Comparison of Standard- and Proprietary-Based Approaches to Detailed 3D City Mapping

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Introduction

According to the United Nations, Population Division (2013) most of the world's population lives in urban areas. Urbanized areas with a high population density are abundant in the developed world. Specific abilities for mobility and orientation are required in these urban areas. Modern urban space is not only defined by latitude and longitude, but also highly affected by altitude or elevation. Elevation information does not represent only altitude values, relative heights, or elevation, but also information about the number of floors. Urban areas are therefore often depicted using 3D visualization. Details of 3D models have been significantly enhanced and improved with the development of technology in recent years. Detailed 3D models provide a more realistic impression and higher immersion. Konečný (2011) explains immersion in the scope of 3D virtual environments.

Detailed 3D models on the scale of a city (e.g. Berlin or London) usually contain detailed textures. Spatial information about the interiors is a part of less territorially extensive models (examples of these 3D models are discussed below). Detailed three-dimensional modelling of indoor space is valuable for many applications like navigation, indoor facilities, energy management, and architectural information systems. This paper is devoted only to methods, technologies and applications of 3D models that contain information about the interiors and exteriors of buildings.

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Existing Detailed 3D City Models

Application of 3D Models

Today, even 3D models are nothing new in GIS, since they are very popular among layman users. Besides providing an attractive view of landscape or city, these models also cover many practical aspects. Decades ago, building a model meant a physical model from paper or balsa. Today, talking about models or 3D models means, for many people, virtual digital models. These models are used across different application areas.

3D models bring, for example, new possibilities to the tourist industry, because they are good for the presentation and promotion of historical sites, castles or monuments (Jedlička et al. 2012; Popelka and Brychtová 2012). However, techniques of 3D city modelling are also used for the reconstruction of already defunct towns or their parts, as in the *Rome Reborn* project, which deals with the reconstruction of Rome from 320 AD (University of Virginia 2010).

Realistic building models have mode forward disciplines such as architecture or the building industry. We may also expect that the 3D model will be a necessary part of the documentation of public utility networks, which may result in the 3D cadastre for estate evidence. Using 3D building models for facility management and BIM (*Building Information Modelling*) is also quite common (Kolbe 2009). A useful application based on the model of a real town is the German energy-GIS project Sun Area. It uses 3D data to evaluate which roofs are well situated for solar energy generation (SUN-AREA 2011). 3D city models are also used for analysing heating and building energy demands (Strzalka et al. 2011).

3D building models are also very useful for navigation in large buildings, such as, for example, indoor navigation for the visually impaired tested at the University of Nevada (Wolterbeek 2012). A very important project using 3D building models is the NATO STANDEX Counter Terrorism Project. This project deals with the remote detection of suicide attacks based on microwave scanning in real time and 3D space (STANDEX 2012). Other utilizations, in addition to those mentioned above, are also possible. Löwner et al. (2013b) provides a general overview of the applications of 3D city models.

Detailed 3D City Models

Detailed 3D models usually have a smaller territorial extent. 3D campus maps are good examples of this. 3D models of campuses may be found all over the world, e.g. at airports in Beijing, London, Prague, Rotterdam; at hospitals in Johannesburg, Panama, Sevilla; at commercial and financial centres such as the World Financial Center in New York and the World Trade Center in Barcelona; at convention and exhibition centres in Hong Kong, Las Vegas, etc. (3D Warehouse 2013).

University campuses are also a very popular subject to model. Most 3D virtual campuses have been published on Google Earth. In 2007 and 2008, the motivation to create 3D models of university buildings on Google Earth was reinforced by Google's announcement of the "Model Your Campus Competition". Detailed models of Zhongnan University of Economics and Law, China; Nicolas Copernicus University, Poland; Stockholm University and KTH, Sweden; and Cardiff University, UK, were among the winners in 2008 (Winners Collection 2008). In Armenakis and Sohn (2009), a 3D model of York University was created.

However, several other approaches to 3D campus modelling have also been published. Over et al. (2010) dealt with the generation of interactive 3D city models based on the OpenStreetMap (OSM) project and presented a virtual complex of the University of Heidelberg online at www.osm-3d.org. A CityGML-based 3D model of the University of Cologne Campus was published in Willmes et al. (2010).

Mapping interiors and navigating inside buildings have become recent topics for Google (GoogleBlog 2011), OpenStreetMap (IndoorOSM 2013) and also other companies and researchers (Řezník et al. 2013; Indoor/Projects 2013). Goetz and Zipf (2012) presented an approach extending an OSM tagging schema to the indoor environment and applied the extension in modelling a selected building of the University of Heidelberg.

In the Czech Republic, several 3D models of campuses were created as part of theses. Slováček (2002) processed a pair of aerial photogrammetric images in ERDAS IMAGINE software to model a building complex of the Technical University of Ostrava. The same technique was used in Olivík (2003) to create a virtual 3D model of the University of West Bohemia. Malý (2009) and Russnák (2012) used a building passport to model the University Campus at Bohunice and the Faculty of Science at Masaryk University. A detailed interactive indoor 3D model of the Faculty of Electrical Engineering, Czech Technical University in Prague, was created by Kratochvíl (2006) and Holý (2008).

Technologies for Detailed 3D City Mapping

3D city models are not only analysed in the context of geoinformation systems. The fields of architecture, engineering, and construction as well as computer graphics provide their own approaches for the representation and exchange of 3D models. Both proprietary technology and widely accepted standards are applied to all the fields mentioned above. Among the standardized solutions are included IFC (*Industry Foundation Class*), which is designed to store FM data; CityGML, which is described in detail below; and INSPIRE Data specification for Buildings, which has a wide range of applications (Herman and Řezník 2013). The proprietary approach is represented by the Building and Technology Passport.

CityGML

CityGML (*City Geography Markup Language*) is an open data model and XML-based format for sets of 3D urban objects. It is implemented as an application schema for the GML3 (*Geography Markup Language version 3*). Both are extendible international standards for spatial data exchange issued by the OGC (*Open Geospatial Consortium*). CityGML is used for the representation, storage, and exchange of virtual 3D city models. Generalization hierarchies among thematic classes, aggregations, and relations between objects are also included in this application schema (Kolbe 2009). CityGML provides a standard model and mechanisms for describing 3D objects with respect to their geometry, topology, semantics and appearance; furthermore, it defines five levels of detail (LoD). Individual levels of detail contain, for example, following elements:

- LoD0—2,5D model of terrain, building footprints,
- LoD1—extruded building footprints,
- LoD2—3D buildings with simplified modelling of roofs,
- LoD3—3D buildings with modelling of exterior details,
- LoD4—3D buildings with modelling of interior details.

CityGML provides much more than simply 3D content for visualization, as it has many diverse applications. CityGML supports class definitions, regulations, and explanations of the semantics for geographic features in 3D city models, including digital terrain models, buildings, vegetation, transportation objects, and city furniture. Practical applications often require the storage and exchange of data which do not belong to any of the predefined classes. CityGML provides two different methods of extension for such cases. The first is the use of generic features and attributes; however, this method reduces semantic interoperability. A concept called *Application Domain Extension* (ADE) is used to eliminate this problem. In contrast with generic objects and attributes, ADE has to be defined within a separate XML Schema definition.

CityGML includes a relatively general data model, whose content can be linked to a topographic database. Handling specific issues that are associated with the 3D modelling of buildings with interiors requires the extension of this structure. And, for this purpose, various specialized ADEs are used (Kolbe 2009; OGC City Geography Markup Language Encoding Standard 2012).

ADEs, which describe in detail the interiors of buildings and technical facilities inside the building, are for example CAFM (*Computer Aided Facility Management*) ADE, GeoBIM ADE and UtilityNetworkADE. Class Buildings is through CAFM ADE extended to other descriptive information used for facility management. This ADE is designed for LoD 4 and adds to existing classes (e.g. *FloorSurface*), abstract subclasses, and attribute data characterizing a manufacturer, condition, a responsible person, or a year of construction (Bleifuss et al. 2009).

GeoBIM ADE combines information contained in the IFC format with CityGML and designs standard GeoBIM. Like the previous ADE, this ADE extends the *Building* class, but this extension is in LoD 3. Semantic classes, such as Room, are extended by a subclass *VisibleElement* and additional elements (*Railing*, *Beam*, *Stair* or *Annotation*). The classes *Window*, *Door* and *RoofSurface* are extended by attributes (De Laat and Van Berlo 2011). UtilityNetworkADE (latest version 0.9.0) defines a topological network model facilitating analyses and simulations on utility networks. Furthermore, it allows the representation of network components such as 3D topographic city objects (Becker et al. 2011).

Building and Technology Passport: Building Information Modelling

This paper presents a pilot study using data from the Building and Technology Passport. Since 2004, the Facility Management Division of the University Campus at Masaryk University has collected digital spatial data on the real-estate property of the University. Recently, a Building Passport has been created for more than 160 buildings owned by the University. However, this number will continue to grow in the context of new construction. The Building Passport also registers assets in buildings used but not owned by the University. Altogether, this means over 250 buildings with over 20,000 rooms (Glos and Souček 2009; Kroutil 2009).

In 2007, shortly after the Building Passport was created, work on the Technology Passport began, this relating to technologies in buildings and rooms including the location of all electronic devices, air-conditioning systems, fire equipment, water distribution systems, and heat distribution systems. The Building and Technology Passports together form BIM, or Building Information Modelling. Using BIM, the Facility Management Division began modelling a new university campus in Brno Bohunice and has gradually been collecting data about other buildings and rooms at different faculties. So far, the Technology Passport has been completed for 40 buildings all over the University. The University Campus, the Faculty of Economics and Administration, the Faculty of Social Studies, and the Faculty of Education have already been finished. In 2013, a test of technology passport data acquisition started at the Faculty of Science (Facility Management Division of the University Campus Bohunice 2013; Kučera et al. 2013).

Spatial data include DWGs (*DraWinG*) of all floors, side-sights or cuts of each university building. DWG blends symbology and attributes together, so, for the GIS solution and web presentation as well, the most important features like ground plans, steps, windows, and load bearing walls are also saved in ESRI geodatabases. Passportization documentation is executed according to methodologies for building and technological passports, which are an integral part of the tender documentation for construction. Methodologies establish and describe the necessary operations in the process of collecting, managing and updating data passports (Facility Management Division of the University Campus Bohunice 2012).

Naturally, the Building Passport is used for building and room plans. However, the main utilization is the connection of spatial data and context, such as in key-room systems, academic computer network information systems, alarm system zones, evacuation fire plans, and interior drafts. This means that these data are used by both the concrete faculty and the all university organizations. Many theses based on the Building Passport have already been published at Masaryk University from the GIS and IT points of view (Glos and Souček 2009; Kroutil 2009). Height values stored in attributes can also be used to create a 3D building model, such as the model of the Faculty of Science at Masaryk University shown in Fig. 2.

Comparison and Conversion

CityGML as a standardized solution is suitable for exchanging 3D data among different organizations and institutions. However, the Building and Technology Passports are optimized for use in the Facility Management Division. In the Building Documentation System, the unified identification of rooms, buildings and sites is realised through hierarchical identifiers. Position code looks for example like: BVB04N01023a, where meaning of each component is:

- BVB—identification of locality,
- 04—number of the building,
- N—type of the storey
- 01—number of the storey,
- 023a—marking of the room.

UUID (*Universally Unique IDentifier*) stored as gml-id attributes are usually used in CityGML and this notation is not hierarchical.

LoD used in CityGML represents another mechanism for the easier selection of elements. The concept of LoD enables features on a given scale or on a given significance to be identified and selected. LoD can differ for various objects (*Roof* as LoD 2, *Door* as LoD 3). In the future, this multi-level approach may also be suitable for the Building Documentation System. The LoD concept is the most successful (and the most cited) part of CityGML.

The Building Documentation System is primarily 2D. Transformation to 3D visualization can be laborious and some inconsistencies can arise during this process. In contrast to the Building Documentation System, CityGML supports full 3D geometry. In addition, it is XML-based and thus supports automated processing, which is better with respect to consistency. On the other hand, the use of ESRI technology in the Building Documentation System allows, among other things, the relatively simple creation of 2D printed plans of buildings and rooms.

Despite the existing differences, it is possible to transform data from building passports to CityGML and vice versa. Conversion from the Building Passport into CityGML is demanding from the conceptual point of view. It is necessary to:

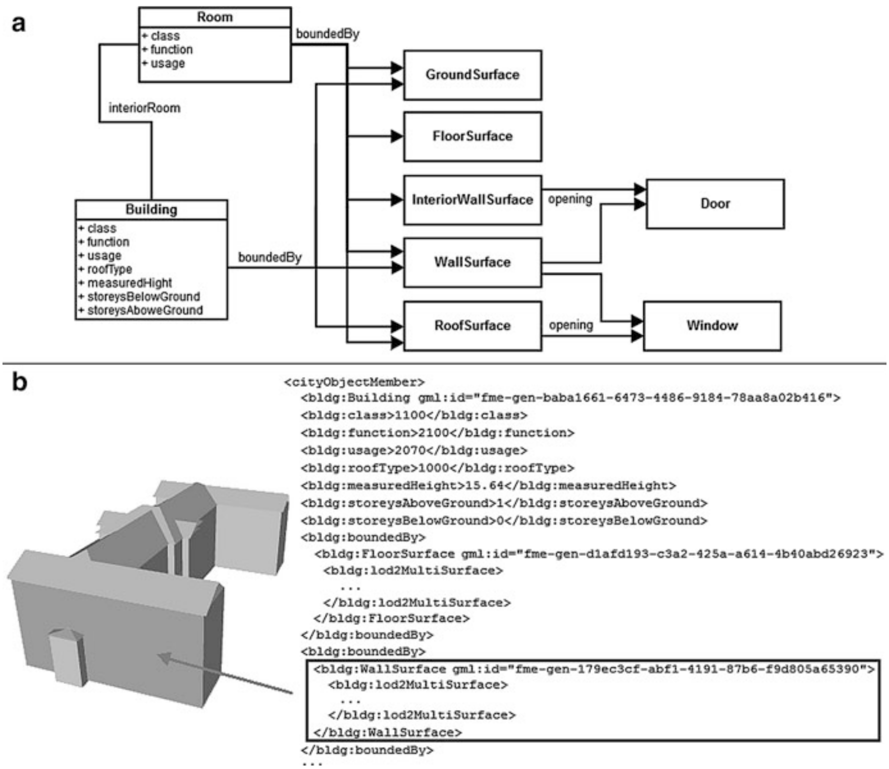

Fig. 1 Conceptual scheme of 3D model of buildings from Faculty of Science campus formed according to CityGML in LoD 4 (**a**) and 3D model of buildings from the Faculty of Science campus in CityGML format in LoD 2 and the record of this data structure in XML (**b**)

- define semantic classes,
- supplement information about level of detail,
- add attribute values or derive them from the geometry.

Individual steps can be performed either automatically or manually. Both approaches were tested and their combination was used to perform the final conversion. The conversion was carried out on two levels: 3D models in LoD 2 (see Fig. 1a) and LoD 4 were made (the data model of this level is shown in Fig. 1b).

ArcGIS 10.0 software was used for manual pre-processing, which was the first step in conversion. The extrusion of vertical surfaces (walls), the base height definition for horizontal surfaces (surfaces of ground, floors and flat roofs) and the completely manual creation (in ArcScene module) of complex gabled roof surfaces were performed in this step. While processing the variant in LoD 4, 3D versions of difference and intersect operations were also used (these algorithms are in ArcGIS parts of 3D Analyst extension).

The second step of the transformation was the conversion of pre-processed Shapefiles themselves. These Shapefiles have polygon geometry with Z (elevation) information (in LoD 2) and Multipatch geometry (in LoD 4). This part of the conversion was implemented in FME software 2012 and included the assignment of individual elements into semantic classes, and the definition and fulfilment of attributes.

Utilization of the Campus Map of the Faculty of Science

Visualization of BIM Through Web and Printed Maps

Data from the Building Passport are widely used for navigation, people and place location, and orientation at various levels of Masaryk University. They are used at the level of the entire university for the searching of persons and premises within the Information System of Masaryk University (IS MU). However, they are also used for specific purposes at the Facility Management Division of the Management of the University Campus, for example to analyse and visualize heating data. The following paragraphs are devoted to the utilization of Building Passport data at the Faculty of Science and the Department of Geography.

The plan of the Department of Geography was made both in the form of a static plan and in the form of a web map. The web map[1] is based on open internet technologies (JavaScript and SVG—*Scalable Vector Graphics*) and uses simple methods of representation with added interactivity. This interactive map appears on the Department's website. The main purpose of the static plan is the possibility of printing, which is offered by the web map. For this reason, the plan optimized for A4 pages is saved in PDF (*Portable Document Format*). However, the static plan does not illustrate all floors of the buildings of the Department of Geography, but only those that provide information required by readers. An emphasis on cognitive style was applied and verified by usability testing (these concepts are explained, for example, in Konečný et al. 2011). The selected floor is viewed from the side, creating the impression of 3D. Each building is shown separately and list of employees can be displayed for individual rooms.

Another variant of the web map is used at faculty level. The webpage of the Faculty of Science uses a simple static campus map[2] in PNG format (*Portable Network Graphics*), which contains the localization of individual departments. Printed campus maps with thematic information are used for various promotional events (e. g. open days or "Night of Scientists" actions), when the Faculty of Science is visited by people who are unfamiliar with the area. Maps for these events include information about buildings and places where the program runs.

[1] http://geogr.muni.cz/plan-gu-eng.

[2] http://www.sci.muni.cz/cz/Kontakty/Mapka-arealu-Kotlarska.

3D Visualization

A 3D model can be saved in many formats, only a few of which can be easily opened directly in a web browser, i.e. without the necessity to add a plug-in and/or customize the Web browser in some way. The web presentation of 3D models created from the Building Passport and in the CityGML format requires their transformation into a different form. Both 3D models created in ArcGIS from the Building Passport and CityGML data can be transformed to X3D format.

The CityGML format can be displayed in a web browser using a plug-in, which is an obstacle to use. A number of programming libraries in JavaScript language that display 3D information in the web browser have been developed in recent years. Such a technology is the X3DOM library, which renders data stored in the X3D (*eXtensible 3D*) format. A 3D model made in the ArcScene module can be exported to VRML (*Virtual Reality Modeling Language*), which can be transformed through freely available tools to X3D. This conversion is not difficult, as X3D is based on VRML. The conversion of CityGML is not complicated either. Although both formats are based on XML, CityGML is transformed into X3D using an XSLT (*eXtensible Stylesheet Language Transformations*) stylesheet and XSLT processor. The issue of the XSL transformation of 3D building data is described in detail in Herman and Řezník (2013).

The advantage of X3DOM is the relatively simple construction of 3D scenes and also considerable support in different web browsers, not only on desktop computers, but also on mobile devices. X3DOM is thus useful for developing 3D navigation applications for these devices. It is planned to place the described X3D model on the Department of Geography website or, alternatively, the Faculty of Science website (the first version of this 3D model is shown in Fig. 2).

Future Development

The previous sections showed the various ways of utilizing detailed data about buildings, and the various options available. These data, whose acquisition is not cheap, can be assessed mainly by multiple applications. In addition to the examples mentioned above, these data can also be used for interactive mobile applications for navigation. As mentioned above, CityGML and the Building Passport are conceived quite generally and the indoor navigation issue requires an extension or modification of these general data models. However, creating functional interactive indoor navigation may not require further transformation into a new specific format.

The navigation extension that is designed to work with different types of 3D geometry is IndoorGML. CityGML, IFC, KML (*Keyhole Markup Language*) and 2D digital data represent, for IndoorGML, sources of geometry. IndoorGML will be derived from these datasets and contain mainly topological data supplemented with semantic information. Original technologies are also used for the visualization of

Fig. 2 3D visualization of Faculty of Science campus on Kotlářská street in web browser

buildings, rooms and routes. Synchronization between CityGML and IndoorGML will be implemented through XLink technology (OGC Candidate Standard for Indoor Spatial Information 2013).

In addition, new specialized standards are constantly developed; the continuous adjustment of existing standards is ongoing. Currently, CityGML 2.0 is being revised and discussed and a new version, 3.0, will be prepared. The major changes include the revision of the LoD concept. Definitions of LoDs are currently vague, informal and allow a great deal of ambiguity. Thus, the LoDs in the next version of CityGML will be described by separately specifying:

- semantic and geometric LoDs,
- the definition of separate interior LoDs and LoDs for the building's exterior shell

This division produces four different variants of LoD; each of these options contains five levels of detail. This approach has so far been proposed only for the Building semantic class, since it is complicated; however, it is possible to apply it to other semantic classes. Different testing use-cases bring different requirements. The division into indoor and outdoor LoD is important for combined indoor and outdoor navigation. However, this new concept of LoD brings new challenges as well. It will be composed of many combinations which it will be necessary to quantify and sort (Löwner et al. 2013a). Benner et al. (2013) propose a solution to this task.

Another modification which can improve the use of indoor navigation is support for dynamic (time-dependent) entities. Dynamic entities contain dynamic properties (e.g. energy demand) and moving objects (dynamic geometry). Dynamic features and attributes are not yet supported in CityGML. The utilization of 3D building models in navigation or in simulations has wider consequences including the modeling of the functional dependencies between objects and the functions of objects and also use of metadata. These should include representation of the quality of individual information pieces (metadata at the levels of objects, attributes), lineage, acquisition methods, accuracy, age, and propagation of quality data for aggregations and other types of computations (Löwner et al. 2013a).

While the changing of standardized technologies is a complex process based on a broad consensus and compromises, updates of the Building Documentation System data model are implemented in a simpler and faster way. Regarding the development of the Building Passport, besides updating data due to renovations and other adjustments, updates are also made to acquisition data from buildings under construction (new buildings of the Faculty of Informatics or the Faculty of Arts). It is being planned to create 3D geometry in LoD 2 for each building owned or used by Masaryk University.

Even greater use of data maintained for operating activities, property records, and facility management is assumed (e.g. there are requirements for determining the number of windows for cleaning). This includes the area of space management for maintaining, updating and displaying data relating to the use of Masaryk university's space, where a building or part thereof is used by external entities.

Finally, there should be greater integration with the Information System of Masaryk University (IS MU) and with other existing spatial data (indoor spherical images, thermal images of facades) to provide data from the Building Passport for study purposes and research activities. In this area, an advanced application for navigation will be implemented. This navigation will not simply search for the shortest route, but should also take account of the user's context. Thus, for example, if the building has an access control system, navigation will be addressed with regard to whether the user has access rights to the room. Navigation can also be adapted to the needs of disabled users

Conclusions

This article presents the issues relating to the re-use of a Building Information Model (BIM) in the form of 3D models and visualizations. One of the main motivations for this re-use is the value of data acquisition needed to establish a BIM. Re-use of a BIM in the form of 3D models and visualizations opens the door to various fields of study, such as architecture, engineering, or spatial planning. We may also perceive these models as a foundation stone for a 3D cadastre supporting decision making processes within and beyond public administration. 3D models and visualizations based on spatial data from BIM are also closely connected to existing standardization activities. The implementation specification of the Open Geospatial Consortium (OGC) called CityGML enables the handling of BIM spatial data. Feedback on CityGML was given to the OGC to support progress in the standardization of CityGML. The authors of this paper have recommended correcting

(continued)

inconsistencies in enumerations which occurred in the previous version of the specification.

Transformation from proprietary BIM to CityGML and vice versa was successfully verified. Moreover, 3D models were visualized in an opened way in Web browsers when using X3D technology. As such, 3D models and visualizations created from BIM are useful for creation harmonized background spatial data as in the European Location Framework (see http://www.elfproject.eu for more information).

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References

3D Warehouse (2013) http://sketchup.google.com/3dwarehouse/. Accessed 5 Dec 2013

Armenakis C, Sohn G (2009) iCampus: 3D modeling of York University Campus. In: Proceedings of American Society for photogrammetry and remote sensing 2009 annual conference. American Society for Photogrammetry and Remote Sensing, Baltimore, pp 66–71. ISBN:978-1-615-67322-3

Becker T, Nagel C, Kolbe TH (2011) Integrated 3D modeling of multi-utility networks and their interdependencies for critical infrastructure analysis. In: Kolbe TH, König G, Nagel C (eds) Advances in 3D geo-information sciences. Springer, Berlin, pp 1–20. ISBN 978-3-642-12669-7

Benner J, Geiger A, Gröger G, Häfele KH, Löwner MO (2013) Enhanced LoD concepts for virtual 3D city models. In: ISPRS annals of the photogrammetry remote sensing and spatial information science. Copernicus GmbH, Göttingen, II. No. 2, pp 51–61. ISSN: 2194-9042

Bleifuss R, Donaubauer A, Liebscher J, Seitle M (2009) Entwicklung einer CityGML-Erweiterung fűr das Facility Management am Beispiel Landeshaupstadt Műnchen http://www.gis.bv.tum.de/tum_content/tum_files/Publikationen/studentischeArbeiten/agit_citygml_ade.pdf. Accessed 29 Oct 2013

De Laat R, Van Berlo L (2011) Integration of BIM and GIS: the development of the CityGML GeoBIM extension. In: Kolbe TH, König G, Nagel C (eds) Advances in 3D geo-information sciences. Springer, Berlin, pp 211–225. ISBN 978-3-642-12669-7

Facility Management Division of the University Campus Bohunice (2012) Methodology for building passportization in the scope of the integrated management system (in Czech). Masaryk University, Brno

Facility Management Division of the University Campus Bohunice (2013) Methodology of passportization at Masaryk University (in Czech). Masaryk University, Brno

Glos P, Souček J (2009) Manager, whom nothing escapes (in Czech). In: CAD.cz. http://www.cad.cz/component/content/article/2350.html. Accessed 29 Nov 2013

Goetz M, Zipf A (2012) Extending OpenStreetMap to indoor environments: bringing volunteered geographic information to the next level. In: Zlatanova S, Ledoux H, Fendel EM, Rumor M (eds) Urban and regional data management: UDMS annual 2011. CRC, Leiden, pp 51–62. ISBN 978-0-415-67491-1

GoogleBlog (2011) http://googleblog.blogspot.cz/2011/11/new-frontier-for-google-maps-mapping.html. Accessed 4 Dec 2013

Herman L, Řezník T (2013) Web 3D visualization of noise mapping for extended INSPIRE buildings model. In: Hřebíček J, Schimak G, Kubásek M, Rizzoli AE (eds) Environmental software systems. Fostering information sharing. Springer, Heidelberg, pp 414–424. ISBN: 978-3-642-41150-2. doi:10.1007/978-3-642-41151-9_39

Holý P (2008) Virtual guide through FEE building (in Czech). Bachelor's thesis, Faculty of Electrical Engineering, Czech Technical University, Praha

Indoor/Projects (2013) http://wiki.openstreetmap.org/wiki/Indoor/Projects. Accessed 5 Dec 2013

IndoorOSM (2013) http://wiki.openstreetmap.org/wiki/IndoorOSM. Accessed 2 Dec 2013

Jedlička K, Hájek P, Čerba O (2012) Experience with methods of 3D cartography gained during visualization of detailed geographic data for purposes of documenting cultural heritage (case study at the castle Kozel). In: GeoCart'2012 and ICA regional symposium on cartography for Australasia and Oceania. New Zealand Cartographic Society Inc., Auckland, pp 89–100. ISBN: 978-0-473-22313-7

Kolbe TH (2009) Representing and exchanging 3D city models with CityGML. In: Lee J, Zlatanova S (eds) 3D geo-information sciences. Springer, Heidelberg, pp 15–31. ISBN 978-3-540-87395-2

Konečný M (2011) Cartography: challenges and potentials in virtual geographic environments era. Ann GIS 17(3):135–146. ISSN: 1947-5683. doi:10.1080/19475683.2011.602027 (Taylor&Francis, Honkong)

Konečný M, Kubíček P, Stachoň Z, Šašinka Č (2011) The usability of selected base maps for crises management: users' perspectives. Appl Geomatics 3(4):189–198. ISSN: 1866-9298. doi:10.1007/s12518-011-0053-1 (Springer, Heidelberg)

Kratochvíl P (2006) 3D model of CTU building in Dejvice (in Czech). Bachelor's thesis, Faculty of Electrical Engineering, Czech Technical University, Praha

Kroutil P (2009) Building passport MU in present (in Czech). Zpravodaj UVT MU XIX(5). http://www.ics.muni.cz/zpravodaj/articles/619.html. Accessed 29 Nov 2013

Kučera A, Glos P, Pitner T (2013) Fault detection in building management system networks. In Slanina Z (ed) 12th IFAC conference on programmable devices and embedded systems. International Federation of Automatic Control, Velke Karlovice, pp 416–421. ISBN: 978-3-902823-53-3. doi:10.3182/20130925-3-CZ-3023.00027

Löwner MO, Benner J, Gröger G, Häfele KH (2013a) New concepts for structuring 3D city models – an extended level of detail concept for CityGML buildings. In: Murgante B et al (eds) Computational science and its applications – ICCSA. Springer, Heidelberg, pp 466–480. ISBN: 978-3-642-39645-8

Löwner MO, Casper E, Becker T, Benner J, Gröger G, Gruber U, Häfele KH, Kaden R, Schlüter S (2013b) CityGML 2.0 – ein internationaler Standard für 3D-Stadtmodelle, Teil 2: CityGML in der Praxis. In: Zeitschrift für Geodäsie, Geoinformation und Landmanagement, Augsburg: DVW – Gesellschaft für Geodäsie, Geoinformation und Landmanagement e.V. 138 (2):131–143. ISSN: 1618-8950

Malý M (2009) 3D visualization of selected build-up area (in Czech). Master's thesis, Faculty of Science, Masaryk University, Brno

OGC Candidate Standard for Indoor Spatial Information (2013) http://indoorgml.net/. Accessed 8 Dec 2013

OGC City Geography Markup Language Encoding Standard (2012) http://www.opengeospatial.org/standards/citygml. Accessed 25 Oct 2013

Olivík S (2003) 3D virtual model of UWB Borské pole campus (in Czech). Master's thesis, Faculty of Applied Sciences, University of West Bohemia, Plzeň

Over M, Schilling A, Neubauer S, Zipf A (2010) Generating web-based 3D city models from OpenStreetMap: the current situation in Germany. Comput Environ Urban Syst 34 (6):496–507. ISSN: 0198-9715 (Elsevier, Philadelphia)

Popelka S, Brychtová A (2012) The historical 3D map of lost Olomouc fortress creation. In: Svobodova H (ed) Proceedings of the 19th international conference on geography and geoinformatics: challenge for practise and education. Masaryk University, Brno. ISBN: 978-80-210-5799-9

Řezník T, Horáková B, Szturc R (2013) Advanced methods of cell phone localization for crisis and emergency management applications. Int J Digital Earth. doi:10.1080/17538947.2013.860197

Russnák J (2012) 3D model of the Faculty of Science at the Masaryk University (in Czech). Master's thesis, Faculty of Science, Masaryk University, Brno

Slováček R (2002) Creation of 3D model of buildings from aerial images (in Czech). Master's thesis, Faculty of Mining and Geology, VŠB – Technical University of Ostrava, Ostrava

STANDEX Counter Terrorism Project: 10 Years 10 Stories Anniversary Feature. (2012) http://www.nato-russia-council.info/en/articles/20121123-nrc-10-years-standex/. Accessed 12 Dec 2013

Strzalka A, Bogdahn J, Coors V, Eicker U (2011) 3D city modeling for urban scale heating energy demand forecasting. HVAC&R Res 17(4):526–539. ISSN: 1078-9669. doi:10.1080/10789669.2011.582920 (Taylor&Francis, Honkong)

SUN-AREA (2011) Nutzen für den Bürger. http://www.sun-area.net/Nutzen-fuer-den-Buerger.93.0.html. Accessed 1 Dec 2013

United Nations, Population Division: UN Population Division Urban and Rural Population – Population in urban and rural areas 2012 (2013) http://esa.un.org/unup/unup/index_panel1.html. Accessed 10 Dec 2013

University of Virginia: Rome Reborn (2010) http://www.romereborn.virginia.edu/. Accessed 24 Nov 2013

Willmes C, Baaser U, Volland K, Bareth G (2010) Internet based distribution and visualization of a 3D model of the University of Cologne Campus. In: Bandrova T, Konečný M (eds) Proceedings of the digital earth summit. Digital Earth Society, Nessebar. ISBN: 978-9-547-24039-1

Winners Collection (2008) http://sketchup.google.com/3dwarehouse/cldetails?mid=2d5e8dfbfd5d9985bdac737426f6915&prevstart=0&hl=en. Accessed 4 Dec 2013

Wolterbeek M (2012) University of Nevada, Reno scientists design low-cost indoor navigation system for blind http://newsroom.unr.edu/2012/05/18/university-of-nevada-reno-scientists-design-low-cost-indoor-navigation-system-for-blind/. Accessed 24 Nov 2013