GENERALIZATION OF 3D BUILDING DATA BASED ON A SCALE-SPACE APPROACH

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ABSTRACT:

In image analysis, scale-space theory is used, e.g., for object recognition. A scale-space is obtained by deriving coarser representations at different scales from an image. With it, the behaviour of image features over scales can be analysed. One example of a scale-space is the reaction-diffusion-space, a combination of linear scale-space and mathematical morphology. As scale-spaces have an inherent abstraction capability, they are used here for the development of an automatic generalization procedure for three-dimensional (3D) building models. It can be used to generate level of detail (LOD) representations of 3D city models. Practically, it works by moving parallel facets towards each other until a 3D feature under a certain extent is eliminated or a gap is closed. As not all building structures consist of perpendicular facets, means for a squaring of non-orthogonal structures are given. Results for generalization and squaring are shown and remaining problems are discussed.

1 INTRODUCTION

The Level of Detail (LOD) concept is a common way to enhance the performance of interactive visualization of polyhedral data. To reduce the number of polygons to be displayed, objects, that are closer, are represented with more detail than objects that are far away (cf. Fig. 1).

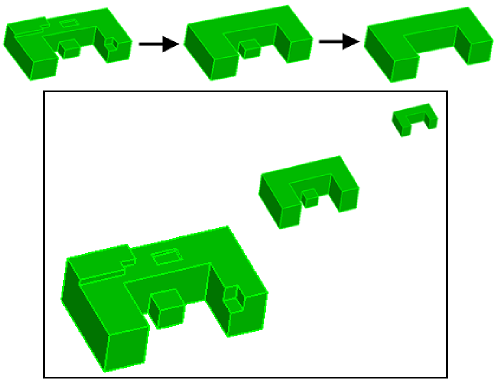

Figure 1: Different Levels of Detail (LOD) of a building automatically generated by scale-space based generalization

The focus of this work lies on the simplification of three dimensional (3D) building data for the generation of LOD representations of city models. For the automatic derivation of coarser models from a fine-scale model, i.e., for 3D generalization, different approaches from computer graphics and computational geometry exist. Most of them are developed for general objects and do not consider the specific structure of buildings, which consist mainly of right angles. (Heckbert and Garland 1997) give a summary of common approaches for surface simplification. Approaches for automatic LOD generation are represented by (Varshney et al. 1995) and (Schmalstieg 1996). An important approach for the simplification of objects with perpendicular structures is given by (Ribelles et al. 2001). In order to obtain a coarser representation for computer aided design (CAD) models, features of polyhedra are found and removed based on planar cuts. The approach can be generalized to deal with quadric and other implicit surfaces.

Approaches from cartography or Geographic Information Systems (GIS) take into account the properties of buildings, but mostly focus on 2D generalization. Some of them are described by (Staufenbiel 1973, Mackaness et al. 1997, Meng 1997, and Weibel and Jones 1998). An approach, which applies least squares adjustment for generalization of building ground plans, can be found in (Sester 2000). (Kada 2002) presents one of the rare approaches for automatic 3D generalization of buildings. A least-squares adjustment is combined with an elaborate set of surface classification and simplification operations. Another work on 3D generalization of buildings is (Thieman 2002), which proposes to decompose a building into basic 3D-primitives. Primitives with a small volume are eliminated.

In this paper 3D generalization is realized based on scale-space theory. In image analysis, a scale-space is obtained by deriving representations at different scale from an image. In Section 2 scale-spaces for 2D images are investigated. Their application to 2D ground plans, i.e., vector data, is described and an approach for a 3D-generalization of orthogonal structures is introduced. As not all buildings consist only of right angles, in Section 3 meanings for squaring non-orthogonal 3D structures are given. The focus lies on the squaring of inclined roof-structures. Results for the simplification of orthogonal structures as well as for the roof-squaring are presented. The paper ends up with conclusions and an outlook.

2 SCALE-SPACE BASED GENERALIZATION

2.1 Scale-Spaces and Image Analysis

Every object has a certain scale range, in which it can be represented. For a wood another scale is appropriate than for a single tree or for the leaves of a branch. For object recognition, it is often reasonable to analyse the image at different scales. In many cases a one-parameter-family of derived signals is generated, where the different representations depend only on the current scale described by the scale-parameter σ. There are several means to generate a scale-space.

In image processing often the ***Linear scale-space*** is used. It is obtained by convolving an image with a Gaussian kernel. It combines causality, isotropy, and inhomogeneity. The most important constraint is causality. This means, that each feature in a coarse scale has to have a reason in fine scale (Koenderink 1984). In Figure 2 it can be seen, that after the convolution (and the additional application of a threshold on the right hand side) the original object is split at one scale and merged at another. Because they can cause these so-called scale-space events, scale-spaces are suited for generalization, especially for simplification and aggregation (Mayer 1998). Scale-space events can be external events such as the split or merge of objects, or internal events, that affect only topologically related object parts, e.g., the elimination of a small protrusion. For the generalization of buildings the linear scale-space has the disadvantage, that corners are rounded and straight lines get lost (cf. Fig. 2).

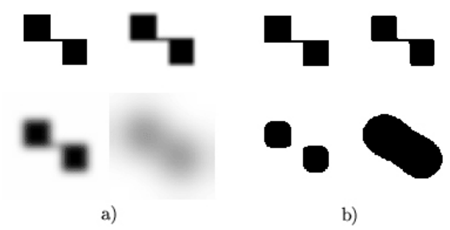

Figure 2: a) An object is convolved with a Gaussian kernel of different sizes, b) After applying a threshold a split and a merge become visible (Mayer 1998).

A scale-space with different characteristics is ***mathematical morphology*** (Serra 1982). The two basic transformations dilation and erosion and the two combined transformations opening and closing are formulated as follows for n-dimensional binary images (Haralick and Shapiro 1992):

Dilation: $A \oplus B = \{c \in E^N | c = a + b \text{ for some } a \in A \text{ and } b \in B\}$ (1)
Erosion: $A \ominus B = \{x \in E^N | \ x + b \in A \text{ for all } b \in B\}$ (2)
Opening: $A \circ B = (A \ominus B) \oplus B$ (3)
Closing: $A \bullet B = (A \oplus B) \ominus B$ (4)

A is the original binary image to be processed and *B* is called structure or structuring element (Serra 1982, Su et al. 1997). By varying the size of a usually square or circular structuring element, a scale-space with a predictable behavior over the scales (causality) is obtained. The basic operations erosion and dilation are combined to opening or closing in order to "reset" an object to its original range of size. Opening eliminates object parts, which are smaller than the structuring element. Closing fills small gaps (cf. Fig.3).

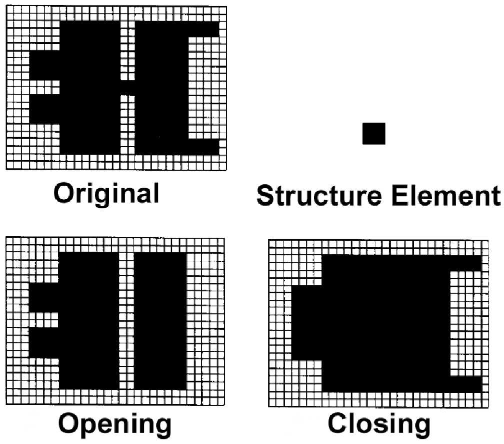

Figure 3: Mathematical morphology for a binary image with a square structuring element. Opening eliminates small parts, closing fills gaps (Su et al. 1997).

A scale-space that combines the two complementary scale-spaces mathematical morphology and linear scale-space is the ***reaction-diffusion-space*** of (Kimia et al. 1985). The reaction part is similar to mathematical morphology, whereas the diffusion part is for a small σ equivalent to linear scale-space. For a large σ it diverges in this respect that only parts with high curvature are eliminated.

2.2 Scale-Spaces for 2D Ground Plans

(Li 1996) and (Mayer 1998) showed, that scale-space theory together with scale-space events are suitable for generalization. For the simplification of 2D vector data, particularly building ground plans, i.e., objects that consist mostly of straight lines arranged in right angles, (Mayer 1998) proposes a process similar to the reaction-diffusion-space. Reaction part and diffusion part are applied sequentially.

The reaction part, i.e., mathematical morphology, is realized by incrementally shifting all segments inwards or outwards, intersecting the segments to preserve the corners. Objects can be split or merged and small protrusions or notches can be eliminated or filled (cf. Fig.4).

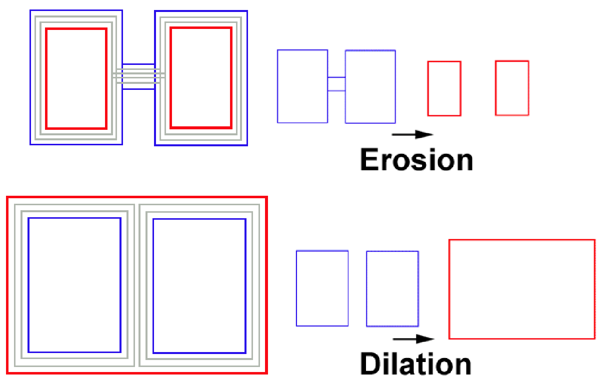

Figure 4: Mathematical morphology applied to vector data - split (top) for erosion and merge for dilation (bottom)

Structures, which describe Z- or L-shapes, cannot be handled by mathematical morphology. For them, a diffusion part is necessary, which is termed “curvature-space” in (Mayer 1998). In contrast to mathematical morphology only specific segments are shifted. The choice which segment has to be moved in what direction depends on the local curvature. Curvature is equated with the occurrence of short segments and (Mayer 1998) distinguishes different treatments for U-, L- and Z-structures (cf. Fig.6).

2.3 Scale-Spaces for 3D Building Data

Our first idea for a 3D generalization also consisted of a sequential processing of mathematical morphology and curvature space. Implemented in Visual C++, using the ACIS class library (www.spatial.com), mathematical morphology was easy to realize by an incremental movement of all facets inwards or outwards with respect to the direction of the normal (cf. Fig.5).

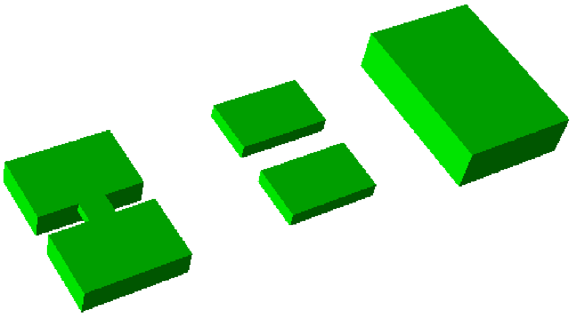

Figure 5: From left to right: original building, result after erosion (split), and result after dilation (merge) in 3D.

Again split, merge, and the elimination of protrusions and notches are possible. Box-structures and step- / stair-structures, which correspond to the L- and Z-structure of the 2D case (cf. Fig.6), have to be handled with curvature space.

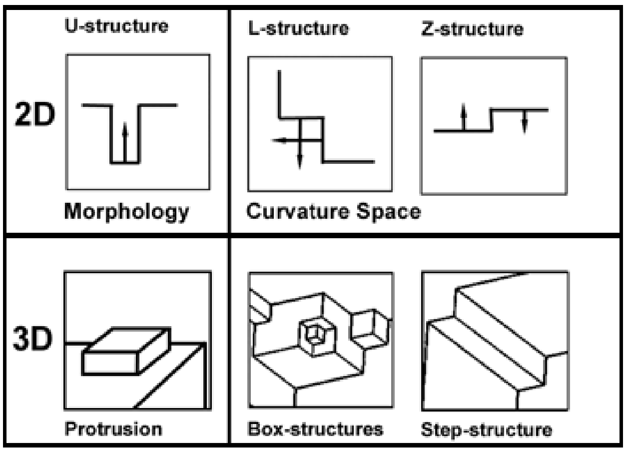

Figure 6: U-, L-, and Z-structures in 2D versus protrusions, box-, and step- / stair-structures in 3D

In (Forberg and Mayer 2002) a complex procedure for curvature space in 3D was introduced. It is based on the analysis of the convexity and concavity of vertices and their relations within facets. Complicated rules were devised, but it was still not guaranteed, that the result is satisfying. Due to the more complex geometry of 3D objects we were not able to consider all cases.

Therefore, instead of using a sequential combination of mathematical morphology and curvature space, a new approach has been developed. It integrates the treatment of external events, protrusions, as well as box- and step- / stair-structures in one single procedure, following a rather simple principle: Parallel facets are determined and the distance between them is computed. If the distance is under a certain threshold, the facets are shifted towards each other until they merge into one facet, regardless of the direction of the facet’s normal with respect to the inside or outside of the object (cf. Fig.7).

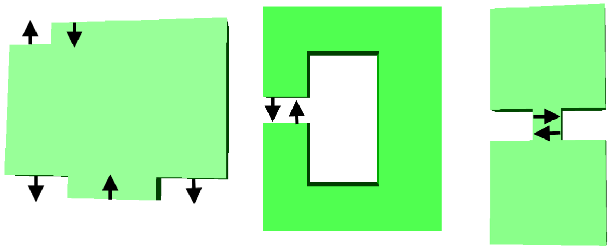

Figure 7. New approach for the generalization of 3D building models. Parallel facets under a certain distance are shifted towards each other.

This rather simple procedure is very general and therefore suitable to cover also complex combinations of orthogonal structures. Besides its simple implementation, it has got the advantage, opposite, e.g., to the approach of (Thiemann 2002), that small structures do not simply vanish, but a shape adjustment takes place (cf. Fig. 8).

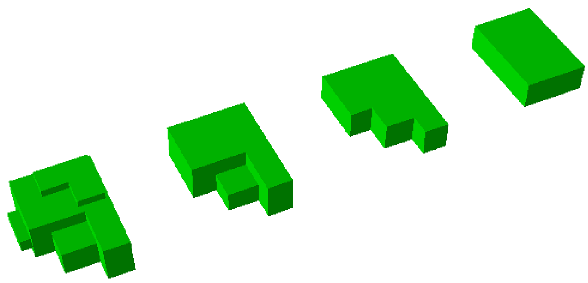

Figure 8: Object parts are not only eliminated, but they are adjusted, so that the characteristic shape is kept.

To intensify this shape-preservation, the distance of the movement for each facet can be weighted depending on the area-relation between the two parallel facets. By now, no weighting algorithm was found, that is suitable for all kinds of orthogonal building structures. Because of that, for the results presented in the remainder of this paper a simple half distance movement was employed. Examples for external events obtained with the approach are given in Figure 9 and 10. Figure 11 shows the elimination of protrusions and a notch, whereas in Figure 12 protrusions and an inward pointing box-structure disappear.

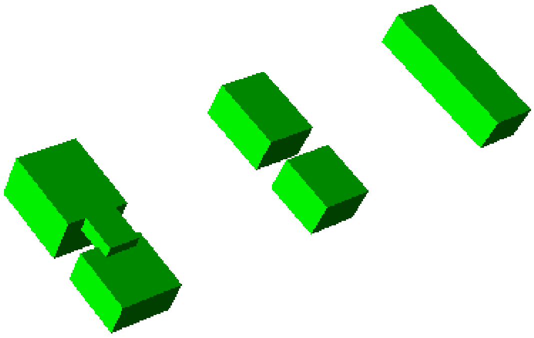

Figure 9: Split and merge of object parts

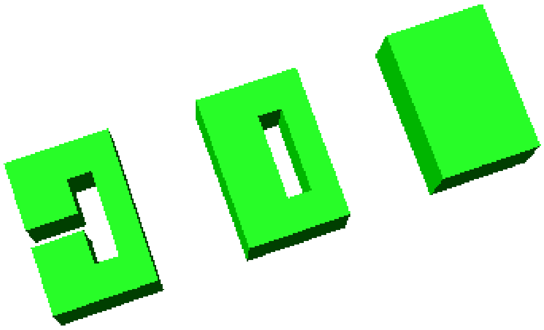

Figure 10: Merge of object parts and filling of a hole

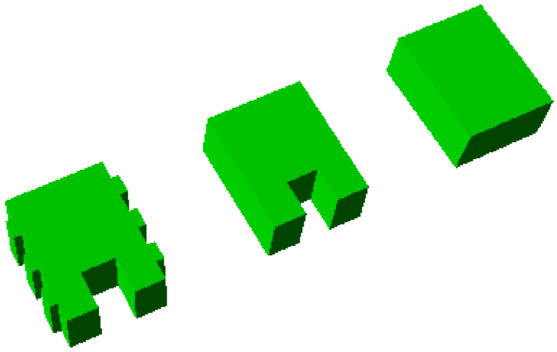

Figure 11: Elimination of protrusions and filling of a notch

In Figure 12 it can be seen, that in some instances constraints have to be added to the algorithm. E.g., the ground plane of a building has to be fixed, so that the building is not hovering in the air after the box-shaped entrance is eliminated. In case one of the parallel facets is lying in the ground plane, it should be fixed and the other facet has to be moved with whole distance between the two facets.

Apart from fixing a ground plane, partial rescaling of the building after the generalization process might be considered, so that the original volume is preserved. It is not trivial to find a good solution, as the changes for each object occur in different directions and sometimes also only for parts of the object. In order to compute the directions and the parts of the object with a need for a volume-reset more research is needed.

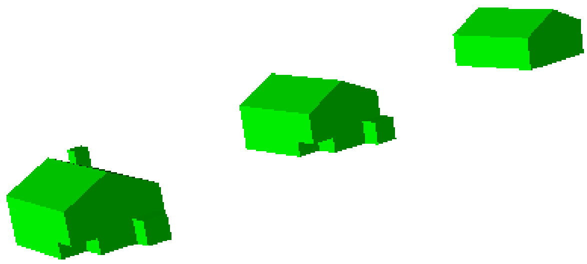

Figure 12: The ground-plane of a building should be kept fixed, otherwise, after the generalization, the building can hover above the ground.

3 SQUARING

3.1 Squaring of Roof-Structures

Up to this point orthogonal structures were assumed. Even the slightest deviations due to measurement errors can heavily influence the result, as facets might not be merged anymore. City models with exact orthogonal geometry can be achieved, e.g., by the reconstruction method of (Gülch et al. 1999), where a building is generated from generic 3D primitives. Clearly non-orthogonal structures such as roofs need to be kept. During generalization, inclined roof structures are only eliminated for small structures or for very coarse scales, i.e., if the object is almost out of sight. In order to eliminate inclined roof-structures, a roof-facet is forced to be horizontal or vertical by rotating it either around its eave- (cf. Fig. 13) or its ridge-line. This rotation process is called tapering in ACIS.

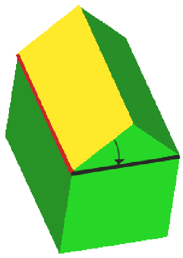

Figure 13. The roof-facet (yellow, bright) is rotated (tapered) around the eave-line (red, dark) so that the roof-facet becomes horizontal.

A roof often consists of more than one or two facets. For a reasonable generalization, the inclined facets can not be seen without their context. If only a part of a roof is eliminated, e.g., a smaller part of an L-shaped roof, the result will be not satisfying. Roof-structures, that belong together, have to be considered as a unit. For that reason, all roof-units of a building have to be detected. In this paper roof-units are seen to be defined by connected horizontal ridge-lines. Figure 14 shows a building with two roof-units, marked by a red and a yellow ridge-line. After connected ridges have been detected, for each unit the average facet-area is computed. If the area is under a certain threshold, the facets are tapered, i.e., the roof structure is eliminated.

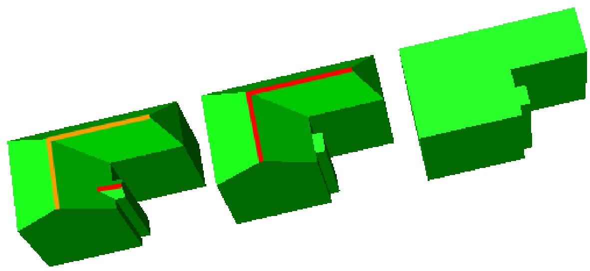

Figure 14: Connected horizontal ridges determine two roof-units (dark red and bright yellow). Dependent on the size of the structure (average facet-area) roof-units are eliminated.

Figure 15 shows results for the squaring of roofs. It can be seen, that additionally triangular facets are eliminated first, so that, e.g., a hip-roof becomes a more simple saddleback-roof. Like for the generalization of orthogonal building structures, a scaling should be added. In this case, it can be restricted to the z-coordinate. The decision if the original ridge-height, eave-height, or, e.g., an average of both should be taken for the result, depends on the goals of the user.

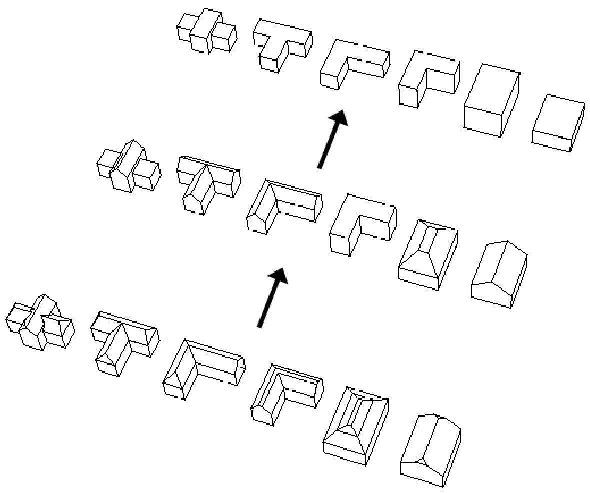

Figure 15: Examples for roof-squaring

3.2 Squaring of wall-structures

The squaring of walls is not realized by now. The basic idea is that in most cases strong deviations from the right angle have to be preserved in order to obtain the characteristic shape of a building (cf. Fig.16, top). Two cases exist, where a wall-squaring would be reasonable before applying our generalization process. On one hand, a squaring should be done, if there are only small deviations from a right angle. This happens, when the building was not reconstructed from ideal 3D primitives. On the other hand, a structure with strong deviations, which is small enough to be eliminated in case of orthogonality (cf. Fig.16, bottom), should be squared, so that the facets can be merged after a parallel movement.

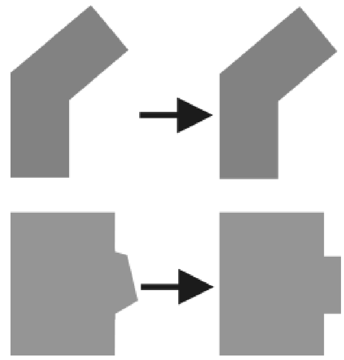

Figure 16. Strong inclinations have to be preserved for large structures (top), whereas small parts need to be squared (bottom)

The squaring of walls is highly non-trivial. While for the detection of inclined roof-facets reference directions are available (a roof facet is neither vertical nor horizontal), for vertical walls the reference directions are the main directions of the building. These can be seen in nearly all cases as 2D vectors in the x-y-plane. Yet, even for 2D generalization of ground plans the derivation of the main orientation is not solved satisfactory. An overview of common approaches and the problems linked with them is given by (Duchêne et al. 2003). In all of them, a maximum of two main directions is obtained. For simplification of building data often more than two main directions would be reasonable (cf. Fig. 17).

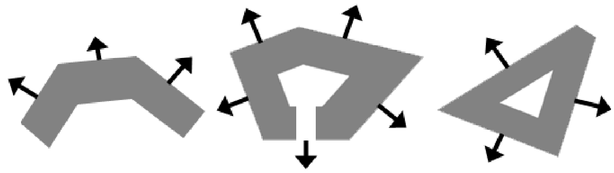

Figure 17: Buildings with more than two main directions.

4 CONCLUSIONS AND OUTLOOK

An approach for generalization of 3D building models is introduced, which is inspired by scale-space theory from image analysis. Whereas first ideas comprised a combination of mathematical morphology and curvature space, similar to reaction-diffusion-space, our new approach allows to simplify all orthogonal building structures in only one process. It works by moving parallel facets towards each other until the facets meet and merge. Because of this it is suitable only for orthogonal building structures.

For the therefore necessary squaring of non-orthogonal structures the treatment of roofs and walls has to be done differently. A procedure for the squaring of roof-units is introduced and the main problem concerning the wall squaring is discussed. The latter is not realized by now. A future goal is the wall-squaring, particularly the determination of the main directions of a building. The procedure has to also find the correspondence between the main directions and building parts.

Results for the simplification of orthogonal building structures as well as for the treatment of inclined roof-structures were presented. For both an appropriate scaling to preserve the original volume after the simplification has still to be devised.

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