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A Contribution to 3D Generalisation

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ABSTRACT

Real-time and web-based visualisation systems like digital city or earth viewers have gained significant public interest in recent years. Due to advances in software, hardware and network bandwith, they are nowadays capable of streaming and presenting spatial information at near photorealistic quality. Such accurate illustrations that are true to detail are, however, not always the most adequate tool to communicate spatial information. Particular location based services and context-aware applications that usually run on mobile devices like personal digital assistants or mobile phones require special presentation techniques to make spatial situations easier to perceive and comprehend. Similar intentions are pursued in the creation of cartographic and map-like presentations where specific requirements about the minimum object and feature size must be met. If these are not satisfied, the objects or even the whole scene must be transformed with the help of generalisation operations. One important operation for the generalisation of three-dimensional urban scenes is the simplification of building models. Many simplification algorithms for general surfaces are already known from the field of computer graphics. For cartographic presentations, however, they are not applicable as they are unable to guarantee the preservation of object properties during their transformation that are specific to buildings. These are the parallel and right-angled arrangements of façade walls and the symmetries of roof structures. Within this paper we put our focus on the simplification of three-dimensional building models and present new generalisation algorithms that are specific to this kind of data.

1. INTRODUCTION

The acquisition and presentation of 3D city models has been a topic of intensive research for more than 15 years. In general, such data sets include digital representations of the landscape, the buildings and more frequently also of the vegetation and the street furniture. A number of commercial software products and service companies exist nowadays for the reconstruction of buildings. For an efficient data collection of large areas, the objects are measured from aerial images or laser data.

Besides the traditional analysis applications of 3D city models, which are e.g. the planning of mobile antennas, alignment of solar installations and noise propagation, the presentation of urban areas gains in importance. Real-time and web-based visualisation systems offer nowadays graphics of near photorealistic quality (cf. Walter, 2005). To limit the amount of data that needs to be transferred over the network and to increase rendering performance, objects are represented in different levels of detail depending on their distance to the viewer. A preliminary survey lists applications of 3D city models and their specific levels of detail requirements (Albert et al., 2003). So far, cities have mostly collected data with roof structures and no façade information. Because of the high costs involved in the acquisition, there are efforts to facilitate the exchange and interoperability between data and application providers (Gröger et al., 2006).

A photorealistic visualisation is not always the most adequate tool to communicate spatial information. Architects and designers often produce sketch like hardcopy outputs to make their objects appear more alive or to express the preliminary status of their designs. Recent works on interactive visualisations of 3D city models (e.g. Buchholz et al., 2005) explore non-photorealistic rendering techniques that imitate this style so that spatial situations are easier to perceive and comprehend. Such techniques, however, rely on information about the characteristic edges that best reflect the global shape of a building. This is basically what results from a cartographic simplification.

Another field of application for 3D city models are location based services or context-aware applications. Their users rely heavily on a location- or situation-dependent presentation of the information that is most relevant to their current task. To be useful anywhere at all times, such systems run on mobile devices like digital personal assistants (PDA) or mobile phones. As their screen size and resolution will always be a limiting factor, a geometric simplification of 3D objects is necessary to guarantee the graphical minimum feature size required by maps or map-like presentations. Otherwise the high line density makes it impossible to recognize important aspects of the building object.

Because it is not reasonable to collect and store data for all requested levels of detail, an automatic process is necessary that transforms 3D building models towards more simplified shapes. Object features that are under a minimum size, which can be determined from the scale parameters of the map projection, should be removed without disturbing the global shape. Properties that are specific for the object itself as well as the object type, however, must be preserved. In the case of 3D building models, these are the parallel and right-angled arrangements of façade walls and the symmetries of the roof structures. Object specific features are especially important for landmarks. The simplified model of a church or cathedral, e.g., must not miss its towers after generalisation as otherwise the object is hardly recognisable anymore.

A simplification of solitary objects under these spatial constraints is one of the elemental operators of cartographic generalisation. In cartography, both the spatial objects themselves as well as their arrangement are transformed with the goal to create maps or map-like presentations that help to communicate a spatial situation. Other generalisation operators omit or emphasise objects depending on their importance, aggregate semantically similar objects, replace a number of objects by fewer entities or displace them to relax the spatial density in areas with many objects. The generation of a situation- and context-dependent abstraction level of the spatial data is therefore possible to help viewers apprehend the presented spatial information.

Our contributions in this paper to the topic of 3D generalisation are algorithms for the simplification of 3D building models. We first present work that is related both to the generalisation of 2D and 3D building data. The main portion of the paper describes two algorithms for simplification. Exemplary results are shown in each chapter. A discussion concludes the paper.

2. RELATED WORK

The automatic generalisation of building models has been a research topic ever since Staufenbiel (1973) proposed a set of generalisation actions for the iterative simplification of 2D ground plans. Several algorithms have been developed that remove line segments under a pre-defined length by extending and crossing their neighbour segments and by introducing constraints about their angles and minimum distances (e.g. Powitz, 1973). Other approaches use vector templates (e.g. Meyer, 1989), morphological operators like opening and closing (e.g. Camara et al., 2005), least-squares adjustment (Sester, 2000) or techniques from scale space theory (Mayer, 1998).

A few algorithms also exist by now for the generalisation of 3D data. Forberg (2004) adapts the morphology and curvature space operators of the scale space approach to work on 3D building models. Thiemann and Sester (2004) do a segmentation of the building's boundary surface with the purpose of generating a hierarchical generalisation tree. An aggregation approach is proposed by Anders (2005). It works for linearly arranged building groups. With a strong focus on the emphasis of landmarks do Thiemann and Sester (2006) present adaptive 3D templates. They categorise building models into a limited number of classes with characteristic shapes. A building model is then replaced by the most similar 3D template that best fits the real object. Because the semantics of the template is known, the object itself or specific features of the model can be emphasised at will.

The simplification of 3D models has been a major topic in the field of computer graphics. However, these algorithms are designed for general models that approximate smooth surfaces and therefore typically do not perform well on 3D building models. The main reason is that building models consist of considerably fewer planar faces, but many sharp edges. Coors (2001) and Rau et al. (2006)

show that the simplification operators and metrics can be modified so that the characteristic properties of the building models can be preserved during their simplification.
Despite the number of available 3D generalisation approaches, a continuous difficulty seems to be the simplification of the roof structure. Most algorithms avoid this problem by simply generating flat or pent roofs or assume that the roof type is already available as the result of a preceding interpretation. In this paper, we describe two complementary generalisation approaches for 3D building models that concentrate on preserving valid roof geometries.

3. GENERALISATION BY SURFACE SIMPLIFICATION

The first generalisation algorithm is based on the concepts of surface simplification. It uses the edge collapse operator to implement feature removal operators to simplify the shape of the input building model. To guarantee geometric relations, a graph structure is used that must not be violated by a simplification step. The information is also used in the final shape fitting step that fits the simplified geometry to the original points of the input model.

3.1. The Geometric Relations Graph

The three geometric relations coplanarity, parallelism and rectangularity that exist between the faces of 3D building models are managed in a graph structure. There, the nodes of the graph represent the polygonal faces which are connected by edges that represent one of the three relations (cf. Fig. 1). A simplification operation that invalidates any relation in the graph is not allowed and must not be executed. However, a parallelism relation may be changed to a coplanarity relation if an extruded face is moved into the plane of another face. Also, if faces are removed by a simplification operation, the respective node and all incidental edges are deleted.
For the automatic generation of a relations graph, the explicit information about the geometric relations of the 3D building model is required. If the relations are not available from the modelling or reconstruction process, then they must be derived from the model by a geometric analysis. Here, the comparison of normal vectors and distances of the plane equations the faces are lying in can be utilised in conjunction with a set of threshold values. However, the acquisition error should be small or the faultless identification of the relations is only possible by a human operator.
To guarantee that a generalisation step is valid, all the relations that are associated with any altered node must be checked. Because the face nodes are not limited to be connected to adjoining faces, the number of relations can be rather high. Furthermore, the relations will also be integrated as constraints in the optimisation stage of the algorithm. So it is necessary to find a minimal set of geometric relations that are sufficient to guarantee the geometric constraints. For this purpose, the edges are weighted depending on the computational costs where rectangularity is rated with the highest and coplanarity with the lowest weight. A graph that connects all nodes with minimal overall weight is called the minimum spanning tree and can be computed with the algorithms of Kruskal (1956) and Prim (1957) (cf. Fig. 1).

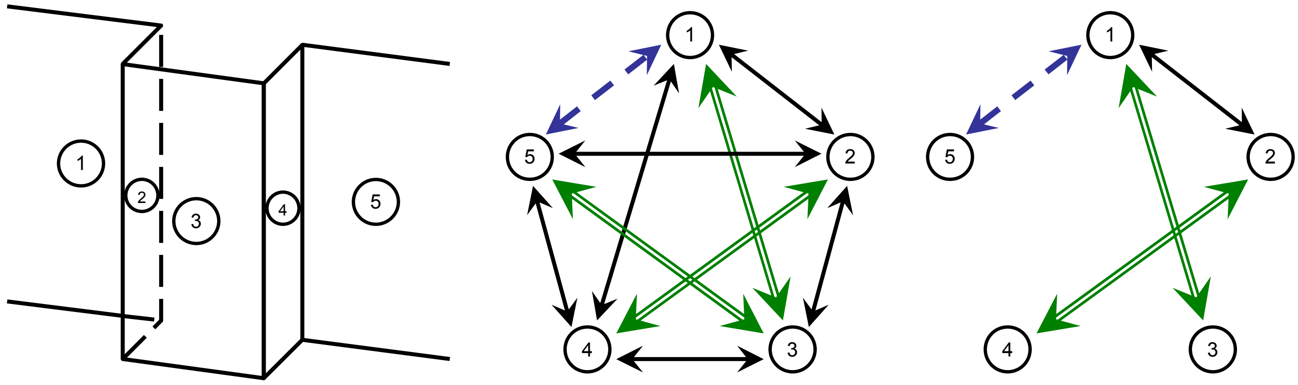

Fig. 1: The relations of an extrusion feature (left) as complete (middle) and minimum (right) graph.

3.2. Shape Simplification

For the simplification of a building's shape, it is not sufficient to just remove arbitrary vertices or edges as this would invalidate the relations graph. Rather an entire feature must be addressed at once while preserving the integrity of the remaining parts of the model. This is accomplished with specific operators that are able to detect and remove well-defined features. The operators are repeatedly used on the building model to detect all features of low importance present in the model. This can be very complex issue as geometrically small features may be important due to their semantic meaning.
In the example of Fig. 2, a detected extrusion feature is removed by a combination of edge collapse operations. Extrusions are detected by the normal directions of the surrounding faces. The feature removal operator for extrusions then deletes edges by merging their two endpoints into single vertices. The original positions of features are not just discarded by the feature removal, but they are stored as interior points of the remaining faces. They are used in the following shape fitting step.

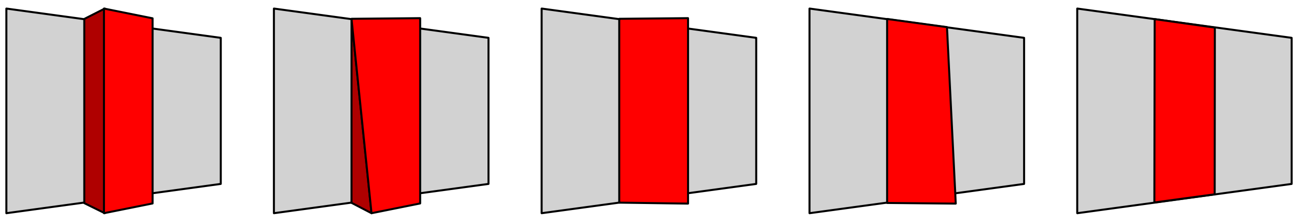

Fig. 2: Example of a shape simplification by the removal of an extrusion feature.

3.3. Shape Fitting

As a result of the shape simplification, the polygonal faces of the 3D building model are displaced when compared to the models original vertices. If e.g. only extrusions are removed with the aforementioned operator, then the resulting model is smaller than the original. To counteract this phenomenon, a shape fitting to the original input points is done via least squares adjustment.
For the parameter estimation the Gauss-Helmert model is used. Here, the planar locations in which the building's faces reside as well as their points of intersection are determined. Therefore, all remaining points as well as the interior points are used in conjunction with the relations from the minimum spanning tree of the geometric relations graph. As can be seen in Fig. 3, the face of the simplified and fitted model approximates very well the original extrusions.

Fig. 3: Original (left) and generalised (middle) 3D building model and an overlay of both models (right).

3.4. Results from the Surface Simplification Approach

Because of the many extrusions, the complexity of the example model of the New Palace of Stuttgart that is shown in Fig. 4 could be reduced from 2730 to 1837 triangles. Many of the resulting faces are coplanar and could even be merged for further geometric simplification. However, the current break-down of the textures and their association with the faces prohibited further generalisation without merging the texture images also. Coplanarity, parallelism and rectangularity of the faces have been preserved nicely. Although the design of the algorithm proved to be valid, more feature types would need to be supported for a production environment.

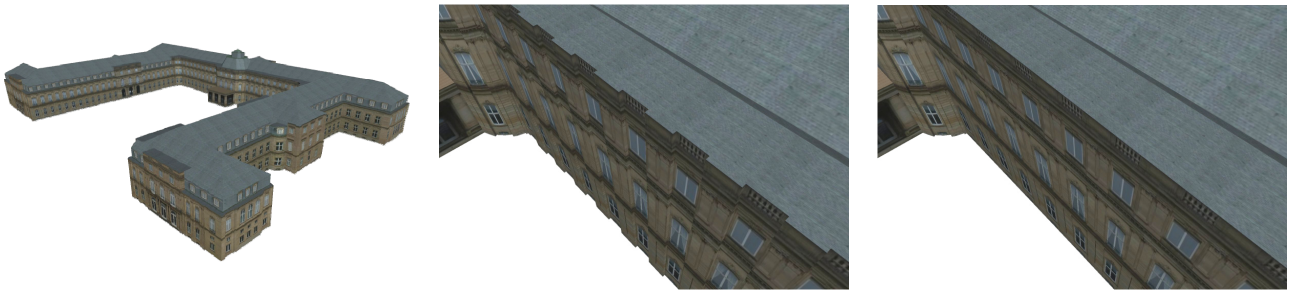

Fig. 4: 3D building model of the New Palace of Stuttgart (left) and two close-up views of the original (middle) and the generalised (right) shape.

4. GENERALISATION BY CELL DECOMPOSITION

We propose a two-stage generalisation algorithm for the geometric simplification of solitary 3D building models. As can be seen from the intermediate results of the example in Fig. 5, the two stages consist in a total of five steps. The first stage generates a 2D decomposition of space that approximates the ground plan polygon by a disjoint set of quadrilateral primitives. We accomplish this by deriving plane equations from the major façade walls (1), subdividing the infinite space along these planes (2) and identifying the resulting cells that feature a high percentage of overlap with the original ground plan polygon (3). The second stage reconstructs the simplified geometry of the roof. Here, a cell decomposition and a new primitive instancing approach is shown where the roof parameters are determined individually for each cell so that they best fit the original model under distinct adjacency constraints (4). By altering those parameters, the simplification of the roof can be properly adjusted. A union operation of the resulting primitives composes the final 3D building model and concludes the generalisation (5).

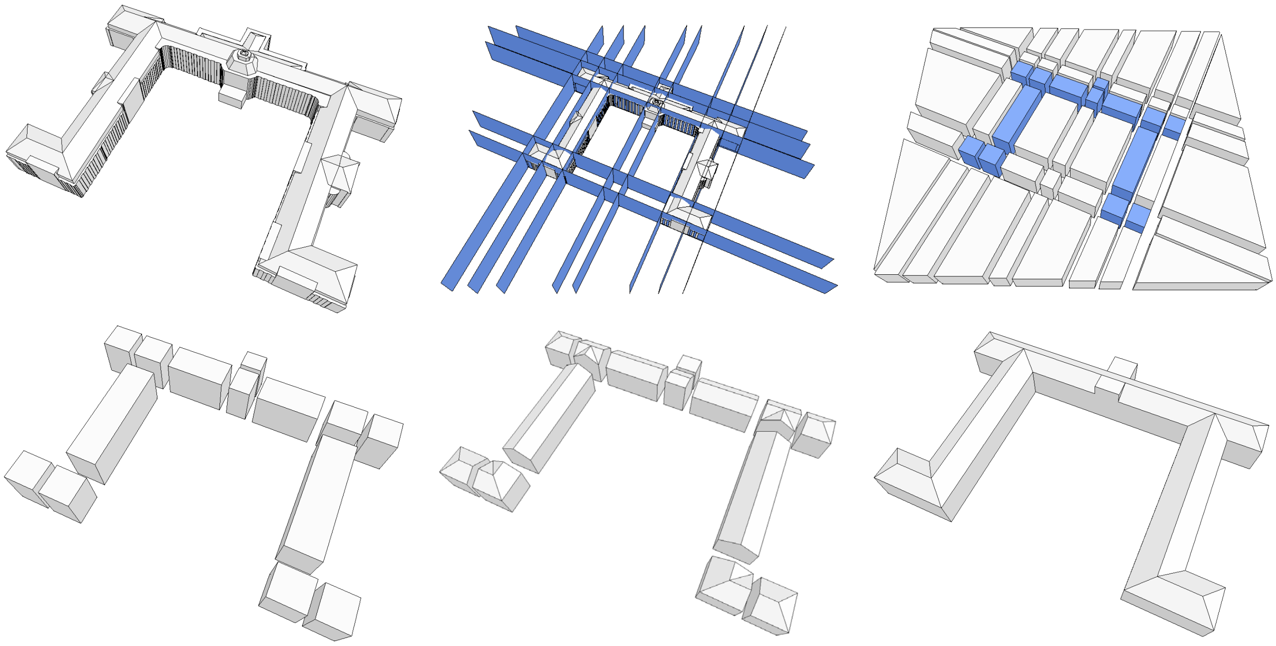

Fig. 5: Original 3D building model (top left) and the five generalisation steps.

4.1. Ground Plan Cell Decomposition

In our algorithm, the cell decomposition serves two purposes: First, it is build as an approximation of the building ground plan and is consequently per se also a generalisation thereof. Second, it provides the basic building blocks for the reconstruction of the roof geometry. Since the input models are provided as 3D data, all computations are also performed in 3D, even though the dimension of the resulting cells is really 2D; or 2.5D if a height is applied like in the example of Fig. 5. For clarity reasons, however, the accompanying Fig. 6 to Fig. 8 are given as 2D sketches.
The faces in a polyhedral building representation are always planar. If the real building façade features round or curved elements, then they must be approximated in the model by small polygons. We therefore generate the cell decomposition by subdividing a finite 3D subspace by a set of vertical planes. Fig. 6 e.g. shows a building and the cell decomposition which results from subdividing space along the façade segments.

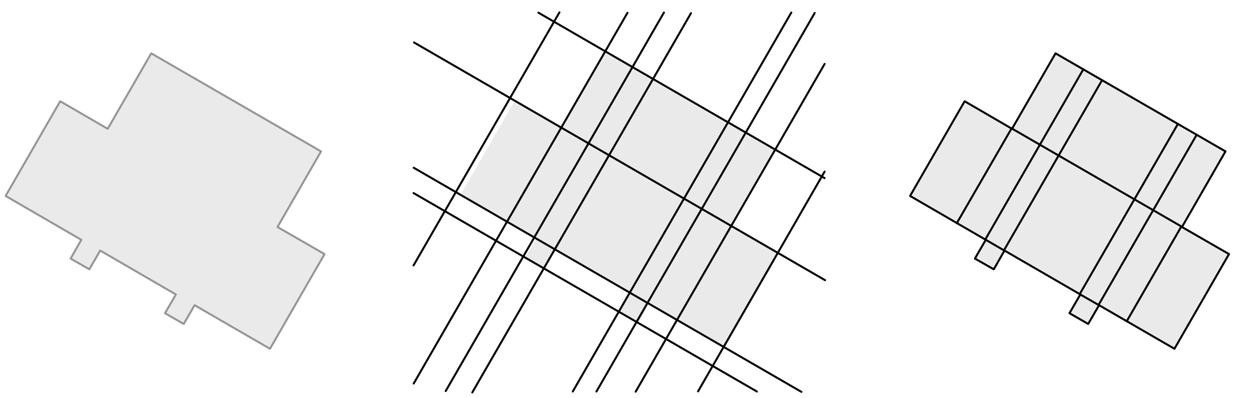

Fig. 6: Building ground plan (left), overlaid decomposition of space along its façade segments (middle) and resulting cell decomposition (right).

As it can be seen, the union of the cells is not yet a simplification of the original shape and the small cells complicate the reconstruction of the roof geometry. So instead of using each individual façade polygon, we cluster them together with a special buffer operation for the purpose of generating fewer planes that in turn produce a decomposition of fewer cells. However, these planes should correspond with the most important façade segments so that the decomposition reflects the characteristic shape of the object. The importance of a plane is measured as the surface area of all polygons that are included in the generating buffer and that are almost parallel to the created plane. Polygons with a different orientation are not counted.

4.2. Generation of Decomposition Planes

We implemented a greedy algorithm that generates the plane of highest importance from a set of input façade polygons. At this point, we ignore all roof polygons and only use polygons with a strict horizontal normal vector. By repeatedly calling the algorithm, new planes are added to the result set and all polygons inside the buffer are discarded from further processing. The generation of planes ends when no input polygons are left or when the importance of the created planes falls under a certain threshold value.

At the beginning of the algorithm, buffers are created from the input polygons (see Fig. 7). Each buffer is defined by two delimiting parallel planes that coincide with the position and normal direction of a generating polygon. These planes may move in opposite directions to increase the buffer area until a generalisation threshold is reached. The buffers are first sorted by their importance and then merged pair wise to create larger buffers. Starting with the buffer of highest importance, the buffers of lower importance are tested for their inclusion in this buffer. If all polygons of a buffer can be included into the one of higher importance without increasing the distance between their delimiting planes above the generalisation value, then the merge is valid and is executed. The algorithm stops when no more buffers can be merged and the averaged plane equation of the polygons of the buffer of highest importance is returned.

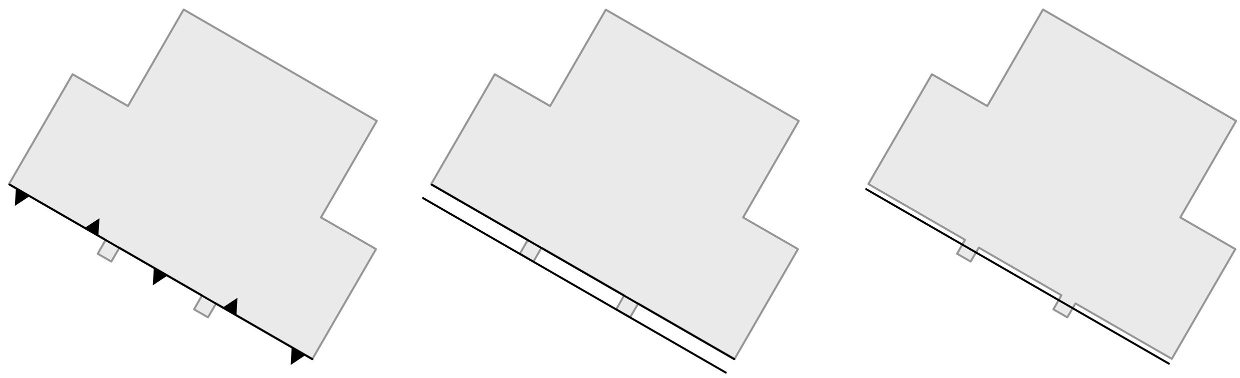

Fig. 7: Initial buffer from façade segments (left), delimiting planes of the maximised buffer (middle) and resulting averaged plane (right).

In order to enforce parallelism and to support right angles of the façade segments, the resulting planes are analysed in a last step. If the angle of the normal vectors from two or more planes is found to be below a certain threshold, these planes are made parallel or rectangular. If the deviation is only a small angle, this can be done by changing the normal vector of the plane equation and adjusting the distance value. For larger values, a rotation of the planes around their weighed centroids of the polygons is chosen. For our computations, we use four threshold values. The most important one is the generalisation distance that the buffer planes may move apart. As this value also determines the distance of the planes used for the decomposition, it is also approximately the smallest ground plan feature length of the resulting set of cells. Another threshold value determines the lowest importance of a plane that is still a valid result. Here, the square of the generalisation distance is used. Buffers below that value probably do not contain polygons with a side length of the generalisation distance and are therefore not important. The last two threshold values are angles. As it is important for the roof construction that the cells are parallelograms, the angle for enforcing parallelism is rather large. We chose 30° for parallelism and 10° for right angles. See Fig. 8 for the set of buffers that result in a simplified cell decomposition.

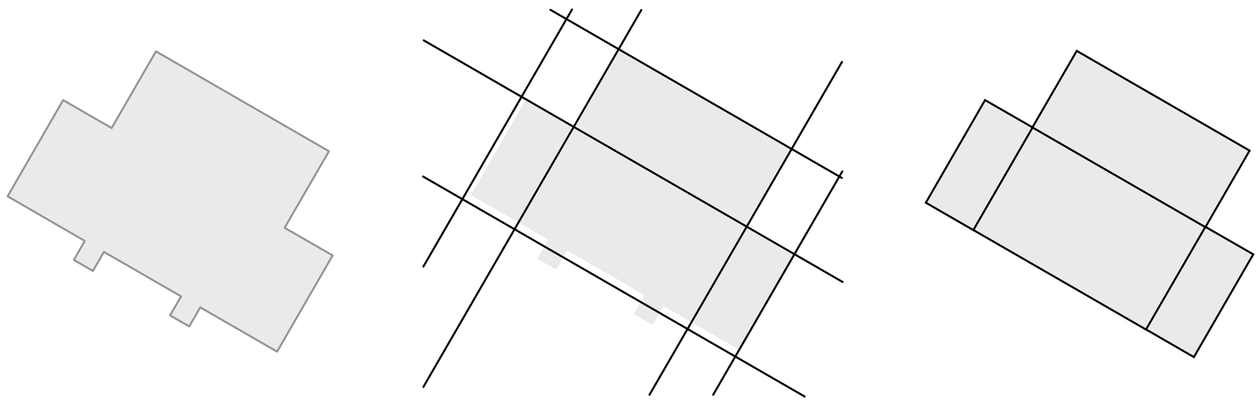

Fig. 8: Building ground plan (left), overlaid simplified decomposition of space along its façade segments (middle) and resulting cell decomposition (right).

4.3. Determination of Building Cells

Once the planes have been determined, they are then used to generate the cell decomposition of the building model. Theoretically, an infinite 3D space should be subdivided brute force by the planes. However, as an infinite space is unpractical, a solid two times the size of the building's bounding box is used. Because the plane equations were averaged from façade segments and therefore have no horizontal component, the space is only divided in two dimensions. The resulting cells are 2D polygons extruded into the third dimension.
The decomposition consists of building and non-building cells. Only the building cells are of interest for further processing. The other cells should be discarded. However, these cells can not directly be identified from the decomposition process. A further step is necessary.
For that reason, a percentage value is calculated that denotes the overlap of the cell with the original building ground plan. Cells that result in a high overlap value are considered building cells whereas the other cells are considered as non-building cells. A precise value can be computed by intersecting the cell with the ground plan polygon and dividing the resulting area by the area of the cell. As the cells are rather big, an overlap threshold of 50% is able to correctly distinguish between building and non-building cells.

4.4. Roof Generalisation by Cell Decomposition

So far, the roof polygons have been neglected. Now they are used to determine the decomposition planes of arbitrary orientation in order to generate 3D cell decompositions from the ground plan cells. Although the decomposition is done per cell, the planes are determined globally from all roof polygons to ensure that neighbouring cells fit well against each other. We use the buffer approach as previously described. The subdivision process is then done with the subset of planes that has polygons in their buffer that intersected the respective cells. This avoids a heavy fragmentation of the cells.

The resulting cells are now real 3D solids, so the classification in building and non-building cells has to be done in 3D space. Consequently, a percentage value that denotes the volume of the original building model inside each respective cell is computed. Inaccuracies occur if planes do not cut the 2.5D cells at exactly the same location in space. We remove them by a vertex contraction process that pulls the roof vertices to the closest ground cell corner point, edge or cell centre if they are within close distance.

4.5. Results from the Cell Decomposition Approach

Fig. 5 and Fig. 9 show some exemplary results from the generalisation approach using cell decomposition. The shape of the generalised models is noticeably simplified while their geometric relations are well preserved. Features that are important for the characteristic of the building, like e.g. the tower of the church, still exist in the resulting models.

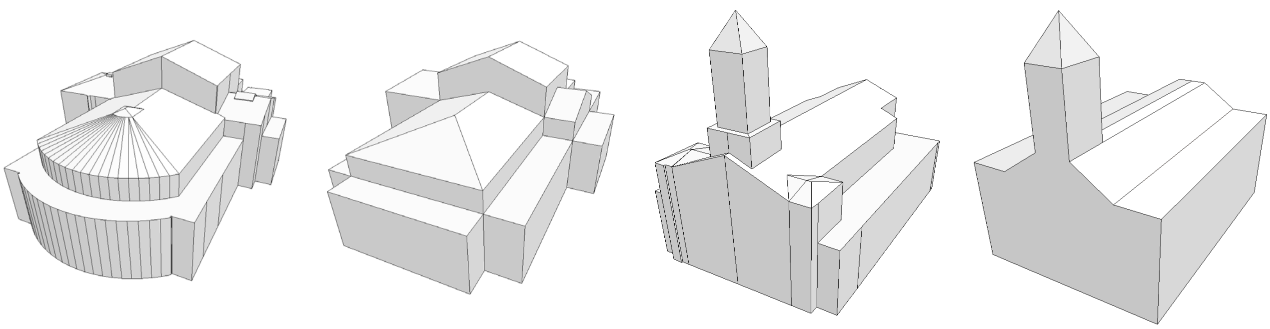

Fig. 9: 3D building models in their original (left) and generalised (right) shape.

5. CONCLUSION

Map and map-like presentations are essential to communicate spatial information. As 3D city models become standard products of surveying offices, map-like 3D presentations are only a matter of time until they become available for a wide audience. Because maps need to be mobile, such applications will run on mobile devices with all their limitations. As 2D generalisation operators are already a common tool to prepare data to the scale of maps, such a scale-depending transformation of 3D data will require new operators.
This paper proposes a two new algorithm for the simplification of solitary 3D building models. They are based on surface simplification and cell decomposition. The geometric properties that are specific to buildings like the coplanarity, parallelism and rectangularity of façade segments are preserved during simplification or can even be enforced if needed. The generalisation is solely controlled by an intuitive distance threshold value that specifies the minimum size of the building elements. Both approaches have their right to exist. The surface simplification approach works well if small features need to be removed whereas the cell decomposition approach finds the global shape of the 3D building model. They are therefore complementary in their procedural method and a combination of both approaches should be investigated in future work.

6. REFERENCES

Albert, J., Bachmann, M., Hellmeier, A. (2003): Zielgruppen und Anwendungen für Digitale Stadtmodelle und Digitale Geländemodelle – Erhebung im Rahmen der Arbeitsgruppe „Anwendungen und Zielgruppen" der SIG3D im Rahmen der Initiative GDI-NRW.

Anders, K.-H. (2005): Level of Detail Generation of 3D Building Groups by Aggregation and Typification. In: Proceedings of the XXII International Cartographic Conference, La Coruna, Spain.

Buchholz, H., Döllner, J., Nienhaus, M., Kirsch, F. (2005): Real-Time Non-Photorealistic Rendering of 3D City Models. In: Proceedings of the 1st International Workshop on Next Generation 3D City Models, Bonn.

Camara, U., Antonio, M., Lopez, A., Javier, F. (2005): Generalization Process for Urban City-Block Maps. In: Proceedings of the XXII International Cartographic Conference, La Coruna, Spain.

Coors, V. (2001): Feature-Preserving Simplification in Web-Based 3D-GIS. In: Proceedings of the 1st International Symposium on Smart Graphics. Hawthorne, USA, pp. 22-28.

Forberg, A. (2004): Generalization of 3D Building Data based on a Scale-Space Approach. In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Istanbul, Turkey, Vol. XXXV, Part B.

Gröger, G., Kolbe, T.H., Czerwinski, A. (2006): City Geography Markup Language. Approved Discussion Paper of the Open Geospatial Consortium, Inc.

Kruskal, J.B., Jr. (1956): On the Shortest Spanning Subtree of a Graph and the Traveling Salesman Problem. In: Proceedings of the American Mathematical Society, 7, pp. 48-50.

Mayer, H. (1998): Scale-Space Events for the Generalization of 3D-Building Data. In: International Archives of Photogrammetry and Remote Sensing, Vol. 32, Part 3/1, pp. 520-536.

Meyer, U. (1989): Generalisierung der Siedlungsdarstellung in digitalen Situationsmodellen. Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover (159), Ph.D. Thesis.

Powitz, B.-M. (1973): Zur Automation der Kartographischen Generalisierung topographischer Daten in Geo-Informationssystemen, Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover (185), Ph.D. Thesis.

Prim, R.C. (1957): Shortest Connection Networks and some Generalizations. In: Bell Systems Technical Journal 36, pp. 1389-1401.

Rau, J.Y., Chen, L.C., Tsai, F., Hsiao, K.H., Hsu, W.C. (2006): Automatic Generation of Pseudo Continuous LoDs for 3D Polyhedral Building Model. In: Innovations in 3D Geo Information Systems, Springer Verlag, Berlin.

Sester, M. (2000): Generalization based on Least Squares Adjustement. In: International Archives of Photogrammetry and Remote Sensing, Vol. 33, Part B4/3, Amsterdam, pp. 931-938.

Staufenbiel, W. (1973): Zur Automation der Generalisierung topographischer Karten mit besonderer Berücksichtigung großmaßstäbiger Gebäudedarstellungen, Wissenschaftliche Arbeiten der Fachrichtung Vermessungswesen der Universität Hannover (51), Ph.D. Thesis.

Thiemann. F, Sester, M. (2004): Segmentation of Buildings for 3D-Generalisation. In: Working Paper of the ICA Workshop on Generalisation and Multiple Representation, Leicester, UK.

Thiemann. F, Sester, M. (2006): 3D-Symbolization using Adaptive Templates. In: Proceedings of the GICON, Wien, Austria.

Walter, V. (2005): Phoogle the Web – Google's Approach of Spatial Data Visualisation. In: Dieter Fritsch (Ed.), Photogrammetric Week '05, Wichmann Verlag, Heidelberg, pp. 321-330.