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Maintainable 3D Models of Cities

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1 ABSTRACT

In the last decade 3D city models received an increasing amount of attention from both, the scientific community and the professional field. One of the requirements for city models is that they should be maintainable, i.e., the system should be kept going and not be created for a specific decision and then abolished. What is the effect of such a requirement? Creating a model that represents the current status of a city is only problematic due to the vast amount of data to be collected and processed. Keeping the resulting model up-to-date, however, is more complex. This requires, for example, the introduction of 'time' as a concept in the model because then it can comprise the history and current status of the city as well as future development scenarios. The processes that lead to changes in the city must thus be represented in the city model to allow the changes. In the paper we discuss these problems and show necessary properties for city models and systems maintaining them to reach a reasonable level of maintainability.

2 INTRODUCTION

Digital city models are an important topic in current research. Topics include automatic building detection (Brenner 2000; Früh and Zakhor 2003) or sub-surface infrastructure (Forkert 2006). Applications of 3D city models include noise modelling (Kurakula and Kuffer 2008). Cities like Berlin (www.3d-stadtmodell-berlin.de/3d/seite0.jsp) or Vienna

(www.wien.gv.at/stadtentwicklung/stadtvermessung/geodaten/stadt¬modell/produkt.html) invest large amounts of money to create such models. Applications must then create enough revenue to justify these expenses. However, cities change constantly and thus the models will be outdated one day. There are two different scenarios to counter this problem:

- 1.The revenue from the applications is large enough to reach the break-even point before the model is outdated. Then again money can be invested to create a new model.
- 2.The model is constantly updated and can thus be used over an extended period. Revenues from applications will then pay for the updates and any profit provides down-payments for the investment.

The remainder of the paper is structured as follows: We start with some definitions to avoid misunderstandings. Then we briefly discuss the different quality levels that have been defined for city models and observation processes suited to collect data for these levels. We then show typical applications where city models are used. These applications demand specific levels of quality from the city models. The next section discusses changes in a city that need to be captured to keep the model up-to-date. Finally, we discuss possible update processes for each quality level and relate it to the applications. Some conclusions finish the paper.

3 DEFINITIONS

Several definitions are necessary as a starting point. We discuss maintainability of city models. Thus we have to explain what we mean by maintainability and city models. A term frequently used when discussing spatial decisions and city models is sustainability. We show how this concept is typically used and argue why this should not be used for the questions addressed in this paper.

3.1 Models of Cities

Models of cities can mean different things. It may be a model of the interactions within a city or a model of topographic relations between objects in cities. We use the second type of city models. Many objects in cities can only be reasonably well described in three dimensions and thus city models are often 3D models. A standard frequently used for structuring the data is CityGML (Kolbe and Bacharach 2006).

3.2 Sustainability

The definitions of sustainability are manifold. It is said, for example, that it “relates to the maintenance or improvement of the integrated natural systems that collectively comprise life on our planet” (Egger 2006, p. 1236) or that it “is related to the life and more specifically to the survival of all beings and humans in the environment” (Mitoula and Economou 2007). Sustainable urban development can then be seen in the context of “environmental stewardship, inter-generational equity, social justice, and geographical equity” (Haughton 1997, p. 189). The goal is typically ecological sustainability (Bandyopadhyay, Bandyopadhyay et al. 2009; Cerreta and Salzano 2009; Mahmoudi and Fanaei 2009) but also economical and social sustainability are discussed (Ostermann and Timpf 2007; Meir 2009; Ostermann 2009). These three kinds of sustainability have been defined in the Agenda 21 (United Nations 1992). These definitions extend the meaning of the term sustainability to cover different kinds of impacts. This is crucial when discussing city development. In this paper we discuss digital city models that serve as data basis for decision making. Above definitions complicate the discussion for the kind of application addressed in this paper and impede the concentration on the core technical problems for digital city models. A completely different definition can be found in the Brundtland report, which defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, Khalid et al. 1987, p. 24) but this is even more difficult to translate to technical issues of 3D city models.

3.3 Maintainability

“To uphold as valid, just, or correct” is another definition of sustainabiliy (Nichols 2001). This is a perfect definition for the purpose of this paper. It is, however, not a typical definition in spatial planning. Thus talking of sustainable models could lead readers to wrong conclusions about the content. We thus decided to use the term maintainability for the fact that the model should be used during an extended period for multiple decisions and applications. The model must then be adapted whenever the city itself is significantly changed. The significance of a change depends on the application.

4 QUALITY CLASSES OF 3D CITY MODELS AND HOW TO OBTAIN THE DATA

CityGML defines five different quality levels for city models (Kolbe, Gröger et al. 2005):

- Level of detail 0 (LoD0): digital terrain model (DTM) + aerial image
- Level of detail 1 (LoD1): Block models of buildings
- Level of detail 2 (LoD2): Roof structures, textures
- Level of detail 3 (LoD3): Detailed roof and wall structures including balconies and vegetation
- Level of detail 4 (LoD4): Interior structures like rooms, doors, stairs, and furniture

These levels of detail require different types of data collection. Models with LoD0 to LoD2 can be produced automatically from aerial images whereas interior structures, for example, depend on the availability of either detailed surveys or architectural documents. Table 1 shows the level of detail needed for different applications.

Aerial photogrammetry can provide information on 3D geometry (height of terrain and buildings, footprints of buildings, and roof structure) and ground texture. It is difficult to get texture for vertical walls from aerial photogrammetry because of the wall’s distortion in the image. Aerial images have been used to provide texture because it is cheaper and sometimes no other sources are available (see, for example, Steidler and Beck 2005). However, aerial images do not lead to high resolution textures. When creating views from a pedestrian perspective then the texture must be applied in resolutions which can be provided only by terrestrial photography (Göbel and Freiwald 2008). Thus many projects use terrestrial images for texturing the objects (Holzer and Forkert 2004; Poesch, Schildwächter et al. 2004).

Airborne laser scanning (ALS) can provide more accurate geometrical data. ALS data have been successfully used for automatic detection and modelling of buildings (Rottensteiner 2003). ALS data contain no information about the texture. However, they may be used to detect vegetation since the different reflection characteristics allow a classification (compare, for example, Maier and Hollaus 2008).

Terrestrial surveys can provide all necessary data but the costs are higher than those of airborne methods. Thus methods like car-mounted fisheye cameras have been adopted to reduce the costs (e.g., Forkert, Haring et al. 2005). Still, these methods are expensive and can only provide data for LoD2 (textures) and LoD3 (façade details). Interior structures still require classical surveys using, for example, laser scanners. However, available architectural maps can provide some information as shown in the case of the Vienna underground modelling (Forkert 2006).

5 USAGE OF 3D CITY MODELS

3D city models have usage in various domains, e.g., urban planning and management, noise and air pollution, disaster management, tourism, facility management and environmental management simulations, homeland security, real estate management, vehicle and pedestrian navigation, and training simulators etc. A rough categorization of tasks in spatial planning includes (Navratil 2006)

- planning for future development,
- planning for dealing with a specific situation where planners propose solutions and a discussion leads to a decision, and
- planning for dealing with a specific situation where the affected agents (lay people) develop a solution.

The three kinds of tasks have different demands for the quality of 3D city models. The planning of future development requires a complete inventory of relevant objects. Precise information on colour, patterns, or shape is not necessary. The presentation of a specific solution to a wide audience, however, is typically done with virtual reality. Then not only the completeness of the inventory is important, but also the detailed graphical representation. In the following paragraphs we give a brief account of the usage of 3D city models for urban planning, disaster management, and noise and air pollution.

Virtual 3D city models enable urban planers to visualize the existing city state, and take decisions for future developments accordingly. The development plans can be simulated before execution, thus enabling intelligent decision making. The possible data sources for a 3D city model are cadastral data, digital terrain models, building models, street-space models and green space models (Döllner, Kolbe et al. 2006). Urban planning is a complex task involving the interplay between multiple aspects of a city, e.g., transport, pollution, and crime. Hamilton, Wang et al. (2005) introduced the concept of nD urban model that provides a holistic view of the city by integrating diverse data sources like 2D maps, 3D urban models, thematic information, historical data, national statistics, local survey, and various policy and regulations.

3D city models are tools for rescue operations during disasters, e.g., flooding, earthquake, and fire, etc. The disaster situations can even be simulated so as to train rescue operators and even preplan the strategies to tackle emergency situations, e.g., location of damaged site, indoor and outdoor navigation for helpers, and determining escape route for affected people from effected site or building (Kolbe, Gröger et al. 2005).

With the growing population in urban areas, there is a dire need to address the issue of noise pollution. The major source of noise is the traffic noise and affects the inhabitants along road sides mostly. In order to mitigate the effects of noise pollution, 3D noise maps in combination with 3D city models are used (Kurakula and Kuffer 2008). Since noise propagation depends on topography, building structures and other structures (trees etc), 3D city models help the decision makers to envisage the intensity, propagation patterns of the noise in cities and take appropriate actions. The data required for noise modeling include road networks, noise sources (traffic information, construction sites, industries etc.), buildings (residential, schools, offices, hospitals etc.), population (inhabitants) and green areas (parks), etc.

3D city models are important tools to visualize and simulate air pollution levels. The pollutants carried by the wind may be trapped in the high building structures and street canyons thus causing high pollution in such areas. One of the dominant sources of air pollution is the traffic pollution. Information about traffic air pollution and distribution of pollutants is therefore important for taking effective decisions for air quality improvement and future urban designs (Wang, van den Bosch et al. 2008). The data sources include pollution sources (vehicles, industry etc), wind data (speed, direction etc.), surface temperature, street canyon geometry (Métral, Falquet et al. 2009), and the shape of buildings etc.

Application Area	Model LOD
Urban Planning	LOD0-LOD3
Noise Pollution	LOD1-LOD3
Disaster Management	LOD3, LOD4
Traffic Management	LOD1
Air pollution	LOD0-LOD3

Table 1: Model LoD for different applications

6 CHANGES IN CITIES

Cities are changing constantly. There are two categories of changes:

- Constant changes, e.g., replacement of a building, construction of a new road, etc.
- Temporal changes, e.g., snow on the streets, trenches along streets to install supply lines, etc.

Typically, only the first kind of change is important for 3D city models. Temporal changes are only necessary for analysis of situations that are affected by the change. Traffic guidance, for example, may be influenced by road construction work because roads are blocked. Such tasks are usually not solved by 3D city models but they may become relevant, e.g., in disaster management. However, such information could be integrated in the application from outside sources and need not be stored in the city model itself. They would not be relevant for the city model itself.

Constant changes may influence different aspects of a 3D city model:

- Creation, change, or destruction of a single object: Examples are the creation of a new building or road, the change of a building façade, the replacement of an old bridge, or the clearance of an old gas station.
- Changing objects in a specific area: The construction of a new road is an example for a situation where above actions are performed on a number of different objects: fences are relocated, traffic signs placed, and trees cut down.

The first type of change has been modelled for database objects (Medak 2001). It not only applies to large changes like the reconstruction of parts of a building since applications may also be sensitive to small changes like repainting a façade. The second type of change comprises a set of changes of the first type. Thus the mechanisms shown by Medak also apply to this case.

All of above examples occur at a specific point in thime. Thus they have a date attached to them. This date may be fuzzy like in 'the building was created in the years 2007 to 2009' but it exists. This is not the case for natural changes like deterioration either by environmental influences on the object or use of the object. Roads with high traffic loads, for example, will show wear and colours on façades change over time. These changes do not fit in Medak's system. However, they may be important for some decisions. Visualizing the existing city state must include the deterioration because otherwise the city planners will come to wrong conclusions. Although inspection of the city area in discussion will clearly show the difference, problematic areas might be missed when only using the digital model. In order to eliminate this problem other tools will have to be used. This somewhat lessens the benefits of the model itself for city planning because it is only one of a few tools.

7 UPDATE OF 3D CITY MODELS

What does the above mean for 3D city models? Objects in the model must be changed if the original changes. The challenge is finding all changes in the city.

7.1 Level of Detail 0

The DTM will only change either due to natural disasters like earthquakes, land slides, or volcanic activities or due to massive earth movement on construction sites. Natural disasters typically cause a large amount of destruction and thus imply dramatic changes. Thus a reconstruction of the affected area will be necessary. Constructions are more difficult to be detected. It may be, however, that constructions with sufficient change of the terrain must be announced. Then the information about the existence of changes is available and only the effects have to be determined.

7.2 Level of Detail 1

For block models most of the changes discussed in section 6 are irrelevant. The only important changes are

- the creation of new buildings,
- the destruction of buildings, and
- a massive change of a building shape.

Again, if these kinds of changes must be announced, the information about the change is available. Otherwise the detection is tricky. Current approaches use the creation of new models and the comparison of the old set of blocks with the new set of blocks. Although the interpretation of the survey data (e.g., GPS tracks or ALS data sets) can be done automatically to a large degree, there is still some effort necessary to classify the deviations. In addition, the surveys themselves are costly and thus performing them without reasonable suspicion that there are changes is questionable.

7.3 Level of Detail 2

LoD2 requires roof modelling in addition to the building outlines. Roofs can be modelled, e.g., by aerial photogrammetry (e.g., Frere, Hendrickx et al. 1997), ALS (e.g., Haala and Brenner 1997), or a combination of both (e.g., Rottensteiner and Briese 2003, Jaw and Cheng 2008). LoD2 only contains the general shape of the roof. The roof of a simple, rectangular building then typically consists of two planes. These can be detected with a high degree of automatization. In this case the main costs for the roof detection emerge from the ALS-flight itself. The situation may be more difficult in old city centres with different and very specific roof structures but results for Vienna (Rottensteiner and Briese 2003) suggest that a combination of ALS and aerial photogrammetry may solve the quality problem. It is questionable, however, if these processes can be fully automated and work without human supervision.

Single roofs can also be determined from other data sets like construction drawings, terrestrial laser scanning, terrestrial photogrammetry, or classical, terrestrial survey at lower costs than by ALS. It is necessary, however, to know which roofs have been changed to adapt these methods. This is simple if changes have to be announced but if this is not done then ALS or aerial photogrammetry seems to be the only method to update the city model. The problem is then reduced to finding significant differences between the roof models.

Textures are also available in LoD2 models. As discussed in section 4 these are difficult to collect because airborne methods currently do not produce textures with the required quality. The texture of the façade may be relevant for different kinds of application. Visualization of urban planning projects may depend heavily on the state of the surrounding façades. Thus current images of façades may be relevant for decisions. Announced changes of façades can be easily tracked. Unannounced changes, however, provide the same problem as the roof structures: Complete resurvey would be necessary to detect all changes and this resurvey is expensive.

7.4 Level of Detail 3

What has been said about the roofs in LoD2 is also true for the detailed root structures in LoD3. The only difference is the detail of the survey and the degree of interpretation. A more detailed survey with ALS may require lower flight height and thus a straight path covers a smaller strip of land. More flight time is then necessary to cover the area of a city. This increases the cost of data collection. Since more data are produced (the amount of data produced by ALS depend on the scan frequency and the scan duration), more effort is necessary to interpret the data. Detailed roof models consist of more parts than the simple ones used in LoD2. Thus both, the interpretation of the ALS data and the change detection are more difficult: Does the difference between the models reflect an actual change or is it based on the specifications of the equipment and interpretation algorithms used? If the difference is based on the equipment, which of the two models is the ‘correct’ one? These questions may be difficult to determine and may require on-site inspection.

Wall structures present another challenge. Some structures may not be visible from above, e.g., a small balcony below a large one. Thus methods like terrestrial photogrammetry or terrestrial laser scanning are necessary to capture the data. Both methods are expensive and periodic application is not feasible.

The collection of vegetation can be done by aerial photogrammetry or ALS. Vegetation is influenced heavily by both types of changes discussed in section 6. Growth models for vegetation and different kinds of rendering algorithms may help determine the natural changes like seasons or growth. This is more difficult for changes by human intervention. The human intervention may aim at keeping vegetation in a specific shape like it is, for example, the case in the garden of castle Schönbrunn. In this case the hedges are kept in a specific shape. City models can ignore these kinds of interventions because they keep the city model up-to-date. The same cannot be said about interventions that are necessary for other reasons like surrogate plantation for trees that had to be cut during construction works. Again missing documentation leads to high costs.

7.5 Level of Detail 4

Adding interior structures like rooms, doors, stairs, and furniture is extremely expensive. Airborne methods cannot provide these data. The only methods are evaluation of existing construction documentation or specific surveys. The use of existing documentation is cheaper, especially if the documentation is available in digital form. However, old buildings typically only have such documentation if they are of public interest (town halls, airports, school, etc.) and these are only a minority within a city. Thus comprehensive city models with LoD4 are not realistic. The data is extremely expensive and the only application for it seems to be disaster management. In detail this is only necessary for crowded buildings. As soon as the people are led out of the buildings then the interior structure is irrelevant. Thus LoD4 is only necessary for the first step during disaster management and this is typically only done in a structured and organized way for public buildings.

8 CONCLUSIONS

We showed that higher levels of detail affect the process of keeping the city model up-to-date. Maintaining a model with LoD0 can be done almost automatically, whereas in theory a model with LoD4 would require an update whenever an apartment is refurnished. This is not feasible. The challenges are

- receiving information about the change and
- assessing the significance of a change.

The main problem is thus the data collection and not the data modelling. Efficient strategies are necessary to acquire all data necessary to keep the model up-to-data. These data can be acquired either for the whole city at once in regular intervals or continuously as the reality changes. In both cases the process must be cost effective. This typically calls for a high degree of automatization or automatic communication from the initiator of the change. There are three possible solutions:

- Keep the 3D city models simple: Models with only blocks for buildings or even with detailed roof models can be automatically updated as long as the data can be generated automatically from sources like aerial photographs, satellite images, and ALS.
- Allow different levels of detail for different parts of the city: Important historic buildings could be modelled with higher level of detail than other parts of the city. It is then necessary to assess the benefits added to the model by these additions. Different levels of detail may be problematic for some tasks that shall be supported by the city model. Judging architectural design, for example, calls for a model with detailed façade textures and vegetation, which is level of detail 3. If parts of the city model only have level of detail 2 or lower then this process cannot be supported throughout the city. How to communicate the level of detail is thus an important question in the design phase.
- Install processes that force citizens to provide data for significant changes: Compulsory building permits, for example, show where new buildings are planned and may also provide detailed 3D geometric data on the building. This would eliminate the need for surveys detecting changes. However, such changes of processes should not be implemented too frequently because they change the way public administration works and public administration should be stable.

Recent developments in data capture include crowd sourcing or volunteered geographic information (Goodchild 2008). It is not yet clear how this method can be used to collect large data sets. First experiences, e.g., with OpenStreetMap, look promising and may be adapted to detect changes in cities that need to be included in city models.

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