Repair and generalization of hand-made 3D building models

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Abstract
Many 3D GIS applications require 3D building models with different LoD (Level of Detail) that satisfy certain quality criteria. However, because of their complexity, most detailed 3D building models available are still produced manually, which results in inevitable geometric and topological errors. These errors hinder the downstream processing of such models. And existing researches on LoD production either focus on the simplification of smooth polygonal mesh or the generalization of regular prismatic building models. The generalization of detailed 3D building models is still immature. Aiming at producing cleaned models of different LoD for existing hand-made 3D building models, this paper starts by investigating two typical modeling errors of such models, incompleteness and separation. Repair methods with reasonable assumptions of buildings are then proposed for each type of errors. The generalization method based on morphological operations is then employed, coupled with model repair, to generate error-free simplified models.

Keywords: Hand-made 3D building model, LoD, Model repair, Generalization

1. Introduction
Three-dimensional building models have recently become increasingly available in many cities around the world (Döllner et al., 2006; Gruen, 2008; Li et al., 2010). They are used for various applications like 3D GIS, urban planning, noise modeling etc. Because of the limitations of photogrammetry-based modeling techniques, many of the building models, especially those with rich details, are still made by hand using interactive modeling software (Yin et al., 2009; Musialski et al., 2012). In the field of computer graphics, this kind of models is usually treated as triangle soups as they are produced mainly for visualization purpose, without consideration for the geometric and topological consistency (Gröger and Plümer 2012a). Therefore the models are often not modeled by (closed) solids and may contain many artifacts, which make them impossible to be used in most downstream applications such as geometric process and GIS analysis (Campen et al., 2012).

Besides the quality issue, the detailed 3D building models often exceed the capability of human perception and of computing hardware. The generalization or simplification of such models is thus a common choice to produce models of simpler version to meet different requirements. However, existing generalization methods are proposed mainly for regular prismatic building models, which cannot handle more complex aggregate models (Meng and Forberg, 2006; Sester, 2007). And most simplification methods are proposed for smooth mesh surfaces, thus could not keep the characteristics of man-made objects, such as buildings (Glander and Döllner, 2009). More seriously, due to the geometric and topological errors of the input model, many of the existing generalization operations may result in unexpected artifacts or simply fail to work. Thus the production of different LoDs (Levels of Detail) for hand-made building models is often time consuming manual work.

In this paper, the focus is on two typical modeling errors of hand-made 3D building models, i.e. *incompleteness* and *separation* (described in section 3). These two kinds of errors are usually caused by the modeling principles adopted in practice (Mohurd, 2010) and are different from generic geometric and topological errors such as holes, gaps and non-manifold issues which have been intensively studied (Botsch et al., 2007; Campen et al., 2012). They do little harm to the model appearances (for the viewer) but are fatal for other analytical applications that require watertight input. By repairing the error of *incompleteness* (described in section 4), further processing such as generalization (described in section 6) can be conducted on the cleaned output models. The generalization, in turn, can eliminate trivial features during the repair of *separation* (described in section 5), which reduces the computation costs and complexity of model repair.

After these processes, correct 3D building models with desired LoD can be produced. The value of existing 3D building models will be added substantially and the investments in constructing 3D city models will pay off because of higher sustainability of the built information.

2. Related work

2.1. Model repair

There are plenty of researches on the model repair for geometric and topological errors present in polygonal mesh and CAD models (Ju, 2009; Campen et al., 2012). The existing methods can be classified into two categories: the surface-based and the volume-based methods. The surface-based methods detect and repair artifact directly on the input models (Liepa, 2003). These methods work on the local part of the input and thus perform fast. The overall shape of the model can also be kept. However, 3D building models lack the local continuity as smooth mesh does (walls are often at 90 degrees). So the surface based repair methods can not produce satisfied results on such models (Botsch et al., 2007).

The volume-based methods first convert the input model into a volumetric representation (based on voxels). Model repair is then conducted in the volumetric domain. Finally, the surface of the resulting model is extracted (Nooruddin and Turk, 2003; Ju, 2004; Bischoff et al., 2005). These methods are usually robust and they can produce watertight surfaces automatically. However, the shortcoming is that the volumetric representation may introduce sampling artifacts to the input model, even for the structure preserved method (Bischoff et al., 2005).

As far as we know, model repair for 3D building models is still a new research area. Gröger and Plümer (2012a, b) focus mainly on the rules and axioms for consistent model representation and updating. In Akca et al. (2010), the geometric accuracy rather than geometric and topological quality is the major concern. More relevantly, Ledoux et al. (2009) propose methods to validate the GML solids based on a volumetric representation, but use constrained tetrahedralizations instead of voxels. Bogdahn and Coors (2010) and Wagner et al. (2012) propose a model healing pipeline for 3D building models, in both geometric and semantic aspects. However it only repair simple errors such as missing surfaces and orientations of normals. Our work share the similar goal of these methods but the difference is that this work focuses more on the typical modeling errors found in a hand-made model rather than generic geometric and topological errors.

2.2. Building generalization

Since the introduction of LoD concept in 1976 (Clark, 1976), many mesh simplification algorithms have been proposed (Luebke et al., 2003; Cohen and Manocha, 2005). The basic idea is to allocate triangles adaptively according to the local complexity of surface. However, they are proposed mainly for smooth polygonal mesh, such as scanned models. Typical characteristics of a building, like parallelism, symmetry and perpendicularity of walls are not kept well (Poupeau and Ruas, 2007). The 3D generalization research commonly incorporates more generalization operations such as aggregation, deletion, and typification (Anders, 2005; Kada, 2007; Guercke et al., 2011). However, most of the methods are extended from traditional 2D generalization, thus are applicable to prismatic 2.5D building models. Although some approaches use techniques from the mesh simplification to deal with irregular building shapes, they do not handle aggregate models (Kada, 2002; Thiemann and Sester, 2004).

3. Definition of *Incompleteness* and *Separation*

The source of the error of *incompleteness* is that modelers tend to model visually satisfied buildings with least efforts. As a result, invisible parts of the model such as the bottom plane of a building component as well as interior parts of a model which are hidden by the exterior surface are often left unmodeled (Figure 1). In another case, building installations like balcony and railings are usually modeled based on lower dimension representation such as a composite surface rather than solid representation (Figure 1) which often triggers errors like non-manifold in the downstream processing. This kind of geometric errors[1] caused by partial modeling and abstract modeling respectively are thus termed as *incompleteness*.

[1] The geometric error is the artifact on the surface of a model.

Hand-made 3D building models also often contain topological errors[2]. By using the model library in the modeling phase, a building is usually modeled by assembling building components modeled separately. This results in an aggregate model in which building components probably intersect or touch with each other (Figure 2). These separated models should be combined seamlessly in geometry to express the correct topology. We name such kind of errors *separation*.

The taxonomy of the modeling errors discussed in this paper is demonstrated in Figure 3. Generic geometric and topological errors mentioned previously could also occur on this kind of models. However, many methods and tools exist for healing these errors (Campen et al., 2012). We thus assume that the input model is free of these errors in this study.

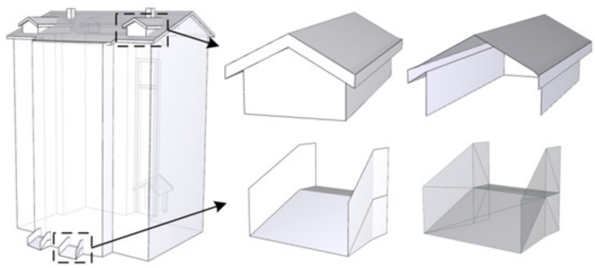

Figure 1 Illustration of the error of *incompleteness*. (right-top: the dormer's front view and back view, in which only the visible part of the dormer is modeled; right-bottom: the railing's shaded view and wireframe view, in which the object is modeled using surfaces)

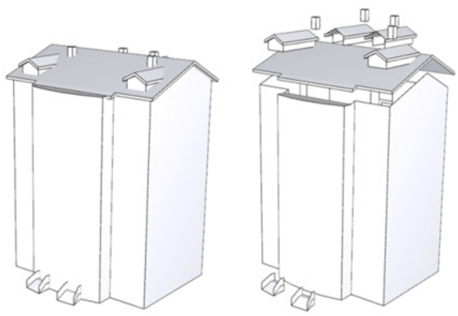

Figure 2 Illustration of the error of *separation* (left: the original model; right: the exploded view of the model which shows the separation of model components)

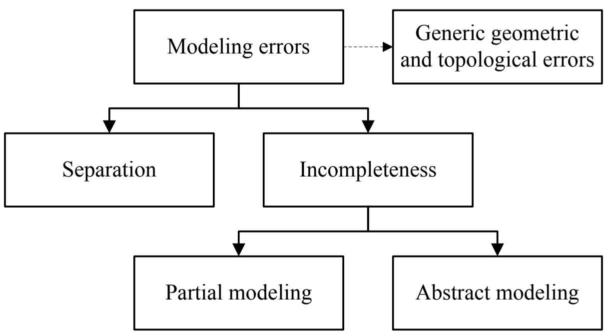

Figure 3 Demonstration of the error taxonomy

[2] The topological error indicates the invalid relationship or connectivity between different model components.

4. Repair method for *incompleteness*

Because the hand-made building models usually contain little semantic information, the errors should be detected geometrically.

A model is considered closed if it is represented by a compact 2-manifold with no boundary (boundary is composed by edges attached with only one face). Since the case of partial modeling leaves invisible faces of a solid unmodeled and since abstract modeling produces surfaces rather than solid, the detection of boundaries is therefore the first step to locate a possible error of *incompleteness*.

After a boundary is detected, one cannot directly close it because unexpected structures can be created in abstract modeled building components. Instead, which of the two cases of error (i.e. intentionally left out details or the use of aggregated surfaces) should be further determined. This is a difficult task because both cases would have similar boundary shapes. Thus some assumptions of building models should be introduced.

The first one is *integrity*. It assumes that all the components of a building model should be integrated with no visible gaps, in other words, either intersect or touch with each other. This assumption is derived from the basic requirements of a modeling task. With this assumption, boundary of a partial modeled building component will be hidden by the surface of its neighbor components. Therefore, we first detect its neighbor components by the intersection test of faces. Then the triangles intersected are re-triangulated and the component is finally closed by triangulating the cross section. The hidden part of the model, which is defined by a connected component with the boundary, should be eliminated (Figure 4).

Some instances of partial modeling, such as the neglect of the bottom plane when a building touches the ground, cannot be directly healed using the above method. However, this error can be repaired using the triangulation of the intersection results of the component with a virtual ground plane as shown in Figure 5. It should be noted that it cannot be guaranteed that the intersection result is always a set of closed polygons in practice. This requires more complex healing procedures which include the repair of polygons in 2D and the hole filling in 3D.

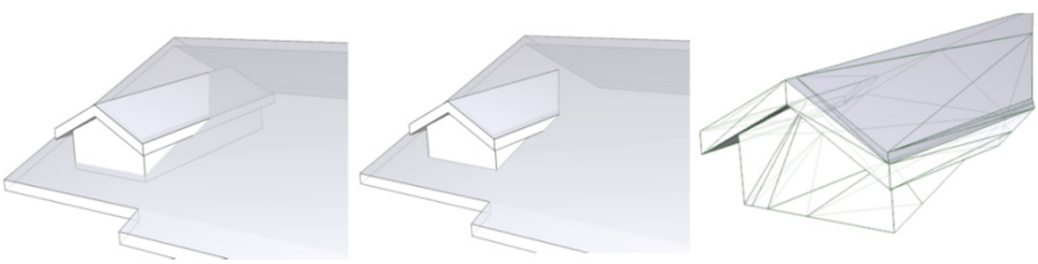

Figure 4 The repair of error of partial modeling (left: the original dormer; middle: intersection with the roof; right: the closed result)

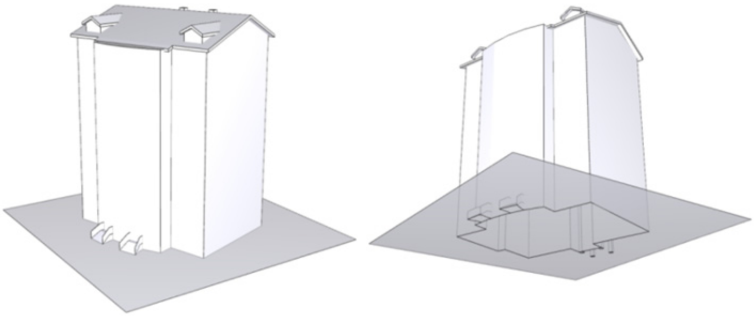

Figure 5 The intersection of the building model with a virtual ground plane

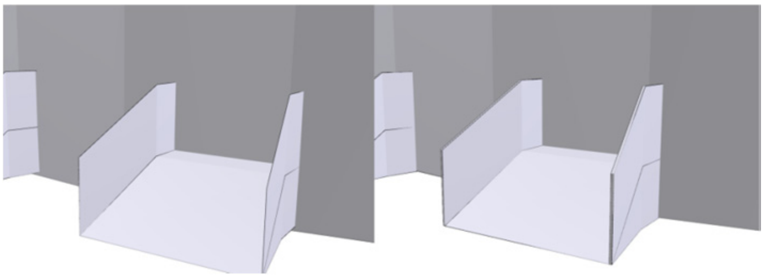

Figure 6 The repair of error of *abstract modeling* (left: the original railing; right: the extruded railing)

After this process, the partial modeled components will be closed. However, boundaries will still be detected for the abstract modeled building components (or there might be no intersected neighbor faces detected for such kind of components). It is because the abstract modeled parts are always visible and not all of the boundaries of these models are hidden by other components or at the bottom. This is the second assumption introduced in this paper, termed *visible abstraction*. With this assumption, if a component still contains boundaries after the repair of *incompleteness*, the previous repair process should be rolled back and such component models should be converted into solid representation instead.

Because the abstract modeling always uses surfaces to represent a solid, the surfaces should be extruded to form a solid. The question here is the choice of the direction of extrusion. One cannot simply use the normal of a surface because sometimes the orientations of faces on a hand-made model are not modeled correctly due to the double-sided rendering. Thus the compromise choice is to extrude the surface in both directions. This would cause some minor mismatches especially when the surface is on the edge of its neighbor component. However, it can be acceptable when the distance of extrusion is small, as demonstrated in Figure 6. It is also possible that both kinds of errors might exist in the same component. In this case, the introduced approach will extrude the surfaces into solids which guarantee the validity of the component.

5. Repair method for *separation*

After repairing the error of *incompleteness*, all the building components should be closed 2-manifolds. Then the error of *separation* can be repaired using morphological operations and Boolean operations.

This method is similar to the handling of masonry structure in (Zhao et al., 2012). For components that touch with each other, firstly, both the components are dilated at a user defined scale parameter. Then, the adjacent components will intersect. The Boolean operation, Union is then employed to combine the intersected components. Finally, the combined model is eroded to restore its original size. For components that already intersect with each other, the Union operation can be employed directly.

As stated at the beginning of this paper, the purpose of this paper is to produce cleaned LoDs for building model. It will be shown in the next section that some generalization steps should be conducted before the repair of *separation* because some of the components may be eliminated during generalization, which can reduce the costs of the repair work for *separation*.

6. 3D Building generalization based on morphological operation

The purpose of generalization for a 3D building model is to progressively eliminate insignificant features of the model while maintaining the general shape of the building. In this paper, features of a 3D building model are evaluated geometrically without concerning about its perception or cognition importance. Therefore, the small protrusions and notches of a building component or a small and thin building component itself can be treated as insignificant features. The quantitative indices to describe the importance of feature can be various, such as the volume of the bounding box of a component, the volume of the component, or the area of the surface of the component. However, the bounding box is not suitable for long and thin features. And the volume and area are not easy to calculated because the feature should be extracted first, which needs sophisticated methods (Lee, 2005).

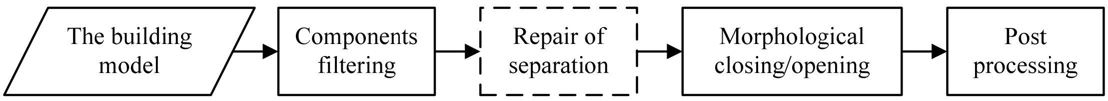

Figure 7 The generalization pipeline (Boxes with solid lines show the generalization processes)

The morphological operations implemented in this research provide a concise way to eliminate insignificant features progressively. The whole generalization includes three steps as illustrated in Figure 7. The first one is the components filtering. In this step, the morphological operation of erosion with a given scale parameter is performed on all the building components as a filter. All the components that are thinner or shorter than the scale parameter will be deleted (as illustrated in Figure 8). After the process, the error of *separation* is repaired using the previously introduced method. To further eliminate notches and protrusions, the morphological operations of closing and opening are employed (Zhao et al., 2012). The results are demonstrated in Figure 9).

Since the morphological operation may introduces redundant triangles to the model, mesh simplification method such as QEM (Garland and Heckbert, 1997) is deployed as post-processing to further optimize the result. Figure 10 shows the generalization results of a hand-made dataset that have been generalized following the above procedure. The similar morphology based method for 3D generalization has been proposed by (Mayer, 2005; Forberg, 2007). However, their method requires the squaring of the model. The approach deployed in this paper is more generic by exploring the capability of Minkowski sum based on Nef-polyhedron (Hachenberger, 2007).

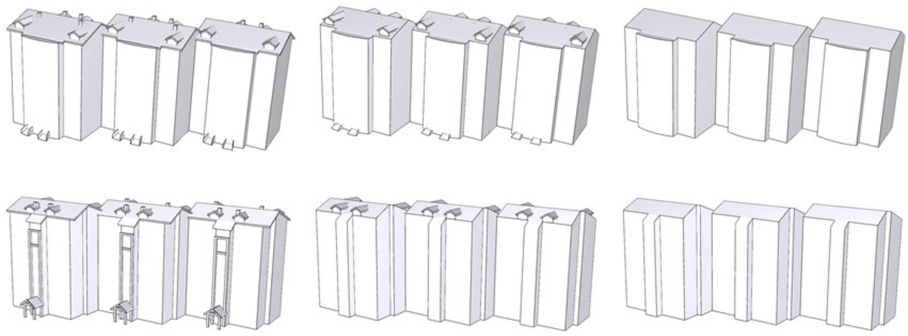

Figure 8 Building components filtering (top: the front view; bottom: the back view, in which trivial components are gradually eliminated)

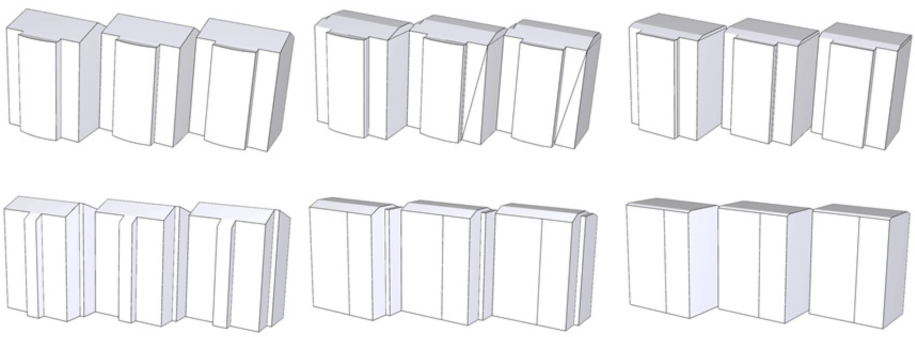

Figure 9 The result of morphological opening (top: the front view; bottom: the back view. The input is the result of components filtering and the protrusions are gradually eliminated)

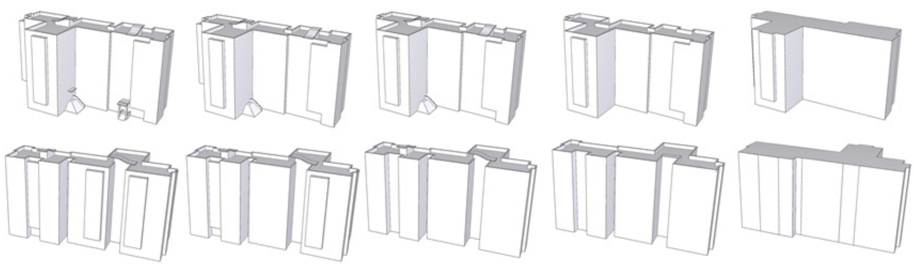

Figure 10 The generalization results of a hand-made building model (The number of triangles from left to right: 739, 623, 587, 394, 127)

7. Conclusion and Future work

Model repair and generalization are the essential processes for hand-made 3D building models to be fully used in GIS applications. This paper gives an attempt to investigate the errors of such kind of models. Then the repair algorithms are proposed for the errors of *incompleteness* and *separation*. To generate models of different LoD, generalization methods based on morphological operations are introduced. By assigning different scale parameters, the insignificant features of the building can be eliminated gradually.

The computing complexity of the generalization algorithm is up to the implementation of Minkowski sum, which is $O(n^3m^3)$ in CGAL[3](CGAL, 2010). Further researches include the review of all kinds of modeling errors for 3D building models and the assessment of the proposed methods on more datasets. The effectiveness of different indices for evaluating importance of features should also be studied. Finally, more rules and knowledge of the building model can be incorporated to guide the repair and generalization processes.

Acknowledgements

This work is supported by the National Natural Science Foundation of China (41201379 and 41171311), the Dutch Technology Foundation STW, which is part of the Netherlands Organization for Scientific Research (NWO) and partly funded by the Ministry of Economic Affairs, Agriculture and Innovation. (Project code: 11300).

References

Akca, D., Freeman, M., Sargent, I. and Gruen, A., 2010. Quality assessment of 3D building data. The Photogrammetric Record, 25(132): 339-355.

Anders, K.H., 2005. Level of Detail generation of 3D building groups by aggregation and typification, *Proceedings of the 22nd international cartographic conference: mapping approaches into a changing world*, A Coruña, Spain, 9-16 July., pp. 8.

Bischoff, S., Pavic, D. and Kobbelt, L., 2005. Automatic restoration of polygon models. *ACM Transactions on Graphics (TOG)*, 24(4): 1332-1352.

Bogdahn, J. and Coors, V., 2010. Towards an automated healing of 3D urban models. In: T. Kolbe, G. König and N. Claus (Editors), *Archives of Photogrammetry, Remote Sensing and Spatial Information Science*, *Vol XXXVIII-4/W15 (3D Geoinfo 2010)*. Aachen: Shaker Verlag GmbH, pp. 13-17.

Botsch, M. et al., 2007. Geometric modeling based on polygonal meshes, *ACM SIGGRAPH 2007 courses*. ACM New York, NY, USA.

Campen, M., Attene, M. and Kobbelt, L., 2012. A Practical Guide to Polygon Mesh Repairing. The Eurographics Association.

CGAL, 2010. Computational Geometry Algorithms Library, http://www.cgal.org.

Clark, J.H., 1976. Geometric models for visible surface algorithms. *Communications of the ACM*, 19(10): 547-554.

Cohen, J.D. and Manocha, D., 2005. Model simplification. In: C.D. Hansen and C.R. Johnson (Eds.), *The Visualization Handbook*. Academic Press, Inc, Orlando, pp. 393-411.

Döllner, J., Kolbe, T.H., Liecke, F., Sgouros, T. and Teichmann, K., 2006. The virtual 3D city model of Berlin-managing, integrating, and communicating complex urban information, *Proceedings of the 25th International Symposium on Urban Data Management*. Citeseer, Aalborg, Denmark, pp. 15-17.

Forberg, A., 2007. Generalization of 3D building data based on a scale-space approach. *ISPRS Journal of Photogrammetry and Remote Sensing*, 62(2): 104-111.

[3] n and m indicate the complicities of the two input polyhedra

Garland, M. and Heckbert, P.S., 1997. Surface simplification using quadric error metrics, *Proceedings of ACM SIGGRAPH '97*. ACM press, New York, LA, US, 3-8 August, pp. 209-216.

Glander, T. and Döllner, J., 2009. Automated Cell-Based Generalization of Virtual 3D City Models with Dynamic Landmark Highlighting. In: T.H. Kolbe, H. Zhang and S. Zlatanova (Eds.), GeoWeb 2009 Academic Track - Cityscapes, Vancouver, BC, Canada.

Gröger, G. and Plümer, L., 2012a. Provably correct and complete transaction rules for updating 3D city models. *Geoinformatica*: 1-34.

Gröger, G. and Plümer, L., 2012b. Transaction rules for updating surfaces in 3D GIS. *ISPRS Journal of Photogrammetry and Remote Sensing*, 69: 134-145.

Gruen, A., 2008. Reality-based generation of virtual environments for digital earth. *International Journal of Digital Earth*, 1(1): 88-106.

Guercke, R., Gotzelmann, T., Brenner, C. and Sester, M., 2011. Aggregation of LoD 1 building models as an optimization problem. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66(2): 209-222.

Hachenberger, P, 2007. Exact Minkowski sums of polyhedra and exact and efficient decomposition of polyhedra in convex pieces. Proc.*15th Annual European Symposium on Algorithms* (ESA), Eilat, Israel.

Ju, T., 2009. Fixing geometric errors on polygonal models: a survey. *Journal of Computer Science and Technology*, 24(1): 19-29.

Kada, M., 2002. Automatic generalisation of 3D building models, *Proceedings of the Joint International Symposium on Geospatial Theory, Processing and Applications*, Ottawa, CA, pp. 243-248.

Kada, M., 2007. 3D building generalisation by roof simplification and typification, *Proceedings of the 23th International Cartographic Conference*, Moscow, Russian Federation.

Ledoux, H., Verbree, E. and Si, H., 2009. Geometric Validation of GML Solids with the Constrained Delaunay Tetrahedralization, Proceedings of the 4th International Workshop on 3D Geo-Information, Ghent, Belgium.

Lee, S.H., 2005. Feature-based multiresolution modeling of solids. *ACM Transactions on Graphics* (TOG), 24(4): 1417-1441.

Liepa, P., 2003. Filling holes in meshes. *Eurographics Association*, pp. 200-205.

Li, Z., Huang, X., Zhao, Z. and Jiang, P., 2010. 3D digital map of Wuhan: construction and application demonstration. *Geospatial Information* (003): 1-4. (In Chinese)

Luebke, D. et al., 2003. Level of Detail for 3D graphics. Morgan Kaufmann, San Francisco.

Mayer, H., 2005. Scale-spaces for generalization of 3D buildings. *International Journal of Geographical Information Science*, 19(8): 975-997.

Meng, L. and Forberg, A., 2006. 3D building generalisation. In: W. Mackaness, A. Ruas and T. Sarjakoski (Eds.), *Challenges in the Portrayal of Geographic Information: Issues of Generalisation and Multi Scale Representation*. Elsevier Science, pp. 211-232.

MOHURD, 2010. Technical Specification For Three Dimensional City Modeling Of China (In Chinese)

Musialski, P. et al., 2012. A survey of urban reconstruction, *EUROGRAPHICS 2012. State of The Art Report*.

Nooruddin, F.S. and Turk, G., 2003. Simplification and repair of polygonal models using volumetric techniques. *IEEE Transactions on Visualization and Computer Graphics*, 9(2): 191-205.

Poupeau, B. and Ruas, A., 2007. A crystallographic approach to simplify 3D building, Proceedings of the 23rd XXIII International Cartographic Conference, Moscow, Russia.

Sester, M., 2007. 3D visualization and generalization, *51st Photogrammetric Week*, Stuttgart, Germany, 3-7 September, pp. 285-295.

Thiemann, F. and Sester, M., 2004. Segmentation of buildings for 3D-generalisation, *7th ICA Workshop on Generalisation and Multiple Representation*, Leicester, UK, 20-21 August.

Wagner, D. et al., 2012. Geometric-semantical consistency validation of CityGML Models, 3D GeoInfo Conference 2012, Quebec City, Canada, May 16-17.

Yin, X., Wonka, P. and Razdan, A., 2009. Generating 3D building models from architectural drawings: a survey. *IEEE Computer Graphics And Applications*, 1(29): 20-30.

Zhao, J., Zhu, Q., Du, Z., Feng, T. and Zhang, Y., 2012. Mathematical morphology-based generalization of complex 3D building models incorporating semantic relationships. *ISPRS Journal of Photogrammetry and Remote Sensing*, 68: 95-111.