

# GENERALIZATION OF 3D BUILDING MODELS FOR MAP-LIKE PRESENTATIONS

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## ABSTRACT:

The automatic generalization of 3D building models has been a topic of research for almost a decade. Several approaches for the simplification of single objects have been proposed and shown to be valid. Such models of low geometric detail are needed for map-like presentation. In this paper, a generalization algorithm is presented that is based on the decomposition of space along the major planes of the building. In contrast to previous publications, the focus is on the mathematical description of the approach.

## 1. INTRODUCTION

As 3D city models become widely available, the demand for their real-time visualisation also increases. There are a number of software products that allow for a photorealistic presentation like the virtual globes or some commercial packages with a strong focus on urban landscape visualisation. They already offer graphics of near photorealistic quality (see e.g. Walter 2005). Such accurate illustrations that are true to detail might, however, not always be the most adequate tool to communicate spatial information. Expressive rendering techniques imitate a sketchy drawing style so that the spatial situations are easier to perceive and comprehend (see e.g. Buchholz et al. 2005). Similar intentions are pursued in the creation of thematic and map-like presentations where specific requirements about the minimum object and feature size must be met. Such cartographic visualisations place their emphasis on the global shape of objects rather than on unimportant details. Particularly affected by this principle are location based services and context-aware applications. They usually run on mobile devices like personal digital assistants (PDA) or mobile phones which are equipped with displays of limited size and resolution.

Because it is not reasonable to collect and store data for all required levels of detail, an automatic process is necessary that transforms 3D building models towards a more simplified shape. During this transformation, building-specific properties must be preserved. These are, amongst others, the parallel and right-angled arrangement of façade walls and the symmetries of the roof structure. Furthermore, object specific features are especially important for landmarks. The simplified model of a church or cathedral, e.g., must not miss its towers after simplification, 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 object's shape and their arrangement are altered with the goal to create maps or map-like presentations to better communicate spatial situations.

In this article, we describe the generalization algorithm also presented in (Kada 2007). In contrast to previous publications, the focus is on the mathematical description of the approach.

## 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), (Regnauld et al. 1999), (Van Kreveld 2001), (Harrie 1999) and (Weibel 1996)). Other approaches use vector templates (Meyer 1989), (Rainsford and Mackaness 2002), morphological operators like opening and closing (Camara 2005), (Li 1996), least-squares adjustment (Sester 2000) or techniques from scale space theory (Mayer 1998).

Nowadays, a few algorithms also exist that have been specifically designed for the generalisation of 3D building models. 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. After a semantic interpretation of the tree's elements, they can selectively be removed or reorganized to implement the elemental generalisation operators for simplification, emphasis, aggregation and typification. Another aggregation approach is proposed by Anders (2005). It works for linearly arranged building groups. Their 2D silhouettes, which are the results of three projections from orthogonal directions, are simplified, extruded and then intersected to form the generalised 3D model. With a strong focus on the emphasis of landmarks present Thiemann and Sester (2006) 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 is a best fit to 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. See e.g. the survey of Luebke et al. (2002) for an up-to-date summary of the most important work.

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), Rau et al. (2006) and Kada (2002) 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. Glander and Döllner (2007) show a cell-based generalization of building blocks for the visualisation of complex city models.

### 3. 3D BUILDING MODEL GENERALIZATION BASED ON CELL DECOMPOSITION

Our proposed generalisation algorithm automatically simplifies the geometry of solitary 3D building models. Its main idea can be best described by using the analogy of sculpturing. The 3D object in question is reproduced from a large solid block. However, the sculptor is only allowed to make planar cuts through the whole block. Afterwards, she peels away the pieces that do not belong to the resulting sculpture and glues the remaining solids together to form the final shape. In order to create a simplified counterpart of a given 3D building model, the number of executed cuts must be as few as possible. Yet, their number must still be high enough to reproduce the characteristic shape of the original object.

This modus operandi is digitally emulated by first finding a minimal set of planes that approximate the façade and roof polygons of the input model. A so called cell decomposition is then generated from a solid that generously fits the dimension of the original model by subdividing it along the direction of the planes.

Cell decomposition is a form of solid modelling in which objects are represented as a collection of arbitrarily shaped 3D primitives that are topologically equivalent to a sphere (see

Foley et al. 1990). The individual cells are usually created as instances from a pre-defined set of parameterised cell types that may even have curved boundary surfaces. Complex solids are then modelled in a bottom-up fashion by “gluing” the simple cells together. However, this operator restricts the cells to be nonintersecting, which means adjoining cells may touch each other but must not share any interior points. While cell decomposition is not as versatile as constructive solid geometry (CSG), it is sufficient for creating all possible building shapes. Moreover, the limitation to one operator greatly simplifies the whole modelling process and the implementation of the generalisation algorithm. The models in our cell decomposition approach also differ with regard to how they were constructed. Rather than being generated in a bottom-up fashion using parameterised primitives, the shape and the assembly of cells emerge from the subdivision.

For presentation purposes, the generalisation process is divided into five steps (cp. Figure 1): The first three steps generate 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 fourth step (4) reconstructs the simplified geometry of the roof. Here, the three steps are repeated for plane equations derived from the major roof polygons. A union operation of the resulting primitives composes the final 3D building model and concludes the generalisation (5).

The two main challenges of this approach are to automatically derive the planes from the boundary representation and to differentiate between building and non-building cells from the resulting decomposition.

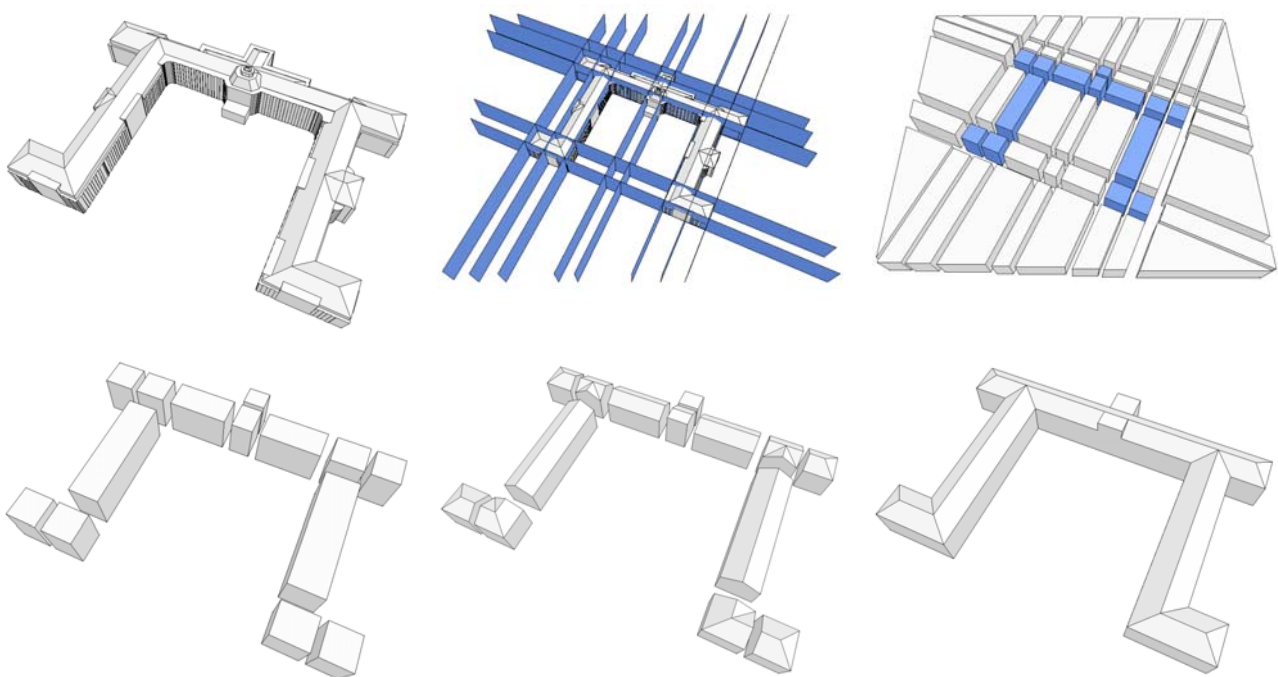


Figure 1. Original 3D building model (top left) and the five generalisation steps.

### 3.1 Derivation of Major Planes

For a building model  $M = (F_1, F_2, \dots, F_n)$  that consists of  $n$  faces  $F_1$  to  $F_n$ , we seek a partition  $P = (P_1, P_2, \dots, P_m)$  where  $m \ll n$ . This means that the faces are arranged in groups, so that the number of groups is much smaller than  $n$ . The faces of a group are said to be on the same major plane and therefore will be "replaced" by this plane in the generalized model.

Each partition element  $P_i = (B_i, F_{P_i}, F_{N_i})$  contains a buffer  $B$  and two sets of faces  $F_P$  and  $F_{NP}$ . The buffer  $B = (A, B, C, D_{min}, D_{max})$  is the region between the two planes  $Ax + By + Cz - D_{min} = 0$  and  $Ax + By + Cz - D_{max} = 0$ . The set  $F_P$  holds all polygonal faces that are parallel to the boundary planes of the buffer  $B$  and  $F_{NP}$  holds all other polygonal faces. All points  $p$  of the faces in both sets must completely lie inside the buffer:

$$\forall p \in F_P \cup F_{NP}: Ap_x + Bp_y + Cp_z \geq D_{min} \wedge Ap_x + Bp_y + Cp_z \leq D_{max} \wedge D_{max} - D_{min} < \epsilon_{distance}$$

The normalization  $(A^2 + B^2 + C^2 = 1)$  ensures that  $D_{min}$  and  $D_{max}$  can be directly compared. Their difference must be below the generalization threshold. All faces inside a buffer will later be represented by the major plane that is derived from this buffer. To not generate major planes with too many different angles, the faces in  $F_P$  are said to be parallel if the angle between their normal direction  $\vec{n}$  and the vector  $(A, B, C)$  of the buffer boundaries are below the angle threshold  $\epsilon_{angle}$ :

$$\forall \vec{n} \in F_P: \arccos\left(\frac{\vec{n} \cdot (A, B, C)^T}{\sqrt{\vec{n}^2} \sqrt{A^2 + B^2 + C^2}}\right) < \epsilon_{angle}$$

Once the partition has been generated, the set of major planes are defined by the normal vectors  $(A, B, C)$  of their buffers  $B$  and the distance values  $D$  averaged from the faces in the set  $F_P$ :

$$D = \forall p_i \in f_j \in F_P: \frac{\sum Area(f_j)(Ap_{i_x} + Bp_{i_y} + Cp_{i_z})}{\sum Area(f_j)}$$

The area value  $Area(f_j)$  of a face  $f_j$  gives larger faces more influence on the plane's location. We also use the sum of all face areas  $\sum Area(f_j)$  and specify it as the importance of the particular major plane.

To generate the major plane of highest importance, we implemented a greedy algorithm. As already mentioned, the first generalization step generates major planes from the façade polygons. So roof polygons are omitted for now. Each repetition of the algorithm adds a new element to the partition. The process ends when no input polygons are left or when the importance of the created planes falls under a certain threshold value. 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.

At the beginning of the algorithm, a set of buffers is created with only a single face in the set  $F_P$ . They are then 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.

### 3.2 Subdivision of Space

Once the major 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.

### 3.3 Identification of Building Cells

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. For that reason, a percentage value is calculated that denotes the overlap of the cell  $C$  with the original building ground plan  $G$ :

$$Overlap = \frac{C \cap G}{C}$$

Cells that result in a high overlap value are considered building cells whereas the other cells are considered as non-building cells. As the cells are rather big, an overlap threshold of 50% is able to correctly distinguish between building and non-building cells. The set of building cells form a generalized shape of the ground plan polygon. However, not only the façade polygons that adjoin to the ground plan polygon have been used for the derivation of the major planes. Rather all non-roof polygons affect the set of major planes. So the cells are also divided at the discontinuities of the roof structure which helps to correctly reconstruct the simplified roof shape.

### 3.4 Reconstruction of the Roof

The cell decomposition is now extended to the third dimension. Now, the major planes are determined from the remaining roof polygons that can have any orientation. This is done globally to ensure that neighbouring cells fit well against each other. However, the decomposition is done per cell. A major plane will only subdivide a cell if at least one face  $f$  in the set  $F_P$  from the buffer  $B$  (from which the major plane was derived) at least partially lies inside that cell:

$$\exists f \in F_P: f \cap C \neq \emptyset$$

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 (see Figure 2).

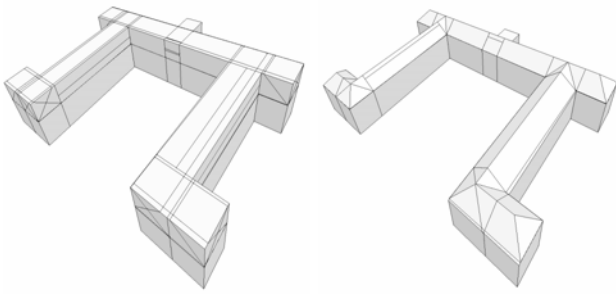


Figure 2. Decomposition of the roof before (left) and after (right) identification of building cells.

### 3.5 Elimination of Inaccuracies

As the decomposition planes are averaged from its set of faces, three or more planes seldom meet at precisely one point. Rather, there are some inaccuracies which results in choppy edges and points and very small, superfluous cells. We remove these inaccuracies by a vertex contraction process (cp. Figure 3) that pulls the roof vertices to the closest ground cell corner point (blue), edge or cell centre (red) if they are within close distance. Their heights are also adjusted to a small set of discrete height levels. Cells that degenerate during this process are removed.

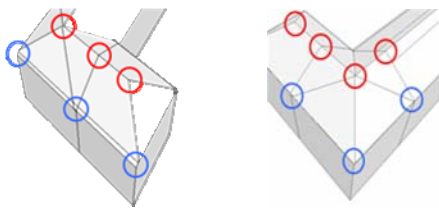


Figure 3. Small inaccuracies are eliminated by pulling vertices to the nearest ground cell corner point (blue) or the nearest edge or cell centre (red).

### 3.6 Union to Final Building Model

The final step is to “glue” the simple cells together (see Figure 4). As the cells are topologically equivalent to a sphere and nonintersecting, which means adjoining cells may touch each other, but must not share any interior points, the union is quite

straight forward to implement. The limitation to one operator also greatly simplifies the whole modelling process. While cell

decomposition is not as versatile as constructive solid geometry (CSG), it is sufficient for creating all possible building shapes.

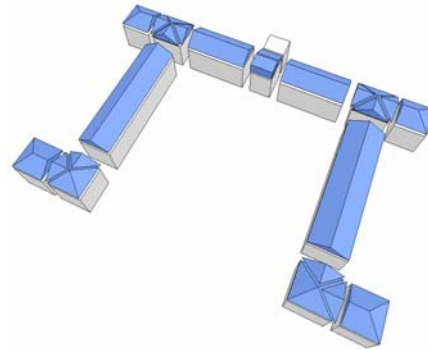


Figure 4. Cells from the ground plan decomposition (grey) and from the roof generation (blue) are united to form the final building shape.

## 4. RESULT

The results of the generalization algorithm can be seen in Figure 6 and Figure 7. The shapes of the building models in Figure 6 are very simple and the results, which are depicted in blue, are also presented as overlays to the original model. Here, it can be nicely seen that the decomposition planes approximates the original facade faces. Figure 7 shows the results for models of higher complexity.

As can be seen in Figure 5, the generalization algorithm also works for non-interpreted data. The extruded ground plan with a triangulated LIDAR point cloud as roof is also simplified. Parallelism and rectangularity are enforced both for the facades and the roof. It has to be noted that the final model shows the result before the union of the cells.

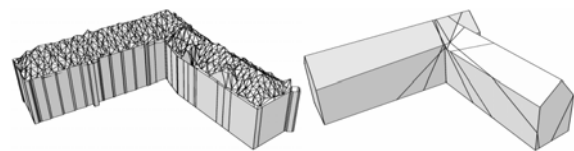


Figure 5. Generalization of an extruded 2D ground plan with a triangulated LIDAR point cloud. The result is shown before the cells are united.

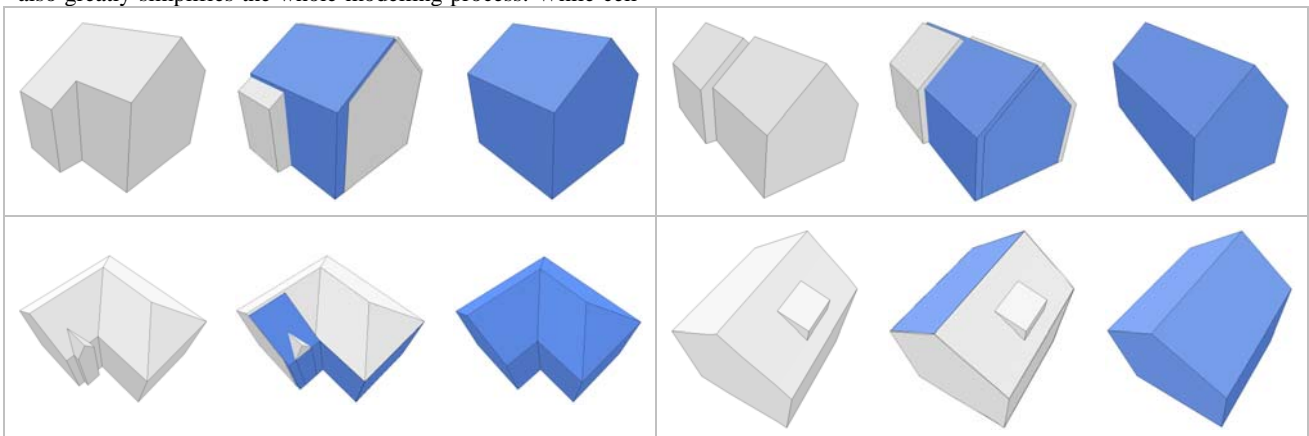


Figure 6. Simple example buildings in their original (grey) and generalised (blue) shapes.

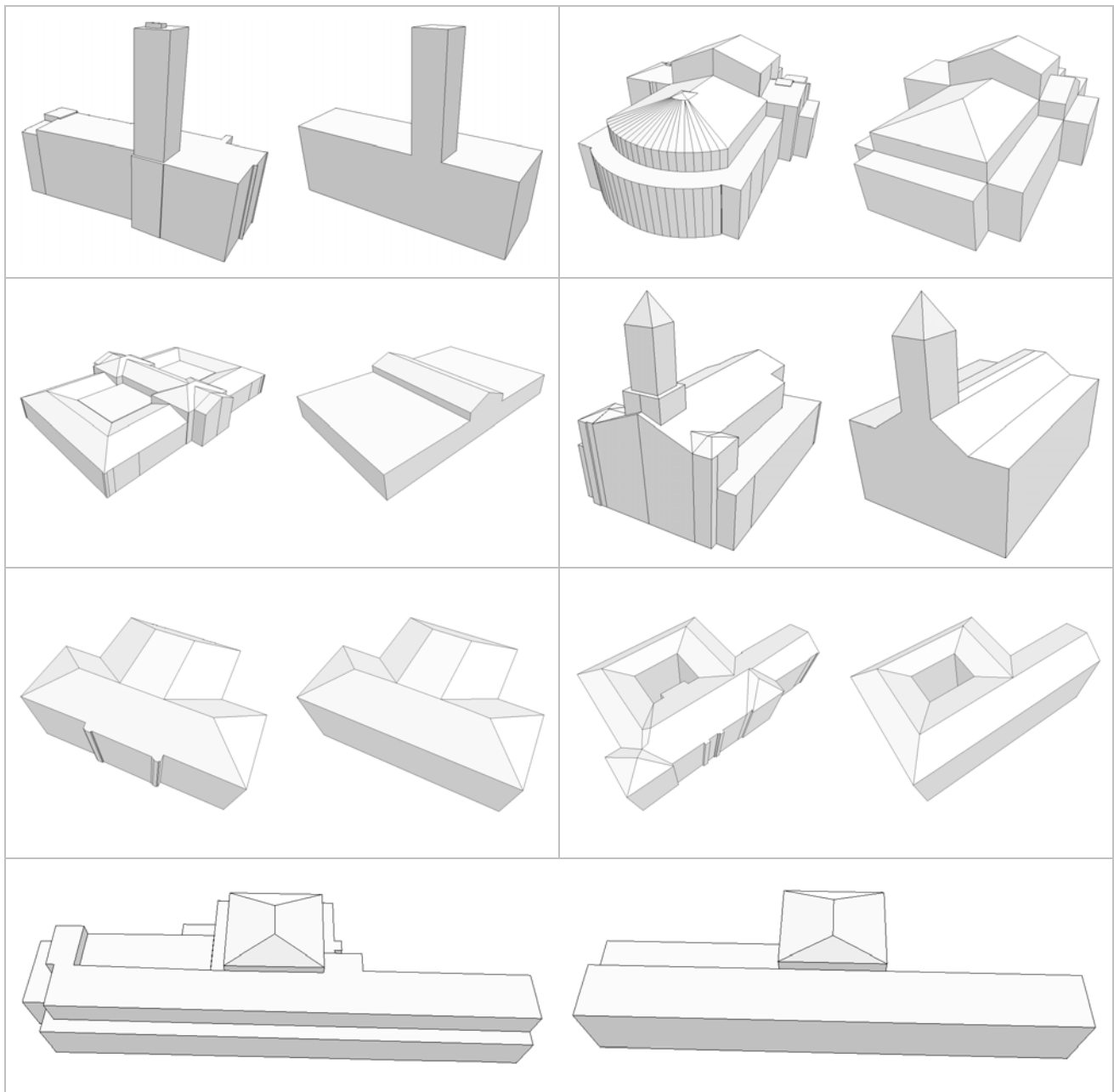


Figure 7. 3D landmarks in their original (left) and generalised (right) shape.

## 5. CONCLUSION

Map and map-like presentations are essential to communicate spatial information. As 3D city models are becoming 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 an algorithm for the simplification of solitary 3D building models. It is based on the decomposition of space along the major planes of the building. 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 by adjusting the major planes. The generalisation is solely controlled by an intuitive distance threshold value that specifies the minimum size of the building elements that are created. In contrast to former publications, this paper describes the generalization with a mathematical focus.

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