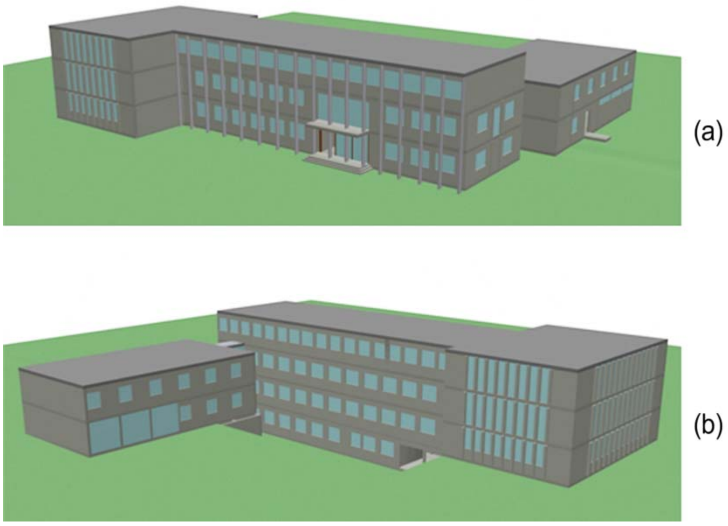

Figure 10-4. A 3D model of the use case building: the front side with the main entrance (a) and the back side with the garage doors and basement windows (b).

As a test case, the building of the GIScience research group of the University of Heidelberg has been utilized. It is an averaged sized university building consisting of one basement and three floors above the ground. Figure 10-4 (a) depicts a 3D model of the front side of the building with the main entrance, whereas Figure 10-4 (b) shows the building back side with the basement windows and garage doors (they can serve as an emergency exit). Inside the building, the different floors are connected via two staircases with each other. The building contains one big lecture room with a capacity of 120 persons, one smaller lecture room for 30 persons and two computer pools with capacities of 25 and 16 persons.

Furthermore, there are several offices which are occupied by one to three persons. For both evacuation simulation scenarios it is assumed that the building is fully occupied, which leads to a total amount of 313 inhabitants in the building. Table 10-1 contains the distribution of those to the different floors. For both scenarios, a *MATSim* evacuation simulation has been performed. All required input files have been automatically generated from *IndoorOSM* data.

Table 10-1. Aggregated population distribution for the different building floors.

Building Floor	Population
Basement (Floor -1)	24
Ground (Floor 0)	178
Floor 1	74
Floor 2	37
Total	**313**

10.4.1 Scenario 1: Planned Site Clearing

The first evacuation scenario represents a planned site clearing. Since all agents should leave the building through the main entrance, the evacuationarea.xml file contains all links except the link from the main entrance to the outside of the building. A total amount of 100 simulations has been performed, because *MATSim* agents can learn from previous simulations, which influences their behavior in future simulation iterations. Regarding all iterations, the average travel distance is 39.55 m for the executed plan, 39.62 m for the worst plan (*i.e.*, the longest overall evacuation time for the complete building), 39.52 m for the average plan and 39.46 m for the best plan (*i.e.*, the shortest overall evacuation time). By investigating the different iterations in more detail, the learning mechanisms of *MATSim* become apparent. One example is that in the very first iterations all students from the big lecture room (which is in the ground floor) use the direct path to the exit of the building. This results in a huge traffic jam in the corridors. In contrast, in the very last iterations, some agents avoid those traffic jams by directly walking to the first floor (via the staircase next to the lecture room), traversing the corridor and then returning to the ground floor via the other staircase (which is directly adjacent to the exit). However, although this learning leads to shorter evacuation times (*i.e.*, the time required to reach a safe place) for some individual agents, the overall scenario does hardly change (*cf.* Table 10-2).

Table 10-2. Evacuation time statistics: Scenario 1.

Figure	**Iteration 1**	**Iteration 50**	**Iteration 100**	**Average**
Evacuation time for first agent	7.1 s	7.1 s	7.1 s	7.1 s
Evacuation time for last agent (*i.e.*, complete building	166.2 s	166.0 s	165.8 s	166.0 s
Average trip duration for one agent	80.53 s	80.82 s	80.86 s	80.85 s

Figure 10-5 depicts the evacuation simulation scenario in an early stage (after 40 s). Thereby the underlying network as well as the building outline is visualized. The different colors of the agents indicate their current situation. Green indicates a free movement at maximum speed, orange indicates a slowdown in the traffic flow and red indicates a traffic jam in the corresponding building part. In Figure 10-5 it can be seen that the staircase next to the building exit is a bottleneck because the agents in this area have to reduce their traveling speed due to a traffic jam.

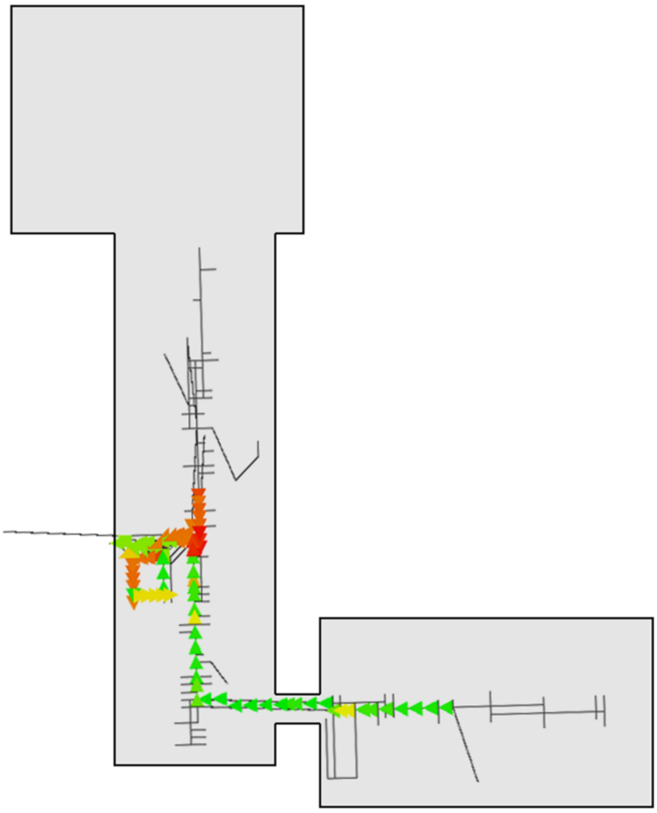

Figure 10-5. Visualization of the evacuation simulation Scenario 1 in its early progress after 40 s.

10.4.2 Scenario 2: Unpredicted Evacuation

The second evacuation scenario represents an unpredicted evacuation. Those are typically required in the case of an unforeseeable incident, such as a fire or an earthquake. In this scenario, all agents instantly try to leave the building as fast as possible. For simplification purposes, it is again assumed that all agents start their movement simultaneously at the beginning of the simulation. Contrary to the previous simulation, Scenario 2 incorporates all possible exits. Essentially, all windows of the basement and ground floor and all (garage) doors are considered as emergency exits. Therefore, the network also contains links between rooms and the corresponding windows. Furthermore, all windows are connected via links to the safe outdoor environment. The *evacuationarea.xml* file contains only the links which are inside the building.

Table 10-3. Evacuation time statistics: Scenario 2.

Figure	**Iteration 1**	**Iteration 50**	**Iteration 100**	**Average**
Evacuation time for first agent	7.1 s	7.1 s	7.1 s	7.1 s
Evacuation time for last agent (*i.e.*, complete building	166.2 s	166.0 s	165.8 s	166.0 s
Average trip duration for one agent	80.53 s	80.82 s	80.86 s	80.85 s

Regarding all 100 iterations, the average travel distance is 22.86 m for the executed plan, 23.06 m for the worst plan, 22.85 m for the average plan and 22.74 m for the best plan. Similar to Scenario 1, Table 10-3 provides evacuation time statistics for evacuation simulation Scenario 2. Again, the evacuation time is defined as the time between the start of the simulation and the time till when the corresponding agent reaches a safe place. The evacuation time for the first agent of 2.1 s results from the assumption of an immediate reaction of the individual agents. Some agents in the basement as well as in the ground floor can use the windows as emergency exits. This leads to a reduced average evacuation time and traveling distance (compared to Scenario 1). Figure 10-6 depicts the evacuation simulation Scenario 2 after a period of 10 s; therein, the main difference is the network which also incorporates the appropriate windows as emergency exits.

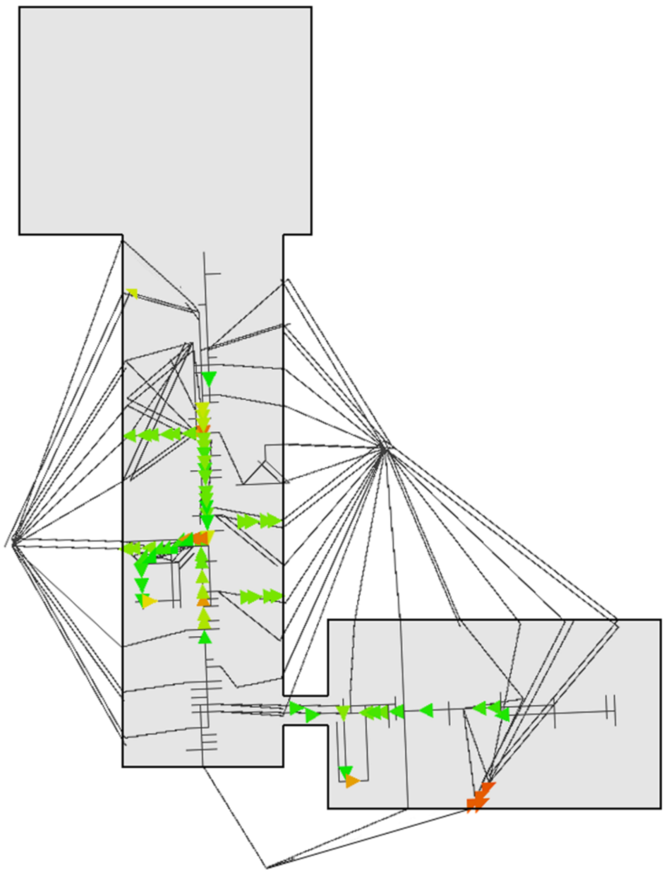

Figure 10-6. Visualization of the evacuation simulation Scenario 2 in its early progress after 10 s.

10.5 Discussion

While investigating the possibilities for an automatic generating of indoor evacuation simulations and performing the two exemplary use-case simulation scenarios, different limitations and issues regarding both the available data in *IndoorOSM* and the *MATSim* simulation framework became apparent. Those will be discussed in the two following sub-sections. Section 10.5.1 focusses on the suitability of crowdsourced indoor geodata for evacuation simulations. Thereafter, Section 10.5.2 discusses several limitations of the *MATSim* simulation framework for indoor evacuation simulations.

10.5.1 Limitations of the *IndoorOSM* data

Crowdsourced indoor geodata from OSM contains very detailed information about the interior structure of a building. In the previous Section it has been furthermore demonstrated that it is possible to use this data for different evacuation simulation scenarios. Nevertheless, while conducting the here presented research, several limitations and constraints became apparent. In general, *IndoorOSM* contains detailed information about the geometry and topology of each individual building floor. That is, detailed floor plans, such as evacuation plans, as well as routing graphs which are suitable for individual indoor routing as well as indoor mass evacuation simulations, can be generated based upon this data source. For investigating the evacuation performance of a future building, *i.e.*, a scenario for which no real world figures are available, this approach leads to satisfying simulation results which provide a first indicator on the safety of the building. Nevertheless, for more realistic results and especially for simulating the performance of existing buildings for which real world data exists, *IndoorOSM* lacks various kinds of information.

As already discussed in Section 10.3.2, real population figures are currently not available in *IndoorOSM*. That is, *IndoorOSM* is suitable for generating the underlying network, but a (either real or synthetic) population cannot be generated by only using *IndoorOSM* data. Due to the open key-value pair methodology of OSM, one could argue that an appropriate key (*e.g., population=2*, etc.) could be easily defined and utilized for this effort; however it is questionable if such a key is suitable for describing (dynamic) population figures, because population numbers typically vary with changing date, time, or function of the room. For example a lecture room with tables can accommodate less students than an emptied out lecture room (*e.g.*, in the case of a ceremony). Another example is that there are more humans in an indoor swimming pool in the winter season than in the summer season. That is, when introducing such a key in OSM, it still is not clear for which time of day or season it is valid. Furthermore, the population might change over time, for example due to people moving from one office to another, and it is questionable if such (fast) changing information is maintained properly in OSM (in contrast to the geometry of a building which is rather static). Nevertheless, a potential key population might provide an indicator on the maximum capacity of a room, such as an office is suitable for accommodating four permanent employees or a lecture room can accommodate 100 students. As a conclusion, such maximum capacity information could then be used for worst-case simulations which furthermore provide an insight on the worst-case evacuation performance of a (future) building. Nevertheless, for gathering more realistic and probable results—especially for existing buildings—the additional incorporation of other available data sources, such as linked geo data (*Auer et. al. 2009*), real-time data (so called *Live Cities*) (*Resch et. al. 2012*), or facility management systems, will probably lead to more realistic simulation results.

Closely related to this issue, *IndoorOSM* (and probably also other data sources) currently lacks more precise information about the individual inhabitants. That is, even if OSM contributors provide population information, more details on the individual persons, such as sex, age, health situation etc., are not available. That is, while performing the evacuation simulation, one still have to assign random values and parameters to the individual agents, manually assign real world figures, or (if only rough results are required) perform a simulation with average values and consider all agents as being physically equal. *IndoorOSM* currently cannot—and very likely will never be able to—provide any precise details on the different inhabitants of a building. Drawing conclusions on the (average) condition of the inhabitants of a building according to the building function is probably the only solution when only using OSM data. For example if a building is tagged with *amenity=university*, one could argue that most of the inhabitants are students, thus healthy and vital, whereas in contrast inhabitants of a building tagged with *amenity=hospital* are probably not that vital and limited regarding their movement and traveling speed.

Depending on the layout of a building and the corresponding evacuation scenario, windows can also be considered as possible emergency exits. However, the selection of windows which can serve as emergency exits is not an easy task. Although information about the location (x, y and z) as well as the height and width of a window is basically available in *IndoorOSM*, selecting appropriate emergency windows is not always easily feasible because both the surrounding terrain as well as the building layout need to be included in the selection process. To some extent, it can be assumed that all windows of the ground floor could potentially serve as emergency window; however it might be quite hard to define which floor the ground floor is, as for example in the case of a hillside building. It might also be possible that a window in the second floor can—due to a sloped terrain—still be used as an emergency exit. Also, if a building is situated directly next to a lake, it might be possible to jump from the roof into the lake. In contrast, in a building which is located next to a canyon, the windows which are faced towards the canyon cannot serve as an emergency exit—even on the ground level. Also, for some building structures it is possible to emerge a building by climbing out of the window on the second floor to the roof of the first floor and then climbing down to the ground. However, *IndoorOSM* currently lacks additional information describing the individual emergency suitability of a window, although this kind of information probably improves the simulation results. Nevertheless, by introducing a new tag, *e.g.*, *emergency:exit=yes*, which is added to the corresponding window node, OSM contributors can easily and clearly define which windows can serve as an emergency exit and which ones not. That is, in principle this kind of information can be added to OSM and then be utilized while selecting appropriate windows for one's own individual evacuation simulation.

Another important aspect which has been hardly considered yet in *IndoorOSM* is the incorporation of barriers and obstacles inside buildings. These can be either static objects, such as furniture or struts, but also dynamic objects, such as parts of the ceiling falling down. Both kinds influence the mass behavior inside the building and therefore also the execution and performance of the evacuation. The former kind of obstacle is not yet available in *IndoorOSM*. Nevertheless, contributors can provide a closed way representing the outline of the obstacle and tag it with an appropriate tag, *e.g.*, *obstacle=table* or *obstacle=cupboard*. That is, a contributor who really cares about detailed indoor environments can basically provide information about obstacles, but such information is not yet available in the current OSM dataset. In contrast, information about dynamic and moving objects cannot be provided, because every object within OSM can only be represented for one single distinct point of time and dynamics cannot be expressed with the current OSM data model. That is, such (either live or synthetic) data needs to be generated manually, for example by calculating and modeling the diffusion of dense smoke, or by integrating live sensors, for example by using an Open Geospatial (OGC) Sensor Observation Service (SOS) (*Botts et. al. 2006*). The latter approach is similar to the before mentioned idea of integrating real-time data from so called *Live Cities* (*cf.* above).

Closely related to this issue, *IndoorOSM* does also only provide limited information about the height of the individual building parts (*e.g.*, rooms or corridors). Although *IndoorOSM* proposes the key height for providing information about the height of a room, it is not always clear for which part of a room this height is valid. Essentially, a ceiling with an inclined surface (which cannot be represented or described in *IndoorOSM*) might have varying heights, or drooping objects, such as lamps, probably reduce the effective height of a room. Furthermore, the effective height might be reduced due to some furniture or obstacle (*cf.* above). Nevertheless, depending on the evacuation scenario, such information needs to be integrated, because potential evacuation routes might be affected by such circumstances, as for example a wheelchair driver cannot pass obstacles lying on the floor.

As a conclusion of this Section, it seems apparent that crowdsourced indoor geodata from OSM contains detailed information about the static features of a building, but currently lacks both dynamic aspects as well as population information. Furthermore, it can be stated that such information probably will be never integrated in OSM That is, evacuation simulations which are purely based on OSM data and especially do not integrate additional (synthetic or real) data, will always result in coarse simulations. However, crowdsourced indoor geodata seems to be a rich additional data source which provides detailed information about the geometry and topology of a building. That is, *IndoorOSM* can be basically used for generating any kind of static component of an indoor evacuation simulation.

10.5.2 Limitations of the *MATSim* simulation framework

It has been proven that *MATSim* is suitable for not only outdoor simulations, but also indoor evacuation simulations. However, it needs to be mentioned that there are some limitations of *MATSim* and essentially its queue model for the conduction of indoor simulations. Since the network within *MATSim* is directed and corridors in indoor environments are typically not limited to a distinct traveling direction (except for some special cases, such as security controls or escalators), the network of *MATSim* typically contains two directed links with the same amount of *permlanes* and the same *capacity*. However, the amount of *permlanes* and the *capacity* of one link strongly depend on the current traffic situation on the opposite link. For example, the *capacity* of a corridor where agents only travel in one direction is different to the *capacity* in the case of agents traveling in both directions. For an appropriate representation of this effect, a dynamic adaptation of both *capacity* and *permlanes* for the affected links would be required. However, this is (at the moment) not feasible with *MATSim*. That is, for the simulation of normal traffic flows in a building, *MATSim* is not suitable. Nevertheless, for simulation evacuation scenarios in which all agents move to the outside of the building, *MATSim* is an appropriate simulation framework. Also, the agents of *MATSim* are not clever. Since they are tied to the simulation network, their movement is rather linear. Furthermore, they are restricted to the direction of the network, thus they cannot change the travel direction while traversing a link. This behavior perfectly suits to car traffic simulation, but brings the before mentioned limitations when simulation pedestrian behavior. That is, a real two-dimensional movement space for the agent would probably lead to different (better) simulation results.

Another kind of dynamic data which cannot be represented in *MATSim* is the consideration of different movement types of an agent, such as sauntering, walking or running. As discussed in the previous Sections, the covered space of a single agent is globally defined for all agents. However, it can be argued that these values vary with the actual movement type of the agent, *e.g.*, a running person probably requires more space (especially in the direction of the movement) than a sauntering person. It can be assumed that different agents (depending on their health condition as well as stress level) prefer different movement types. That is, a dynamic adaptation of the covered space for arbitrary agents would probably lead to more realistic results.

10.6 Conclusion and Future Work

This paper proposed the utilization of crowdsourced indoor geodata from OSM (*IndoorOSM*) for indoor evacuation simulation. It can be concluded that it is basically feasible to perform multi-agent evacuation simulations with *MATSim* based on *IndoorOSM* data. That is, not only simple route planning applications can be created with crowdsourced indoor geodata, but also more complex and advanced applications, such as evacuation simulations, can benefit from *IndoorOSM*. However, as discussed in the previous Section, there are some limitations and restrictions regarding both the *IndoorOSM* data and the *MATSim* simulation framework. Essentially, *IndoorOSM* is only suitable for the generation of static scenario components, such as the geometry and topology of a building interior. Any kind of dynamic factor, such as moving objects or gas emission, cannot be mapped in *IndoorOSM*. That is, such details cannot be populated or simulated with crowdsourced indoor data from OSM. Furthermore, detailed information about the real population of a building can hardly be provided via *IndoorOSM*. Due to the queue model, *MATSim* is not able to simulate real 2D movement. Furthermore, *MATSim* cannot simulate different movement spaces for different kinds of movements. Regarding the conducted experimental simulation, it needs to be stated that various simplifications have been made which are suitable for the purpose of the paper, but influence the simulation results.

Since crowdsourced data is typically created by non-professional users and due to the open-access paradigm of OSM, the available data is always subject to errors as well as vandalism—this also comprises one of the major counter-arguments for third parties when evaluating the potential usage of OSM data. Nevertheless, for the road network it has already been proven that the crowd is able to collect fine-grained data which is comparable to commercially collected data (*Neis et. al. 2012*). Quality concerns are even more crucial for detailed indoor spaces, because indoor environments are typically more fine-grained than outdoor spaces, especially when conducting complex simulations, as for example discussed in this paper. However, due to its novelty, there is not yet enough data available for conducting comprehensive quality analysis or comparing crowdsourced indoor data to commercially collected data. Nevertheless, those will be required as soon as more data is available, for supporting the importance of crowdsourced indoor data. For future work it will be interesting to see if *IndoorOSM* data can be used for indoor evacuation simulations which are not based on a graph, but on polygonal structures (*i.e.*, real two-dimensional movement of the agents). A combination of both indoor and outdoor evacuation simulation based on OSM data is a desirable, but challenging task. As discussed, *IndoorOSM* has some limitations and probably not every building structure can be mapped in OSM. To overcome this issue, researchers intend crowdsourcing virtual 3D cities and especially 3D building models (*Uden & Zipf 2012*), which can potentially be utilized for indoor evacuation simulations. However, since this *OpenBuildingModels* (*Uden & Zipf 2012*) approach currently is still in its infancy and there are not yet so many buildings available, this has yet to be brought into fruition.

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Marcus Götz