TERRAIN-DEPENDENT AGGREGATION OF 3D CITY MODELS

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ABSTRACT:

3D city models offered by digital map providers typically consist of several thousands or even millions of individual buildings. Those buildings are usually generated in an automated fashion by remote sensing methods and can by very detailed. However, not in each application such a high degree of detail is desirable. Whereas in some applications the requirements for storage consumption and processing power exceed the available resources, for visualization purposes it is not optimal to have too detailed graphics as well. Hence, it is necessary to generalize those city models in order to reduce their detail and to remove undesirable visual features. A simple way to remove complexity is to aggregate individual buildings whilst obeying a set of well-introduced rules.

Some visualizations and simulations utilizing city models may greatly benefit from the simultaneous usage with terrain models. By simply displacing the z-coordinate of their nodes the buildings of the city models can by used in conjunction with these terrain models. However, when using terrain models, the use of conventional aggregation techniques for buildings is problematic and may result in faulty visualizations and simulations. This paper introduces the issue of aggregating buildings of city models, when they are used in conjunction with terrain models, presents a solution by considering height dependent constraints and discusses future optimizations of terrain-dependent aggregation of 3D city models.

1. INTRODUCTION

The availability of 3D city models is steadily growing. There are many applications which benefit from these 3D descriptions of urban buildings. They can be used for visualization purposes like navigation systems or simulation tasks like noise scenarios, disaster management, environmental simulations and others. Those 3D city models are available in multiple scales. Regarding the CityGML definition, the first level of detail (LOD1) only consists of buildings with flat roofs [Kolbe et al., 2005], there are also models with detailed roofs and even with modelled inner structure of the buildings. Since currently the greatest coverage is available for LOD1 city models this paper will concentrate on them and postpones the handling of more complex models to the future work.

Albeit LOD1 city models merely consist of flat shaped roofs, they may even be too detailed for many applications. The geometry for those models is usually obtained using photogrammetry or laser scanning. The high degree of detail of the resulting models requires significant resources like storage space and computational power which cannot be served by each application (i.e., embedded systems). Another issue is that too detailed visualizations may be not effective [Schumann & Müller, 1999] and divert the viewer's attention. A practical example is that human cartographers explicitly vary the detail level of buildings for different map scales.

There are a variety of methods to reduce the complexity of 3D city models. Generalization algorithms (e.g., Sester, 2000) aim at removing unnecessary details and to reduce the amount of information needed to store and process those models. An important step for this reduction is the aggregation step. By joining neighbouring buildings a significant number of points can be saved. In order to allow aesthetic aggregation like it is done by human cartographers, specific aggregation rules have been introduced, taking the distance, the form, but also thematic attributes into account.

Beside city models, other data sources can be used to enrich cartographic applications. Those applications may also benefit from the integrated use of different data sources. By combining both city models and terrain models more realistic visualizations and simulations can be realized. Figure 1 shows an illustration of the combination of city models with a terrain model. The individual buildings are shifted in their vertical position, depending on the elevation of the terrain.

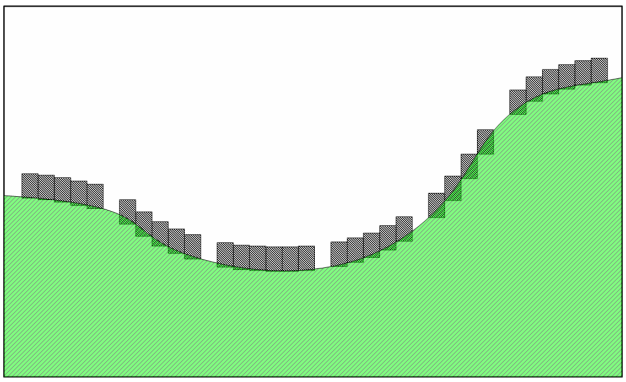

Figure 1. Illustrated combined use of terrain model (green ground) and city models (grey buildings).

The aggregation methods have one common characteristic: they enlarge the size of the buildings – in order to reduce details and make them readable in the map. Whereas this means no problem for applications without terrain model, significant differences in their height may cause visualization artefacts and even computational problems in simulations.

This becomes relevant for cities that are built in steep terrains like Stuttgart, Lisbon, Hong Kong, and San Francisco. Up to now, despite there are numerous applications (e.g., cartographic and navigation software) for the integrated use of city and terrain models this fact is neglected. In CityGML (Kolbe et al., 2005) there is the element of a TerrainIntersectionCurve which defines the link between terrain and building, however, this concerns only to the modelling aspect. Hence, aggregation of city models cannot be run independently, but has to be carried out with respect to the individually employed terrain model. Consequently, city model aggregation rules have to be introduced which cope with elevated terrain. This will allow visualizations without artefacts and better simulation results, whilst reducing the complexity of city models.

This paper is organized as follows: After this introduction section 2 addresses the related work for generalization and aggregation of buildings. Section 3 shows up the issues which arise from the aggregation of city models when terrain models are used. Section 4 proposes a mechanism for avoiding errors due to the aggregation process. Section 5 shows some results and section 6 concludes the paper, discusses the achievements, suggests some extensions and proposes future work.

2. RELATED WORK

The generalization of buildings is a task which is very relevant in the generation of topographic maps in different scales. Approaches for the automatic generalization have been presented for different scale ranges: in large scale maps, the outline of the buildings is simplified using a set of rules that indicate how to eliminate too small features in the outline. Also, buildings in a certain vicinity can be aggregated (see e.g., Staufenbiel, 1973). Going to smaller scales, individual buildings can no longer be displayed due to their limited size; therefore, building typification is applied: schematic building representatives (e.g. squares or rectangles) are used, which are placed according to the spatial distribution of the original scene. To this end, methods from computational geometry (Regnault 1996) or Neural Networks (Sester, 2005) are applied. In even smaller scales, no longer individual building representatives are shown, but larger aggregates of settlement areas. Such areas can either be defined using the meshes of the road network, or by aggregation and buffering of the individual buildings (Chaudhry & Mackaness, 2008).

Concerning 3D-generalization of buildings, many researchers concentrated on the generalization of individual high level detailed buildings (Thiemann, 2002, Forberg, 2004, Kada, 2007). Guercke & Brenner, 2009 introduce a generalization framework which is based on semantic knowledge of the building elements. The generalization of building blocks has been presented by Glander & Döllner, 2008, which is mainly based on the extrusion of road meshes by a certain height derived from the buildings contained in the mesh. Similarly, Chang et al., 2008, propose an approach to cluster buildings in a distance dependent way, which is used for visualization. Anders, 2005, proposed a 3D generalization of adjoining buildings by a 2D-generalization of the projection of the 3D-shape into the 3 main directions of the building. The integration and generalization of roads on the terrain has been tackled by Filin et al., 2007. The problem of 3D-building generalization in the presence and in combination with terrain has, to the best of our knowledge, not been tackled yet.

3. ISSUE OF AGGREGATION USING ELEVATED TERRAIN

Aggregation means to combine individual buildings (see Fig. 1) of city model in order to remove intermediate nodes or faces. It takes different criteria into account, e.g., distance to neighbours but also other features which might be in between like roads. Without terrain model this strategy performs well in order to reduce complexity of the city model. In the past, many rules have been introduced and verified which allow a functional and aesthetic grouping of building blocks in a way like many human illustrators do.

For realistic representations of the environment also other data sources like terrain models can be used for visualization and simulation. Therefore, in some applications the fusion of city models and terrain models makes sense. In this case the individual buildings of the city models are trivially placed on the terrain by adjusting their z-coordinate accordingly. However, when existing aggregation rules are applied to those city models in steep terrain, certain problems may arise.

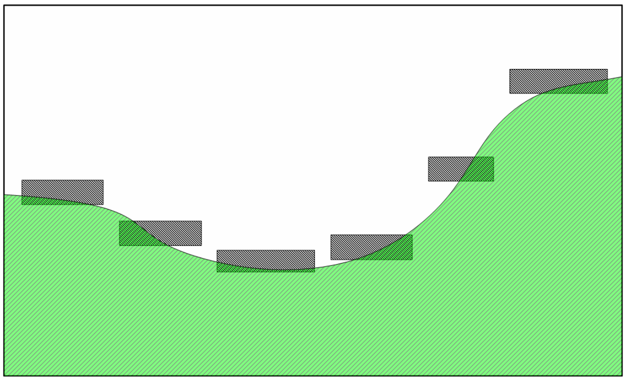

Figure 2. Aggregated buildings cause visualization artefacts on steep terrain.

Figure 2 shows an illustration of aggregated buildings by grouping buildings which share common nodes. On flat segments of terrain this performs well, but it may cause visualization issues on parts with steep terrain. Hence, depending on the visualization method, those buildings partially literally appear like plugged into the terrain or protrude the terrain.

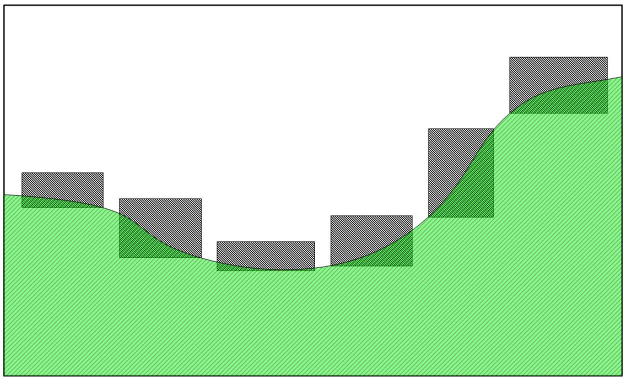

Figure 3. Aggregated buildings with extended wall may cause unrealistic visualizations and simulations.

A small improvement can be found if the walls of the aggregated buildings are extended to the ground (see Fig. 3). But since the buildings are grouped together using one common roof height, this may cause excessive facade heights on steep segments of the terrain which look quite unrealistic.

4. APPROACH FOR INTEGRATED GENERALIZATION OF BUILDINGS AND TERRAIN

As stated above, the issues of visualization artefacts and simulation discrepancies arise when city models are aggregated and used in combination with terrain models. This section presents an approach to cope with these issues.

A pragmatic strategy is to introduce an aggregation error and to constrain the aggregation of buildings according to this error. The error function can be defined in different ways. However, as in the case of flat terrain, ideally for individual buildings there is no extension into the terrain and no protrusion from the terrain. Hence, by this definition the error can be defined by a modified standard deviation of the overall elevation of a building (vertical displacement) and the difference of its basement nodes (footprint) to the underlying terrain (see Eq. 1).

$$e = \sqrt{\frac{\sum_{i=1}^{n}(t_i - h)^2}{n-1}} \quad (1)$$

where e = error for building
h = desired elevation of building
t_i = terrain elevation at position of node i
n = #nodes of buildings in set.

A fast and pragmatic way is to determine a set of connected buildings which are placed on the terrain and to bring them into a defined order whilst preserving their connection (e.g., from north-west to south-east). In the aggregation step, the error now serves for the decision, if two coherent buildings should be aggregated or not. The decision can be taken by defining an upper bound $e_{\max}[0,\infty]$ and testing against it after a tentative aggregation of both buildings (see Eq. 2).

$$e_a = \begin{cases} \leq e_{\max} & : \text{aggregate} \\ else & : \text{reject} \end{cases} \quad (2)$$

where e_a = error of tentative aggregation
e_{max} = upper bound of error.

According to the order defined before, now each pair of connected buildings is iteratively aggregated or rejected, depending on the error value to the underlying terrain. Setting e_{max} to 0 means that each aggregation is rejected, whilst an infinite value allows each aggregation. In practice, an application dependent value has to be determined. In case of an aggregation, conventional city model aggregation rules can be applied (e.g., [Lal & Meng, 2003], [Kolbe & Gröger, 2003]). These rules cover many flat aggregation cases like proximity of buildings and different roof heights.

In Figure 4 the left and the middle building are used for a tentative aggregation. In the illustrated case the error is less than a defined upper bound. Subsequently, the algorithm continues with the next building.

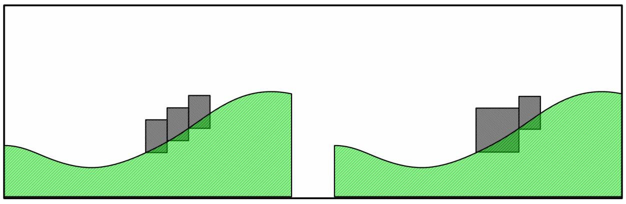

Figure 4. Illustration of iterative aggregation of buildings.

Using this method, it is possible to control the overall error in visualizations and simulations which arises by the combined use of aggregation of city models and terrain models. In steep areas only few buildings are aggregated whereas in flat terrain this additional rule has no influence to the traditional aggregation rules (see Fig. 5).

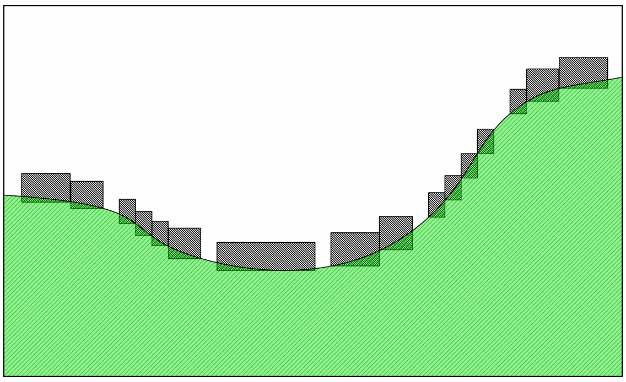

Figure 5. Buildings aggregated with terrain constraint. On steep terrain aggregation is rejected which minimizes the error.

While this approach leads to reasonable building heights after generalization, it has the negative effect that in steep areas hardly any aggregation will be performed due to the large errors it would create. While this is acceptable for large to medium scales, it would lead to a visually disturbing effect when viewed in smaller scales or from large distances.

Thus, in order to accommodate for this cases, similar to the representation of settlements in small scale maps, extruded aggregates of building blocks can be presented. In this case, however, the extrusion is not done horizontally (leading to flat roofs), it is done parallel to the terrain (see Fig. 6). Accordingly, the roofs of the resulting buildings are inclined and adapted to the terrain's inclination. However, for some applications this may cause a more complex triangulation of the buildings' roofs, especially when buildings overlap the borders of multiple terrain tiles.

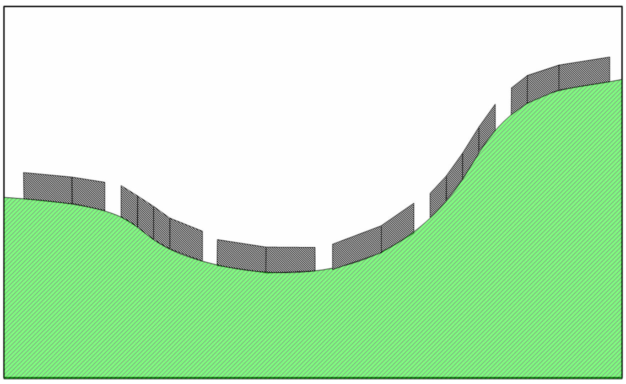

Figure 6. Inclined roofs as visual improvement.

5. RESULTS

In several applications this approach can be used to allow the combination of terrain visualizations as well as city models. One example of these applications are navigation systems. In order to support the user, modern navigation devices employ city models. However, because their storage and processing power are very limited, the amount data delivered from digital map providers has to be reduced drastically. Since those navigation systems also utilize terrain models to support the user's orientation, this approach helps to improve the visualization. Figure 7 shows a part of a city model which has been processed by traditional aggregation rules. The resulting building blocks protrude the terrain because they share one common height.

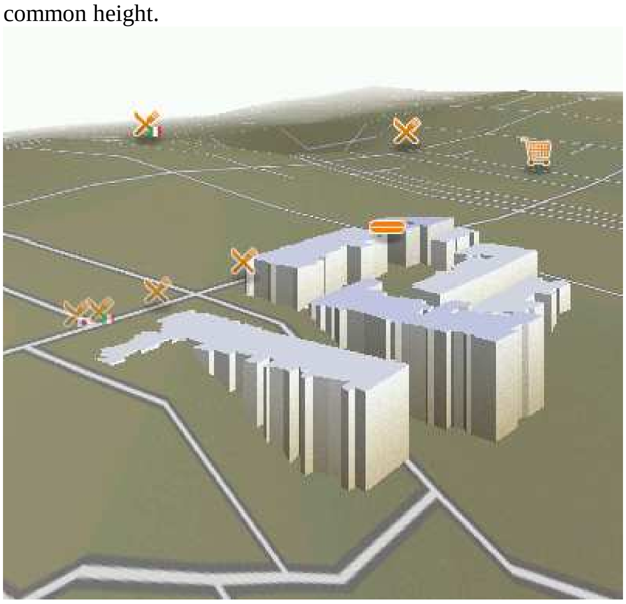

Figure 7. Aggregation without consideration of terrain.

On the contrary, in Figure 8, the same buildings were aggregated with the approach introduced in this paper. Hence, the leftmost building is aggregated since it is built on completely flat terrain. Allowing a very small error the remaining buildings were rejected from aggregation and fit to the terrain.

Figure 8. Terrain-dependent aggregation.

6. CONCLUSION AND DISCUSSION

The aim of this paper was to introduce an issue which has not been addressed in the literature yet. Because the fusion of different data sources is of increasing importance, strategies for their integrated processing including their mutual dependencies have to be found. In this paper we discussed the issue of aggregating city models when they are used in combination with terrain models, proposed an error function and introduced a strategy to limit the inherent error. Moreover, we proposed a technique for further visual improvement. In the following, we discuss the results and present our future work.

The solution introduced in this paper is a quite pragmatic way to solve the problem which arises by aggregating buildings for terrain-supported visualizations and simulations. However, the results may not be optimal, since the error arising by aggregating buildings on terrain depends on the combination of grouped buildings. The naïve approach of testing each combination in order to find the minimum error works for small city models, but for bigger sets of buildings the combinatorial explosion impedes its application. Hence, a more sophisticated strategy could improve the proposed method. In our future work, improved error functions will be introduced and evaluated. Furthermore, as Haunert, 2008, successfully employed for the case of area aggregation, global optimization strategies like linear programming will be applied in order to find good results by a reasonable computational complexity.

Moreover, big buildings defined in original city models (e.g., factory buildings) which are used in combination with terrain models may have a significant inherent error. In order to improve their usability with terrain models, upsampling techniques could be used prior the terrain-dependent aggregation process.

In this paper, we only addressed city models of the lowest level of detail. However, in our future work, aggregation techniques for city models of a higher level of detail (i.e., with roofs) will be extended in order to also cope with terrain models. This is going to be achieved in the same way: By using the actual differences between the heights of the buildings instead of the heights over a virtual "ground plane" (for each building) in the criteria for the decision if the aggregation is valid and in cost functions for an optimizing approach. For gabled roofs, for example, there would be additional constraints postulating that the angle between the ridge lines and the differences between the slopes and the heights of the eaves and gables of the different roofs must not exceed a certain threshold. The development of more sophisticated criteria and sensible values for the different thresholds are topics for further research in this area.

Finally, terrain models are often rendered with multiple levels of detail in order to improve the rendering performance. As shown in this paper, the buildings of city models have to fit the individual terrain model, i.e., the inclinations of its tiles. Hence, in order to support rendering techniques for continuous level of detail, the city models would have to be stored in parallel at different levels of detail. The drawback of this technique is that it generates a significant amount of overhead. Hence, our future research is aiming at developing strategies for storing multiple levels of detail for city models by minimizing the amount of overhead.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

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