SQUARING AND SCALE-SPACE BASED GENERALIZATION OF 3D BUILDING DATA

Andrea Forberg and Helmut Mayer

Institute for Photogrammetry and Cartography, Bundeswehr University Munich, 85577 Neubiberg, Germany
andrea.forberg@unibw-muenchen.de

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ABSTRACT:

Three dimensional (3D) city models are often visualized using a Level of Detail (LOD) representation. For the automatic generation of coarser representations from detailed 3D building models, i.e., generalization, an approach is introduced which uses the formally well defined theory of scale-spaces, including mathematical morphology and curvature-space. A number of examples shows the potential of the approach. Because buildings are perceived to mainly consist of orthogonal structures and as our previous investigations have shown that generalization based on scale-spaces works best for those, the focus of this paper lies on the squaring of non-orthogonal structures. Results for the automatic elimination of inclined roof-structures for a coarse model are given while the squaring of walls is still under investigation.

1 INTRODUCTION

In order to enhance the performance of an interactive visualization of three dimensional (3D) polyhedral data, the number of polygons to be rendered has to be minimized. This is achieved by a Level of Detail (LOD) representation, where objects that are far away are shown with less detail (cf. Fig. 1).

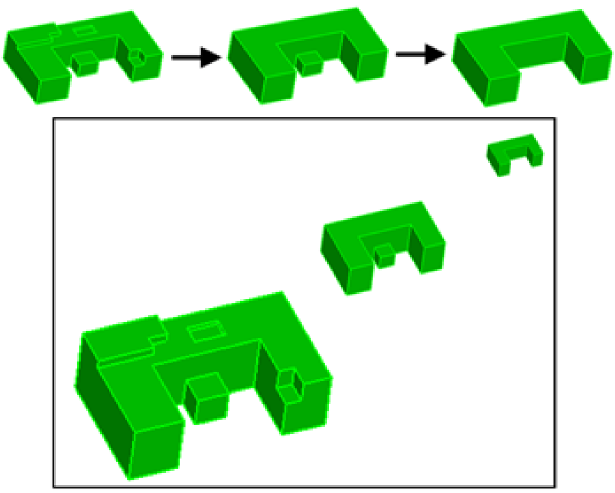

Figure 1. Different Levels of Detail (LOD) of a building automatically generated by scale-space based generalization

The derivation of a coarser representation from a fine-scale 3D model is termed 3D generalization. In this paper the focus lies on the generalization of 3D building models. In computer graphics and computational geometry many approaches for automatic polygon-reduction exist, but most of them are developed for general objects and therefore do not consider building specific properties, e.g., right angles. A good survey on approaches for surface simplification is presented by (Heckbert and Garland 1997). Examples for automatic LOD generation are given by (Varshney et al. 1995) and (Schmalstieg 1996). The approach most relevant to the work presented in this paper is (Ribelles et al. 2001). It treats the problem of finding and removing features from polyhedra in order to coarsen computer aided design (CAD) models based on planar cuts. The approach generalizes naturally to quadric and other implicit surfaces.

Approaches with a cartographical or Geographic Information System (GIS) background, which take into account properties of buildings such as right angles, but mostly focus on 2D generalization, are (Mackaness et al. 1997, Meng 1997, Staufenbiel 1973, and Weibel and Jones 1998). (Sester 2000) uses least squares adjustment for generalization, which is suitable especially for squaring, aggregation, and displacement of building ground plans. One of the rare approaches for automatic 3D generalization of buildings can be found in (Kada 2002). Least-squares adjustment is combined with an elaborate set of surface classification and simplification operations.

In Section 2 an approach for the automatic generalization of 3D building data using the formally well-defined scale-space theory is presented. It is especially suited for orthogonal structures. Therefore, in Section 3 means for the squaring of non-orthogonal 3D structures are introduced. Recent results for the squaring of inclined roof-structures as well as first ideas concerning the squaring of non-orthogonal wall-structures are presented. The paper ends with conclusions and an outlook.

2 SCALE-SPACE BASED GENERALIZATION

2.1 Scale-Spaces in 2D

That scale-space theory together with so-called scale-space events can be used for generalization was already shown by (Li 1996 and Mayer 1998). In scale-space theory the scale-parameter describes the current level of scale. A basic principle of scale-space theory is causality. I.e., when deriving a coarser object-representation from fine scale, every feature in coarse scale has to have a reason in fine scale. For different tasks different scale-spaces are suited best, depending on their specific characteristics.

Linear scale-space is often used in image processing. It combines causality, isotropy, and homogeneity and continuously smoothes the image function (Koenderink 1984). It satisfies the so-called diffusion-equation for which the convolution with the Gaussian Kernel is the solution for an infinite domain. How complex the events occurring in linear scale-space can be is demonstrated in (Kuijper and Florack 2002).

A scale-space with different characteristics is ***mathematical morphology*** (Serra 1982). In this paper the two basic operations erosion and dilation and the two combined operations opening and closing are used, which are defined as follows:

Dilation: $A \oplus B = \{a+b: a \in A, b \in B\} = \cup_{b \in B} A_b$ (1)
Erosion: $A \Theta B = \{a: a+b \in A, b \in B\} = \cap_{b \in B} A_b$ (2)
Opening: $A^\circ B = (A \Theta B) \oplus B$ (3)
Closing: $A \bullet B = (A \oplus B) \Theta B$ (4)

A is the original feature to be processed and *B* is called the structure element (Serra 1982, Su et al. 1997). By varying the size of a usually square or circular structure element, a scale-space complying with the causality constraint is obtained. How mathematical morphology can be employed for the generalization of building data is shown in (Su et al. 1997, Cámara et al. 2000).

Building data usually consists of mostly straight segments. As these have to be preserved, (Mayer 1998) has proposed to realize erosion and dilation for vector data by shifting the segments of the outline inwards or outwards, respectively. In Figure 2 it is shown that erosion in this case results in a split and dilation in a merge of two big blocks.

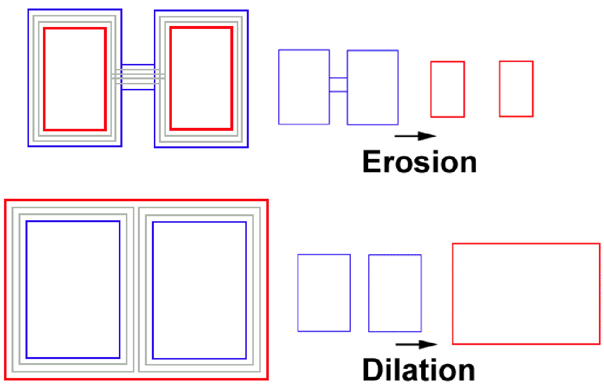

Figure 2. Mathematical morphology applied to vector data - split (top) for erosion; merge for dilation (bottom)

The ***reaction-diffusion***-space is obtained by adding a diffusive component to mathematical morphology (Kimia et al. 1995). The reaction part includes erosion and dilation. The diffusion part, also termed *curvature-space*, is for a small-scale-parameter equivalent to the linear scale-space. For a larger scale-parameter it diverges in a way that only parts with high curvature are eliminated.

When transforming objects from fine scale to coarse scale, on one hand the information can be reduced by means of so-called scale-space events, where parts with too small extent are eliminated or gaps are filled by erosion and dilation, respectively (cf. Fig. 2). On the other hand, by relating the elimination of small parts to the elimination of object parts such as an annex or the closing of gaps to the merge of two building parts into one building, this can be interpreted as a simplification of objects, i.e., an abstraction. Exactly this capability of abstraction makes scale-spaces well suited for generalization.

2.2 Mathematical Morphology in 3D

The procedures described in the following were implemented using Visual C++ and the ACIS class library (www.spatial.com). In 3D dilation and erosion are realized by the movement of all facets of the polyhedral building in the directions of their normals, inwards or outwards, respectively (cf. Fig. 3). In ACIS this is termed offsetting.

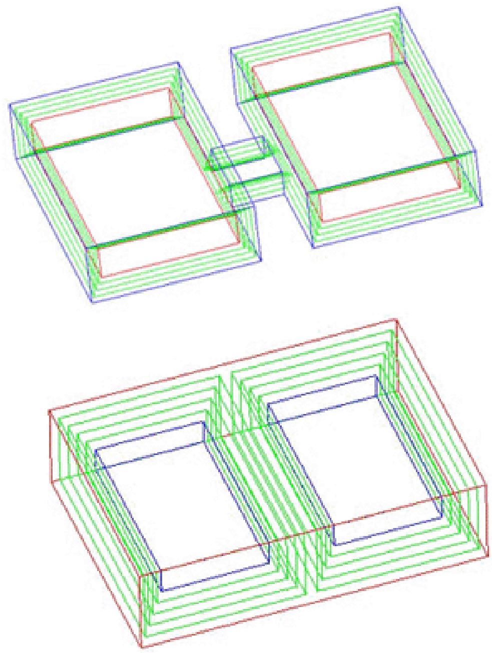

Figure 3. Split (top) and merge (bottom) for erosion and dilation in 3D: blue – original object; green – incremental steps; red – resulting object.

In contrast to erosion and dilation, opening and closing "reset" an object to its original range of size. For small objects such as a local protrusion, inward-moving facets can collide while opening the object, so the protrusion is eliminated. This and similar events for closing occur only in topologically local areas and are therefore termed internal events. External events emerge when topologically non-local segments of a building or arbitrary segments of different buildings touch or overlap while opening or closing (Mayer 1998). Internal and external events are distinguished, because they are differently hard to detect and to handle.

2.3 Curvature-Space in 3D

With mathematical morphology objects can be aggregated or split. Step- / stair-structures and inward- or outward-pointing boxes cannot be eliminated that way. For this task curvature-space is used, where the facets are moved in such a manner that the steps and boxes are eliminated. (Mayer 1998) described this for the two-dimensional case by Z- and L-structures. The 3D-structures corresponding to those are illustrated in Figure 4.

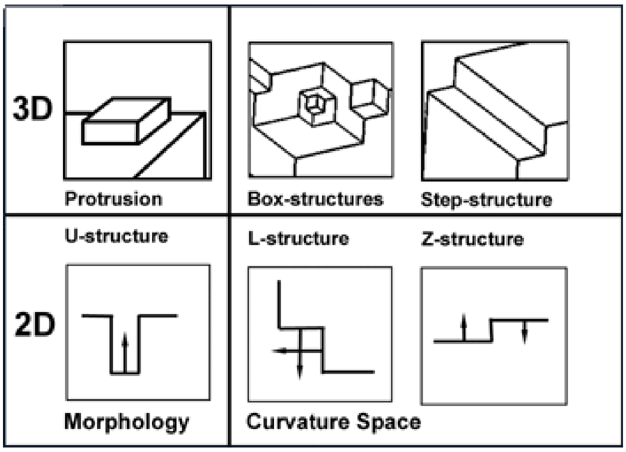

Figure 4. Protrusions, box- and step- / stair-structures in 3D versus U-, L-, and Z-structures in 2D

(Mayer 1998) distinguishes between discrete and continuous curvature-space. In discrete curvature-space only those facets are moved, which belong to stair- or box-structures and for which certain segment lengths are below a threshold. The speed of the movement is the same for all facets. Opposed to this, in continuous curvature-space all facets are moved, but with various distances. A good weight for the speed of the movement was found to be the area of the facets and the length of the corresponding edges.

For this paper operations have been implemented in ACIS, which move a number of facets with the same distance and are in this respect related to discrete curvature-space. But as the decision is based on convexity and concavity (cf. below), i.e., there is no threshold involved, the whole operation is implicitly continuous. Therefore, there will be no distinction made between discrete and continuous curvature-space for the remainder of this paper.

For the decision in what direction facets have to be moved, basic elements such as stairs / steps and outward- and inward-going boxes have to be identified. The differentiating feature was found to be convexity versus concavity. The analysis is described in detail in (Forberg and Mayer 2002). In summary, concave and convex vertices are determined by extending the edges pointing to a vertex and checking the relation of the new endpoints to the object. If the endpoints of all edges belonging to the vertex lie inside the object, it is a fully concave vertex, if they all lie outside, it is a fully convex vertex (cf. Fig. 5).

Depending on the combination of these vertices within a facet, concave and convex facets belonging to box-structures can be determined. If additionally also inflexion points are detected (cf. Fig. 6), where one extended endpoint lies outside and two lie on the boundary of the object, also the concave facets of stair- / step-structures can be found. In curvature-space concave facets are moved outwards and convex facets are moved inwards. The different types of convex and concave facets are illustrated in Figure 6. Results for the detection and elimination of stair- / step- and box-structures, which give an idea of the potential of the approach for the generation of a LOD representation, are shown in Figure 7.

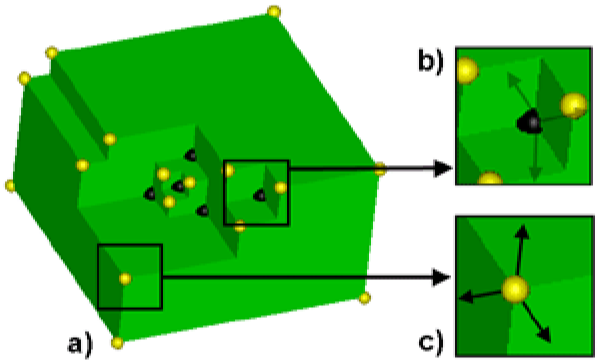

Figure 5. a) Fully convex (yellow) and fully concave (black) vertices, determined by computation of coedge-extension: b) all end points of extended edges inside ⇒ fully concave vertex, c) all end points outside ⇒ fully convex vertex

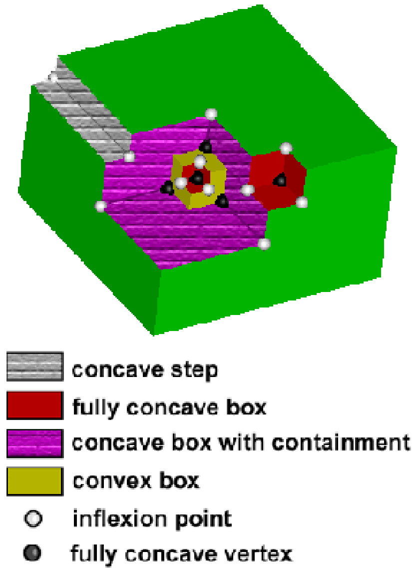

Figure 6. Determination of different types of convex and concave facets

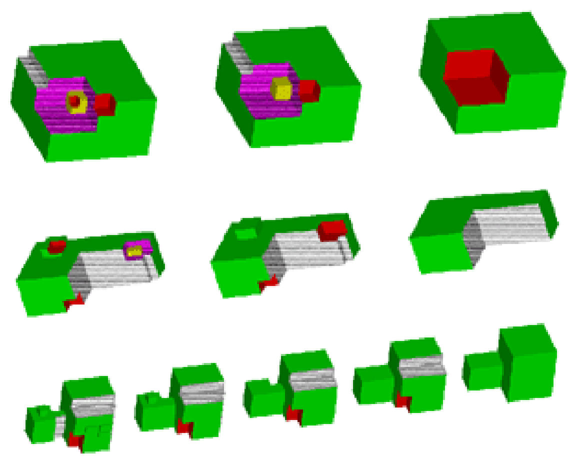

Figure 7. Results for the detection and elimination of stair- / step- and box-structures (several LODs)

The scale-space operations of mathematical morphology and curvature-space work well for orthogonal structures, but inclined structures, especially when the inclination is low, are eliminated rather slowly. For real data the angles between the facets often are not exactly orthogonal. Therefore, an approach for the squaring of structures with small deviations has to be developed. Moreover, even structures that are clearly not orthogonal in fine scale often need to become orthogonal in a coarser scale. E.g., inclined roof-structures will be replaced by flat-roofs in a rather coarse scale. Because squaring can also be understood to be linked to a scale-parameter, it becomes more than only a tool to enhance scale-space operations. It can be conceived as a scale-space operation on its own, although the formal definition of this is not yet clear.

3 SQUARING

The change of angles between facets, which is necessary for squaring non-orthogonal buildings, is termed tapering in ACIS. Before applying tapering to a building, non-orthogonal angles have to be detected and what is even more important, it has to be determined how to change them. Intricate practical but also theoretical problems have to be solved. The most important is, that if the angle between two facets is changed, in most cases other angles of the building will be affected, even those that should be preserved. As a result often a globally more skewed model is obtained. To prevent this, squaring must be tackled from a global and not from a local viewpoint. One way to do this is to take the main directions of the building into account. First results for the elimination of inclined roof-structures are presented in Figure 8, which demonstrates the applicability of the ACIS function. The approach for detecting non-orthogonal structures and for determining the taper angle is described in the following section.

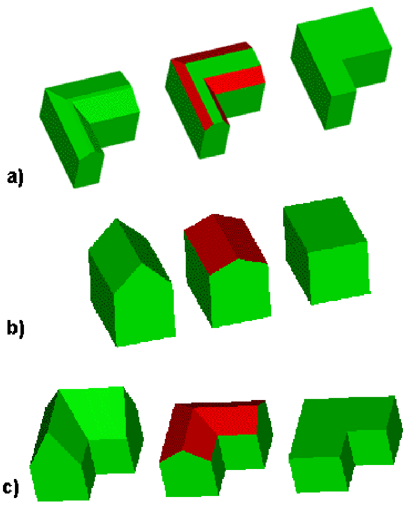

Figure 8. Results for removing inclined roof-structures by means of tapering

3.1 Squaring of roof-structures by means of tapering

In order to eliminate inclined roof-structures by means of tapering, the inclined roof-facets have to be determined. The roof-structures aimed at here all consist of facets that are significantly inclined, i.e., not perpendicular or parallel to the horizontal plane. For each inclined roof-facet the eave-line, i.e., the edge with equal z-values for start- and end-vertex, which is at the bottom of the facet, has to be determined. Then, all inclined facets are rotated, or in ACIS terminology 'tapered', around their eave-lines, until the roof-facets become horizontal (cf. Fig. 9).

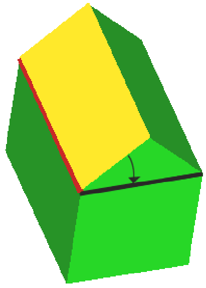

Figure 9. The roof-facet (yellow) is rotated (tapered) around the eave-line (red) until the roof-facet becomes horizontal.

The advantage of using tapering is the automatic treatment of topology-changes by ACIS. A problem occurs when handling differently inclined roof structures of more complex buildings, if vertices are related to four or more facets. In this case, as exemplified in Figure 10, additional elements such as edges or even polygons can be created by tapering. This problem occurs, because the four edges are shifted in a way, that the unique point of intersection is not preserved. In particular, when changing the angle between roof-facets with different inclinations, ridge-lines with different heights are obtained.

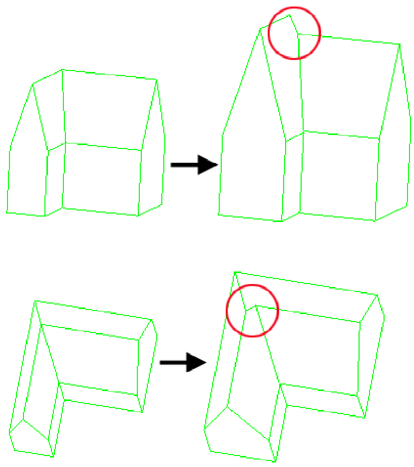

Figure 10. Differently inclined roof-facets can lead to unsatisfactory results when tapering, because no unique intersection point exists due to different heights.

To overcome this problem, another approach for the elimination of inclined roof-structures was developed. Instead of changing the angle between the facets, the ridge-line is moved downwards, until it has the same height as the eave-lines.

3.2 Squaring of roof-structures by moving the ridge-line vertices

Again, all inclined roof-facets are determined. Instead of the eave-lines, the ridge-lines are computed. These consist of vertices with the largest z-value within an inclined facet. These vertices are shifted downwards until they have the same z-values as the vertices of the eave-lines (cf. Fig. 11).

This has the advantage, that there is no problem with differently inclined roof-facets, as all ridge-line vertices are shifted downwards by the same height, independently of the inclination of the individual facets. For the time being the only problem is the handling of topology-changes. Contrary to the application of a specific ACIS-function, for the movement of vertices, these are not handled automatically.

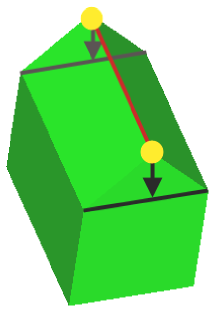

Figure 11. Movement of vertices: The vertices of the ridge are shifted downwards until they have the same height as the eaves.

Besides this problem, which hopefully will be solved soon, the shifting of the ridge-lines provides a rather general procedure for the elimination of inclined roof-structures. On the other hand, for wall-structures, i.e., vertical or almost vertical facets, which can assume any angle, another method has to be found. For this, tapering seems to be well suited.

3.3 Squaring of wall-structures

For walls in most cases strong deviations from the right angles have to be preserved in order to obtain the characteristic shape of a building (cf. Fig. 12, top), even when the model is coarse enough to eliminate its roof-structure. Yet, for small deviations of an only approximately orthogonal building, squaring is required. Additionally to the fact that a building is usually perceived to be made up mostly of right angles, only by squaring a reasonable application of the scale-space operations can be achieved (cf. Fig. 12, bottom).

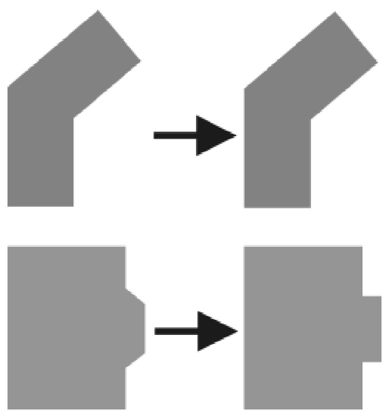

Figure 12. Strong inclinations have to be preserved for large structures (top), whereas small parts need to be squared (bottom)

Compared to the elimination of inclined roof-structures, the squaring of walls is more difficult. There is no predefined (vertical) reference direction to compare the facets with. Whereas only the deviation from the vertical direction is needed in order to determine inclined roof-facets, here the walls can be oriented arbitrarily with respect to the X- axis of the world coordinate system. Thus, for the determination of non-orthogonal wall-facets first the main directions, i.e., the X'- and the Y'-axis of the local coordinate system of the building, have to be determined. In case of the building shown in Figure 12 (top) this is, e.g., ambiguous. If the orientation of the local coordinate system has been computed, the facets, which are not parallel to the main directions, can be classified as inclined wall-facets (cf. Fig. 13).

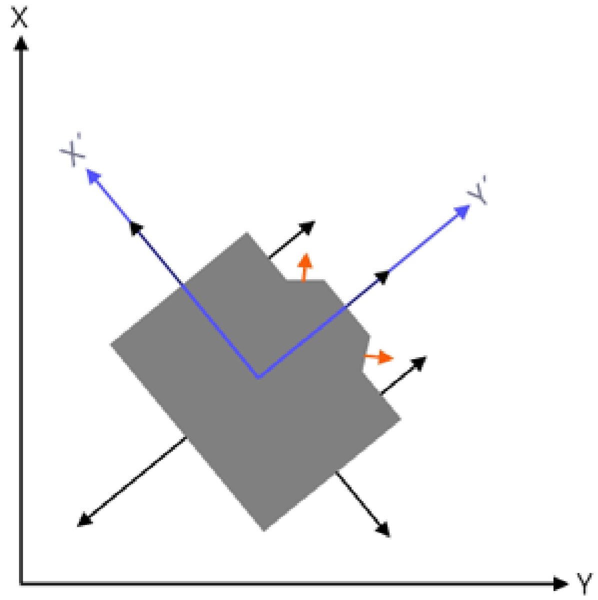

Figure 13. View from the top: X, Y: World coordinate system; X', Y': Local coordinate system; Black arrows: wall-facets parallel to main directions; Red arrows: wall-facets deviating from main directions

The decision, if a wall-structure has to be squared, or if it has to be preserved, can depend on the size of the structure. The details of the procedure, i.e., the exact means for identifying the main directions of a building, the decision if a structure has to be squared or not, and, in case of a squaring, the decision about which edge and with which angle a facet has to be tapered in order to get a reasonable result, still need to be investigated in more detail. As it can be partly treated as a 2D problem, already existing solutions from 2D generalization, e.g., the approach of (Sester 2000, Sester 2001), will be analyzed and adapted to 3D squaring in future.

4 CONCLUSIONS AND OUTLOOK

Using scale-space theory, including mathematical morphology and curvature-space, for the generalization of 3D settlement data, different building types can be simplified. The approach is especially suited for orthogonal models. For an efficient application to non-orthogonal objects, additional procedures for the squaring of slightly distorted angles as well as for the squaring of clearly non-orthogonal structures are needed.

First of all, also squaring can be understood as a scale-space linked to a scale-parameter. The theoretical details of this still need to be further investigated. Then, for 3D squaring a more

global treatment taking into account the main directions has to be employed, in order to avoid a more skewed object. Therefore, the procedures are split into the squaring of roof-structures, i.e., facets that are deviating from the vertical or horizontal direction, and the squaring of walls. The latter is similar to the 2D squaring of building ground plans.
For the squaring of roof-structures, which is important to obtain a rather coarse level of detail, two approaches were introduced. Both work well for a small set of test buildings. The approach based on the movement of the ridge-lines works even for differently inclined structures and therefore provides a more general solution.

Concerning the squaring of walls, existing solutions from 2D will be analyzed and adapted for 3D squaring. In particular, methods for determining the main directions of a building need to be developed. Automatic decisions have to be made about which non-orthogonal structures have to be squared, and which have to be kept, in order to preserve the main character of the building. Finally, it has to be decided, about which edge a facet has to be tapered and for what angle.

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