Footprint-Based Generalization of 3D Building Groups at Medium Level of Detail for Multi-Scale Urban Visualization

Shuang He, Guillaume Moreau, Jean-Yves Martin
L'UNAM Université, Ecole Centrale Nantes, CERMA
Nantes, France
Email: Shuang.He; Guillaume.Moreau; Jean-Yves. Martin@ec-nantes.fr

***Abstract*—In order to enable multi-scale urban visualization, multiple model representations at different levels of detail (LoDs) need to be produced (like by generalization) in advance or on the fly. At local scale, building groups are involved and at least medium LoD is needed in terms of visual perception. Motivated by such demands, this article proposes a novel method for generalizing 3D building groups at medium LoD (the idea was firstly presented in the work of He et al. [1]). The goal is to reduce both geometric complexity and information density. The emphasis is placed on converting 3D generalization tasks into 2D issues via buildings' footprints. The challenge is how to do the mapping from 3D to 2D without losing the information for going back to 3D, especially for a non-prismatic model at medium LoD.**

Instead of treating such model as a whole, two preprocessing steps (model partition and unit division) are introduced to decompose a model into suitable structures for footprint-based generalization. As a result, basic generalizations units are obtained, and each of them is divided into $Top + Body$. The $Body$ part must be a prism for footprint projection. The Top part can include roofs and upper walls, and it can be transplanted onto the extruded model by displacement or be generalized with adjacent Top parts. Two common types of building groups are studied and different algorithms are developed for their generalization. Experimental results validate the effectiveness of our approach.

***Keywords*-3D generalization; building group; footprint; level of detail; multi-scale urban visualization**

I. Introduction

3D city visualization requires different representations of building models at different levels of detail (LoDs) to satisfy different scales and application needs. These LoDs should be generated automatically by specific generalization procedures. Generalization has a long history in cartography [2], with the goal of emphasizing the most important map elements while still representing the world in the most faithful and recognizable way. 3D building generalization in city visualization shares the same goal, but should consider both geographical and 3-dimensional information.

As discussed and listed in [3], unlike 2D maps that have standard official scale series, there are no generally agreed LoDs for 3D buildings. Including the four LoDs defined by CityGML (City Geography Markup Language) [4], the existing definitions of LoDs for 3D buildings only differentiate by 3D details. That is to say, they hardly respond to geographical generalization, like the generalization regarding a group of 3D building, where topological relations should also be considered. This seems to lead more attention to single building generalization.

A number of algorithms have been developed for 3D building generalization. Most of those algorithms deal with single buildings. Generalization of building groups is seldom addressed. In 3D city visualization, the goal of generalization is not only to simplify individual objects, but also so to achieve better cognition by emphasizing important features. Thus, there rises a generalization need for building groups. Both 3-dimensional detail and geographical relations should be taken into account. More generalization operations like selection, aggregation, typification and their combinations are expected.

Footprint has been serving as the connection between 2D and 3D. Plenty of block models of buildings were extruded from cadastral maps using their footprints and heights. But more detailed models could not be acquired in this way. Therefore, a question rises here: how can we translate 3D building generalization issues into 2D scope for generalizing more detailed 3D building models?

This article is organized as below: related work is reviewed in Section II. Concerned issues are discussed in Section III. Section IV gives an overview of our approach. Section V and Section VI focus on decomposing a 3D building model into suitable units for footprint-based generalization through model partition and unit division. Generalization algorithms for two types of building groups are developed in Section VII. Section VIII implements the proposed approach and presents the results. Section IX concludes the article. Section X discusses the future work.

II. Related Work

Compared with the history and achievements in 2D generalization, 3D generalization is still very young and immature. A number of algorithms have been developed for generalizing single buildings. Thiemann proposed to segment a building into basic 3D primitives and to decompose the whole generalization process into segmentation, interpretation and generalization phases [5]. Mayer [6] and

Forberg [7] developed scale-space techniques for simplifying buildings, partly based on the opening and closing morphological operators. Kada proposed to define parts of simplified buildings as intersections of half-planes [8] and to divide buildings into cells and to detect features by primitive instancing [9]. Without semantic information, these methods mainly detect building features based on pure geometry.

By taking semantic information into account, Fan et al. [10] proposed a method for generalization of 3D buildings modeled by CityGML from LoD3 to lower LoDs. Their research showed that good visualization properties could be obtained by only using the exterior shell of the building model that drastically decreases the required number of polygons. Fan and Meng [11] extended their work to the generalization of CityGML LoD4 building models, and concentrated on deriving LoD2 CityGML buildings from LoD3 [12]. However, the above mentioned methods are all limited to generalization regarding single buildings.

Anders [13] proposed an approach for the aggregation of linearly arranged building groups. Their 2D silhouettes, which are the results of three orthogonal projections, are used to form the generalized 3D model. Guercke et al. [14] studied the aggregation of LoD1 building models in the form of Mixed Integer Programming (MIP) problems.

Techniques start emerging for generalizing 3D building groups in the context of city visualization. Glander and Döllner [15] proposed cell-base generalization by maintaining a hierarchy of landmarks. In each cell, only landmark buildings can be seen, the other buildings are replaced by a cell block. In the work of Mao et al. [16], buildings are divided into clusters by road network, and grouped with close neighbors in each cluster. However, only LoD1 buildings were handled.

Moreover, many other algorithms have been developed emphasizing different aspects. Putting the emphasis on progressively removing details, Sester and Klein [17] introduced a rule base which can guide facade generalization including aggregation of neighboring windows, elimination, enlargement or displacement of small facade features depending on their relative importance. Kada [18] introduced an algorithm of constrained invasive edge reduction. Rau et al. [19] focus on automatic generation of pseudo-continuous LoD polyhedral 3D building models, using only one parameter, i.e. feature resolution. For the purpose of simplifying and emphasizing 3D buildings, Thiemann and Sester [20] presented adaptive 3D templates. They categorize building models into a limited number of classes with characteristic shapes, and then use these templates for typical 3D buildings and replace the original 3D shape with the most similarity of those templates. Zhang et al. [21] studied geometry and texture coupled generalization towards realistic urban visualization. He et al. [22] proposed a new way to produce LoDs for 3D city models at (pseudo) all range of scales, by combining generalization and procedural modeling.

III. Concerned Issues

A. Levels of detail for buildings

The existing methods for measuring levels of detail of building models mainly use descriptive expressions, such as listed in the survey of Meng and Forberg [3] and defined in CityGML standard [4]. CityGML differentiates five building LoDs. A LoD0 building can be represented by footprint or roof edge polygon. LoD1 is the well-known blocks model comprising prismatic buildings with flat roofs. In contrast, a building at LoD2 has differentiated roof structures and thematically differentiated surfaces. LoD3 denotes architectural models with detailed wall and roof structures, balconies, bays and projections. LoD4 completes a LoD3 model by adding interior structures for 3D objects. In general, we can consider LoD0 and LoD1 as low LoDs, LoD2 as medium LoD, LoD3 and LoD4 as high LoDs.

The five CityGML's LoDs are generally accepted, however, each LoD obviously covers a rather wide range. Thus, many in-between LoDs can hardly be distinguished. Moreover, these LoDs are made for individual buildings. They will face more challenges when a number of building models are involved. We also adopts CityGML's definitions, but trying to extend them for denoting LoDs for building groups and indicating more in-between levels.

B. Generalization scale and complexity

At different scales, 3D building models have different features and the corresponding generalization faces different types of complexity, such as geographic complexity and geometric complexity. Here we use the term - geographic complexity - to refer to the complexity related to geographic distribution, including topological relation, information density, etc. Geometric complexity refers to the complexity of geometric representation of models, such as the number of primitive elements.

At city scale, low LoD building models are mostly involved, so the generalization task mainly deals with geographic complexity. At object scale (e.g. single buildings), high LoD models are often required, so the generalization focus is on geometric complexity. At local scale (e.g. building groups), medium LoD models are usually concerned, thus both geographic complexity and geometric complexity should be considered. Compared with single building generalization, building group generalization is seldom addressed but also quite needed, for example, when we want to reduce computational complexity without losing the recognizability of a building cluster. Therefore, the proposed generalization approach aims at reducing both geometric and geographic complexity of a group of buildings, meanwhile maintaining the general aspect of the group.

For the reduction of geometric complexity, a number of generalization algorithms have been specifically designed for single buildings. Can we make generic approaches that suit to both (complex) single buildings and building groups? For the reduction of geographic complexity, can we adapt 2D generalization techniques to 3D scope? Both of these two challenges are concerned in the development of our approach.

C. Object nature and model quality

A proper generalization approach is firstly oriented by the object nature. In 3D computer graphics, a great number of algorithms have been developed for simplifying polygonal representations of solids and surfaces for general 3D objects. However, these algorithms can hardly be applied to buildings, because most 3D building models are already low-polygon models. Besides, parallel and orthogonal properties of buildings need to be respected during simplification. Interdependency between building components, adjacent buildings, and other city objects should also be considered. Therefore, determined by the nature of building, generalization algorithms for 3D building models are usually specifically designed.

Semantics plays an important role in building generalization. If we know the semantic meaning (wall, roof, window, door, balcony etc.) of each geometry, it can be properly treated according to its kind. The existing algorithms for building generalization can be grouped into two categories decided by whether semantic information is provided along with the geometric model. For generalizing pure geometry building models, the primary effort is mainly devoted to feature detection and segmentation. Such effort can be exempted if semantics is provided. Moreover, the coherence of geometry and semantics is also influential. Stadler and Kolbe [23] pointed out that the more information is provided by the semantic layer, the less ambiguity remains for geometrical integration. We believe it is also true for generalization task. Figure 1 shows two extreme cases of the level of coherence.

IV. Approach overview

The generalization target of this approach is a group of building models at medium LoD. The emphasis is placed on translating 3D generalization tasks into 2D problems. The strategy is to generate footprints of 3D buildings, perform 2D generalization on their footprints, and then extend the result to 3D.

Figure 2 depicts the main flow of the proposed footprint-based approach for generalizing building groups. Because the available 3D building models usually come with unfavorable data structures for direct footprint projection, preprocessing is needed to obtain suitable units for projection and generalization (step 1). Because we are coping with building models at medium LoD, roof structures should be properly handled. Another preprocessing method (step 2) is introduced to divide each generalization unit into $Top + Body$, so that footprints can be projected from each $Body$ (step 3), and Top parts can be preserved for separated generalization. Any 2D generalization operators and algorithms can then be applied to their footprints (step 4), hence allowing arbitrary levels of generalization. Prismatic bodies can be extruded from generalized footprints (step 5). The $Top + Body$ division supports flexible roof generalization (e.g. displacement and flattening) on Top parts (step 6). Assembling the results of extrusion and Top generalization (step 7), the final result of the generalized 3D building group can be obtained.

V. Preprocessing I: model partition

The goal of partitioning is to decompose the original model into basic units favorable for generalization. Here rises the question: what makes a favorable unit for generalization? We believe there are two important criteria for such unit: 1) it has coherent structure in geometry and semantics; 2) it (or a part of it) can be fully represented by its footprint. The first criterion is one of the emphases addressed by CityGML [24]. The second criterion is seldom mentioned, but very important for facilitating generalization tasks and for adapting 2D generalization techniques into 3D scope. Using CityGML LoD2 building model as example, partition rules are developed, so that basic units can be obtained with beneficial attributes for generalization.

A. CityGML LoD2 building model

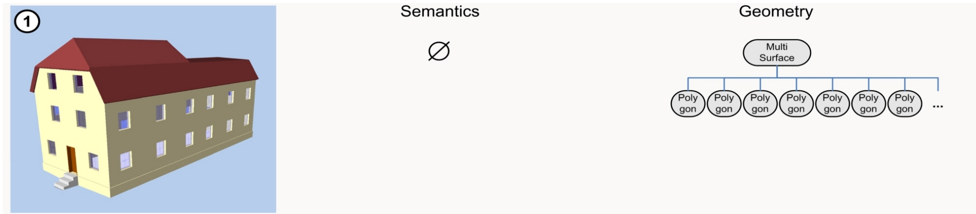
In order to develop proper strategy for partitioning, we should be aware of the data structure and all possible elements of the target model. The original UML diagram of CityGML building model [4] includes all four LoDs. To be more concentrated, we redraw a UML diagram exclusively for LoD2. See Figure 3.

In Figure 3, «$Geometry$» implies purely geometric representation, whereas «$Feature$» implies geometric/semantic representation. According to CityGML standard [4], the concerned features are explained as below:

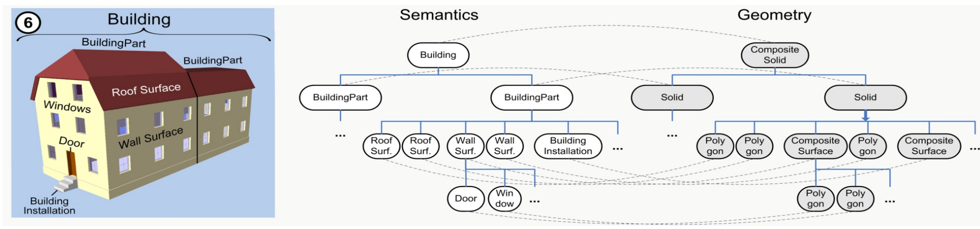
A $Building$ can consist of many $BuildingParts$, and each $BuildingPart$ can also consists of many $BuildingParts$. That is to say, a hierarchical building tree of arbitrary depth may be realized. Moreover, each $Building/BuildingPart$ could consist of three types of elements: text attributes, pure geometry, and geometric/semantic features (for LoD2, they are $BuildingInstallations$, $\_BoundarySurfaces$, and $BuildingParts$). All these elements will be treated differently in our generalization approach. Figure 4 depicts all possible elements and their treatments in the following generalization.

B. Partition rules

Above all, we would like to clarify that the following rules are designed to partition common buildings. It is reasonable to believe that a common building has all the main walls starting from and orthogonal to the (local) ground



(a) Unstructured geometry without semantic object information [23]



(b) Complex object with fully coherent spatio-semantic structure [23]

Figure 1: Comparison of two extreme cases in terms of spatio-semantic coherence.

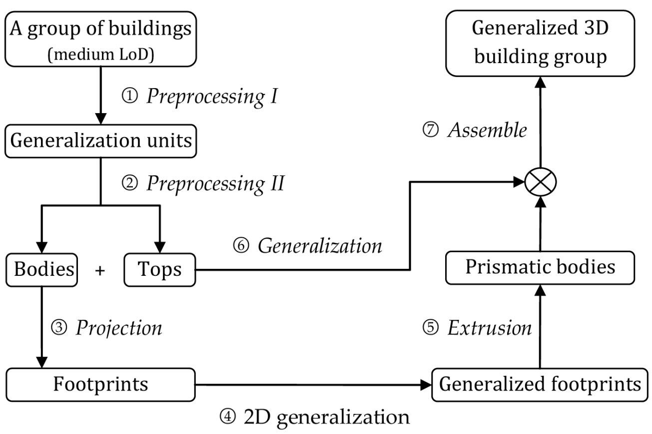


Figure 2: Main flow of the approach for generalizing building groups.

plane. Otherwise, we'd better consider this building as an uncommon building, and prescribe different treatment for generalization. In many cases, uncommon buildings are landmark buildings which may not need to be generalized.

The goal of partition is to get a well structured building in both semantic and geometric sense, so as to extract suitable unit for generalization. As mentioned above, we believe a favorable generalization unit should be able to be fully represented by its footprint. Even though a CityGML building model already has semantically structured geometry, the geometry of each feature may still not be applicable due to the different habits in modeling process. For instance, a complex building may not be decomposed into different building parts; the protruded surfaces of a balcony may be modeled as a part of the wall surfaces. In order to regulate such kind of geometry, the partition rules are introduced as below:

- If a $Building$ is composed of unconnected segments, partition them into different $Buildings$.
- If a $Building$ is composed of structural segments differing in e.g. height or roof type, partition them into different $BuildingParts$.
- If a $Building/BuildingPart$ has smaller components which are not significant as $BuildingParts$ (e.g. chimneys, dormers, and balconies), partition them into $BuildingInstallations$.
- If a $Building/BuildingPart$ has geometries without semantic information, partition them into pure geometries.
- If a $Building/BuildingPart$ has $BuildingParts$ and $\_BoundarySurfaces$ at the same level, make the $\_BoundarySurfaces$ into a new $BuildingPart$.
- If a $Building/BuildingPart$ includes only one $BuildingPart$, move the included $BuildingPart$ into its parent $Building/BuildingPart$.
- If a $Building$ has $\_BoundarySurfaces$, there must be a $WallSurface$ starting from and orthogonal to the ground plane; otherwise, partition this $Building$ as a $BuildingInstallation$ into another $Building$.
- If a $BuildingPart$ has $\_BoundarySurfaces$, there must be a $WallSurface$ starting from and orthogonal to the ground plane; otherwise, partition this $BuildingPart$ into a $BuildingInstallation$.
- If a $Building/BuildingPart$ has unconnected or self-intersected $WallSurface$, partition it into more $BuildingParts$.

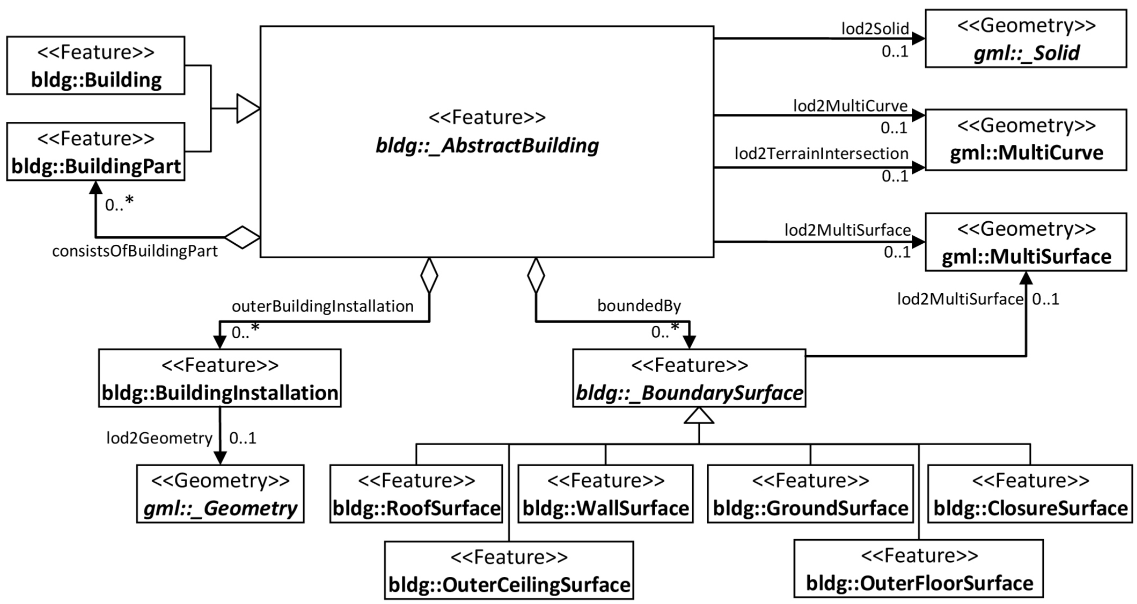


Figure 3: UML diagram of CityGML LoD2 building model drawn based on CityGML standard [4]

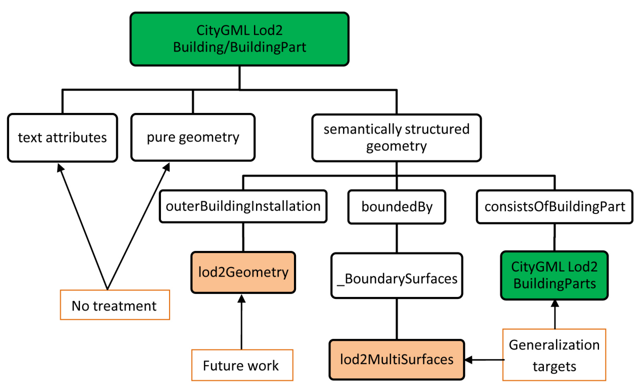


Figure 4: All possible elements of a CityGML LoD2 building model and their treatments in generalization.

C. Partition result

After employing the proposed partition rules, a building tree can be obtained consisting of basic generalization units with beneficial attributes. Although each *Building/BuildingPart* could include text attributes, pure geometry, *BuildingInstallations*, and *_BoundarySurfaces*, only *_BoundarySurfaces* are selected to form the basic generalization unit. The term *unit* will be used in the following discussion, referring to a node of a building tree only consisting of *_BoundarySurfaces*. A simple building only has one generalization unit, which is the root node of its building tree. A complex building has at least two generalization units, including all leaf nodes of its building tree, as illustrated in Figure 5.

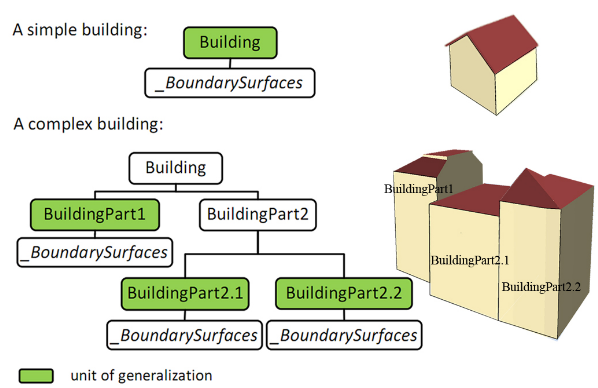


Figure 5: Two examples of building trees consisting of basic generalization units.

The beneficial attributes of a basic generalization unit are listed as below:

- Each basic unit only consists of *_BoundarySurfaces*.
- Each basic unit has unique height.
- If there are *_BoundarySurfaces*, there must be a *WallSurface*; other types of surfaces are optional.
- A *WallSurface* must start from and be orthogonal to the ground plane.
- The orthogonal projection of *WallSurfaces* of each leaf node form a simple polygon or polyline.

So far, we have obtained basic units with favorable *WallSurfaces*, but each unit still cannot be fully represented by footprint fp, which is obtain by projecting all its walls without considering the roof. There also rises the issue of roof generalization. We propose to use fp to fully represent only a part of the unit and to handle roof generalization separately in preprocessing II.

VI. Preprocessing II: unit division

A common way of roof generalization is by primitive matching of different roof types. But type detection is a costly (most often manual) and uncertain process depending on the given types and lots of parameters. In CityGML building models, roof surfaces are separated from walls, but roof type is not always available in attributes. Even if given the roof type, the rebuilding of roof after extrusion would be another difficulty without knowing parameters.

Our approach places the emphasis on converting 3D generalization tasks into 2D scope via footprints. But direct footprint projection of basic generalization units will still lose the roof information, which is important when extending 2D generalization results to 3D. We propose to divide each generalization unit into $Top+Body$ before conducting footprint projection. The $Body$ part is a prismatic model, which can be fully represented by its footprint and associated height. The Top part consists of the rest structures (e.g. roofs and upper walls) of the unit, which can be easily transplanted to a prismatic model and can also be generalized with adjacent Top parts. Thus, only the $Body$ part of each unit is used for footprint projection, and the Top part is preserved for roof generalization.

For a building, if all of its walls end at the top in the same horizontal plane, the Top only consists of its roof; otherwise, the Top consists of its roof and the end walls. An example is given in Figure 6.

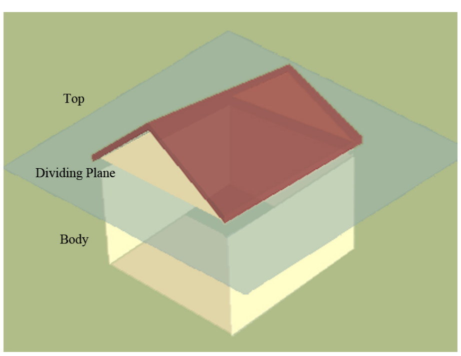


Figure 6: An example of dividing a building into $Top + Body$.

VII. Generalization algorithms

After having partitioned each original model into basic generalization units, and having performed $Top + Body$ division on all the units, footprint-based generalization can then be enabled. Generalization tasks always need human analysis and human decision on what to generalize and how to generalize. Therefore, different strategies and algorithms should be developed for generalizing different types of building groups.

Here we study two types of building groups which widely exist especially in European cities (as illustrated in Figure 7): 1) traditional building groups and 2) modern building groups. It is obvious that type 1) groups have low and crowded buildings with similar heights, but type 2) groups have buildings with prominent difference in height. Therefore, we develop two generalization algorithms for these two types of building groups.

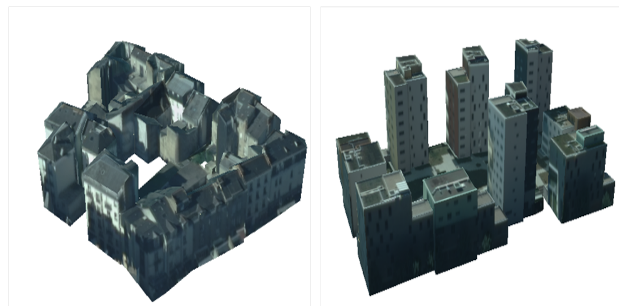


Figure 7: A group of traditional buildings (left) and a group of modern buildings (right), Nantes, France ©IGN BATI 3D

A. Generalization of building groups with a minor difference in height

If a group of buildings have no big difference in height, we believe its outer feature can represent the whole group to a certain extent, like in local scale and or city scale visualization. Therefore, the first generalization task is to detect its outer feature. After have obtained basics generalization units through model partition (Section V), the outer units can be considered as the outer feature of a building group. The outer units can also be aggregated. If all units are outer units, no units will be eliminated, and aggregation can be directly performed on all units. If the outer units have non-flat roofs, two levels of aggregation can be achieved: with or without roof structures. The original roof structures can be preserved based on the $Top + Body$ division (Section VI). They can be transplanted onto the extruded building blocks, and be generalized to flat roofs as well.

Our generalization operations start from a group of LoD2 buildings, but the goal is not to generalize each building to LoD1. Not only each individual building is concerned, but also the overall feature of the group is addressed. We believe that it is better to specify the target when using the concept of LoD, and thereby introduce a more dedicated term - Group LoD - to denote the level of detail of a building group. Group LoD1 and Group LoD2 are defined similar to LoD1 and LoD2 of a building model in CityGML standard.

Another three Group LoDs are introduced to describe more inter-level status. The definitions are given as below:

- Group LoD2: every building model in the group is at LoD2.
- Group LoD1C: the building group is represented by its outer units.
- Group LoD1B: aggregated Group LoD1C model with the same height, but differentiated roof structures.
- Group LoD1A: Group LoD1B model with flattened roof.
- Group LoD1: the building group is a block model, which looks like a LoD1 building model.

The main flow of the algorithm is depicted in Figure 8.

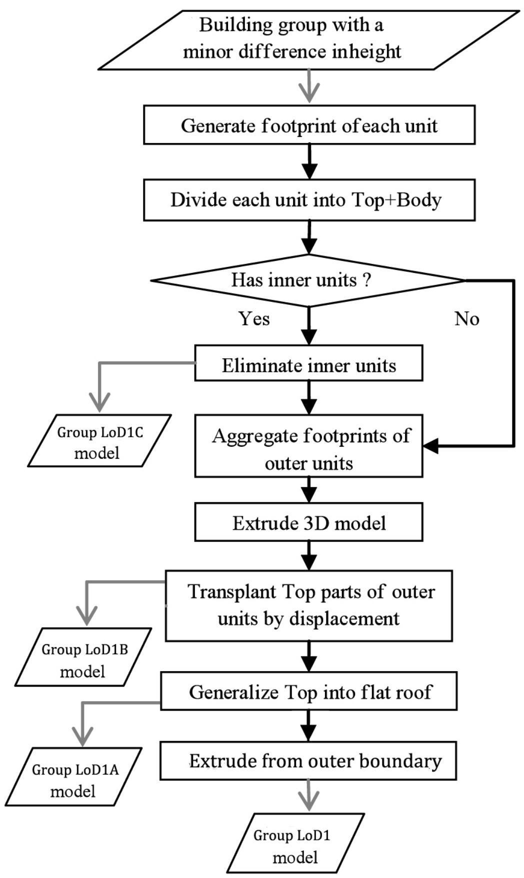


Figure 8: The main flow of the generalization algorithm for building groups with a minor difference in height.

B. Generalization of building groups with a major difference in height

If a building group has a major difference in height, the generalization will be performed on its subgroups. A

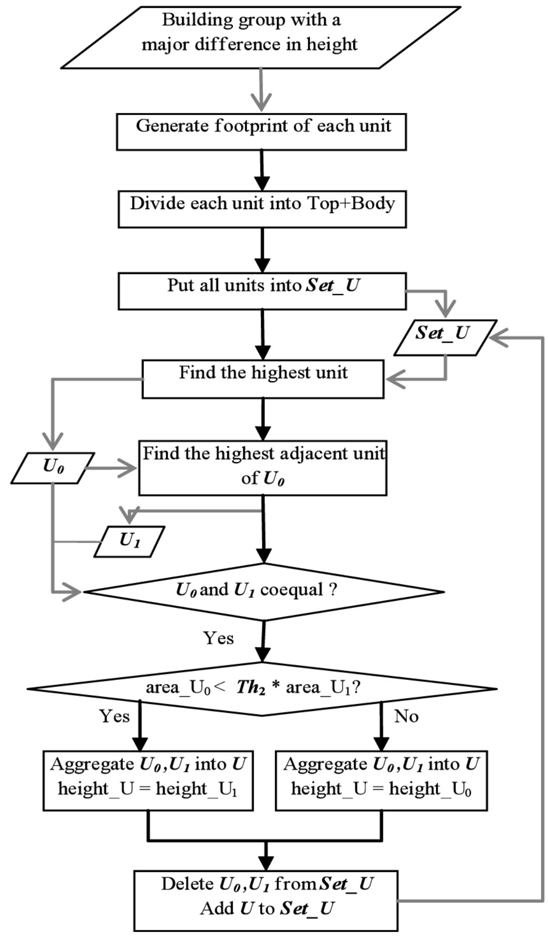


Figure 9: The main flow of the generalization algorithm for building groups with a major difference in height.

subgroup is composed of a center unit and its adjacent neighbors. Each time the highest unit will be chosen from the unprocessed units. If this unit is much higher than its neighbor, they should not be aggregated. We use the term coequal in this paper to indicate that the height difference in two units can be ignored, that is to say, they can be aggregated. Coequal units are defined as below:

Given two units $\boldsymbol{U_1}$ with height $\boldsymbol{h_1}$ and $\boldsymbol{U_2}$ with height $\boldsymbol{h_2}$, if they satisfy the constraint as in Equation (1), $\boldsymbol{U_1}$ and $\boldsymbol{U_2}$ are coequal, where $\boldsymbol{Th_1}$ is a predefined variable as the threshold.

$$\frac{1}{Th_1} < \frac{h_1}{h_2} < Th_1 \qquad (1)$$

When merging two adjacent and coequal units, either height of the original units can be assigned to the new unit. If the lower unit covers a rather large area, the new unit takes the lower height; otherwise, it takes the higher one. We propose a criterion as below:

Given $\boldsymbol{a_1}$, $\boldsymbol{a_2}$, *and* $\boldsymbol{h_1}$, $\boldsymbol{h_2}$ ($\boldsymbol{h_1<h_2}$) *as the areas and heights of two coequal units, the height of new merged unit* $\boldsymbol{h_3}$ *is determined as in Equation (2), where* $\boldsymbol{Th_2}$ *is a predefined variable as the threshold.*

$$h_3 = \begin{cases} h_1 & \text{if } a_1 \geq Th_2 * a_2 \\ h_2 & \text{otherwise} \end{cases} \tag{2}$$

The main flow of the algorithm is depicted in Figure 9.

VIII. Experimental results

The proposed footprint-based generalization approach is tested on two sets of building groups and on a land parcel consisting of 290 buildings.

A. Test 1: Generalization of Building Groups with a Minor Difference in Height

The algorithm for generalizing building groups with minor difference in height (Section VII-A) is tested on a building group consisting of 381 generalization units. The statistics are given in Table I, and the results are shown in Figure 10.

B. Test 2: Generalization of Building Groups with a Major Difference in Height

The algorithm for generalizing building groups with major difference in height (Section VII-B) is tested on a building group consisting of 193 units. The results are shown in Figure 11, and the statistics are given in Table II. In this test we define $\boldsymbol{Th_1}$*=2*, and $\boldsymbol{Th_2}$*=4*. Please see Equation (1) and (2) for the meaning of $\boldsymbol{Th_1}$ and $\boldsymbol{Th_2}$.

C. Test 3: Generalization of Building Groups in A 3D City

A parcel of land consisting of CityGML LoD2 buildings is integrated into a 3D city model, and generalization can be performed on these LoD2 buildings (Figure 12b). With the purpose of conveying the overall feature of building groups, three inter-level models between Group LoD2 and Group LoD1 are generalized using the algorithm proposed in Section VII-A. The results are shown in Figure 12. Table III presents some statistics for each Group LoD, including the number of polygons, buildings, and generalization units. All adjacent buildings are merged into new buildings at Group LoD1C. The following generalization operations are performed on each of these nonadjacent buildings, so the number of building does not change then. But the number of generalization unit drops at each Group LoD, which implies the reduction of information density. The drop of polygon number indicates the reduction of computational complexity.

IX. Conclusion

This article presented a novel approach for generalizing 3D building groups. The goal is to reduce both geometric complexity and information density, meanwhile maintaining recognizability, which requires at least medium LoD models. The emphasis has been placed on translating 3D generalization issues into 2D scope via footprints. First of all, a meaningful partition was suggested so that each footprint can carry feature information. A set of partition rules was developed for partitioning the buildings modeled by CityGML at LoD2.

Footprint-based generalization is then confronted with the difficulty of roof generalization. Unlike the existing approaches such as primitive matching, we proposed to divide a building into $Top+Body$. Thus, a Top part can be easily transplanted onto the extruded model by displacement. Of course, a Top part can also be generalized to a flat roof, or be aggregated with adjacent Top parts.

Two types of building groups were distinguished and further studied in this work: one has major difference in height and the other has minor difference in height. For the former one, we believe its outer feature can represent the whole group to a certain extent. For the latter one, it should not be handled as a whole. An iterative aggregation process is performed by comparing the height and area of every two adjacent units starting from the highest one.

The approach was tested on two building groups and a part of 3D city model. Group generalization shows its advantage in reducing information density, e.g. by eliminating insignificant buildings. Different from the methods only handle LoD1 block models, our approach can handle LoD2 models as well. Instead of aggregating detailed models directly into LoD1 blocks, our approach supports generalization of Group LoDs with geographical features, thereby achieving data reduction and maintaining recognizability at the same time.

As mentioned in Section III-B, we aimed at finding solutions to these two challenges: 1) Can we make generic approaches that suit to both (complex) single buildings and building groups? 2) Can we adapt 2D generalization techniques to 3D scope? Towards the first challenge, we proposed model partition to decompose a building model into generalization units. Thus, a complex building can be seen as a connected building group. Towards the second challenge, we divided each unit into $Top+Body$, so that the $Body$ part can be fully represented by its footprint, through which 3D generalization tasks can be converted to 2D issues.

X. Future work

During unit division, very small upper walls could be generated mostly due to the irregularity of the input model. Those segments are expected to be discarded, but additional roof adjustments are required to keep the topological relation between walls and roof. This will be our next work.

The proposed methods of model partition and unit division are developed for common buildings, with walls starting from and orthogonal to the (local) ground plane. Buildings with special architectural designs with be studied in the future, as well as the necessity of their generalization in the context of urban visualization, since they are usually landmark buildings.

For building group generalization, the ratio of area between space and inner units will be considered during generalizing building groups with a minor difference in height; only two types of building groups have been studied, so more types should be studied in the future; only connected buildings are treated, and building groups with disjoint buildings will be concerned.

Towards LoD measurement of 3D building models, this work introduced a more dedicated term Group LoD and several new Group LoDs to describe in-between levels. There remains open questions: e.g. how to measure LoD with more precision? How many LoDs are there? How to decide LoD according to scale?

REFERENCES

[1] S. He, G. Moreau, and J.-Y. Martin, "Footprint-based 3d generalization of building groups for virtual city visualization," in *GEOProcessing 2012*, 2012, pp. 177–182.

[2] R. B. McMaster and K. S. Shea, *Generalization in Digital Cartography*. Washington, D.C.: Assoc. of American Geographers, 1992.

[3] L. Meng and A. Forberg, *3D Building Generalisation*. Elsevier, 2007, ch. 11, pp. 211–232.

[4] *OSG City Geography Markup Language (CityGML) Encoding Standard (Version 2.0.0)*, Open Geospatial Consortium Inc. Std. OGC 12-019, 2012.

[5] F. Thiemann and M. Sester, "Segmentation of buildings for 3d-generalisation," in *Proceedings of 7th ICA Workshop on Generalisation and Multiple Representation*, 2004.

[6] H. Mayer, "Scale-spaces for generalization of 3d buildings," *International Journal of Geographical Information Science*, vol. 19, no. 8-9, pp. 975–997, 2005.

[7] A. Forberg, "Generalization of 3d building data based on a scale-space approach," in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2004.

[8] M. Kada and F. Luo, "Generalization of building ground plans using half-spaces," in *Proceedings of the International Symposium on Geospatial Databases for Sustainable Development*, 2006.

[9] M. Kada, "Scale-dependent simplification of 3d building models based on cell decomposition and primitive instancing," in *Proceedings of the International Conference on Spatial Information Theory*, 2007.

[10] H. Fan, L. Meng, and M. Jahnke, *Generalization of 3D Buildings Modelled by CityGML*. Springer, 2009, pp. 387–405.

[11] H. Fan and L. Meng, "Automatic derivation of different levels of detail for 3d buildings modeled by citygml," in *Proceedings of 24th International Cartographic Conference*, 2009.

[12] H. Fan and L. Meng, "A three-step approach of simplifying 3d buildings modeled by citygml," *International Journal of Geographical Information Science*, vol. 26, no. 6, pp. 1091–1107, 2012.

[13] K.-H. Anders, "Level of detail generation of 3d building groups by aggregation and typification," in *International Cartographic Conference*, 2005.

[14] R. Guercke, T. Götzelmann, C. Brenner, and M. Sester, "Aggregation of lod 1 building models as an optimization problem," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 66, no. 2, pp. 209–222, 2011.

[15] T. Glander and J. Döllner, "Abstract representations for interactive visualization of virtual 3d city models," *Computers, Environment and Urban Systems*, vol. 33, pp. 375–387, 2009.

[16] B. Mao, Y. Ban, and L. Harrie, "A multiple representation data structure for dynamic visualisation of generalised 3d city models," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 66, no. 2, pp. 198–208, 2011.

[17] M. Sester and A. Klein, "Rule based generalization of buildings for 3d-visualization," in *Proceedings of the International Cartographic Conference*, 1999.

[18] M. Kada, "Automatic generalization of 3d building models," in *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2002.

[19] J.-Y. Rau, L.-C. Chen, F. Tsai, K.-H. Hsiao, and W.-C. Hsu, "Lod generation for 3d polyhedral building model," in *Advances in Image and Video Technology*, ser. Lecture Notes in Computer Science, L.-W. Chang and W.-N. Lie, Eds. Springer Berlin / Heidelberg, 2006, vol. 4319, pp. 44–53.

[20] F. Thiemann and M. Sester, "3d-symbolization using adaptive templates," in *Proceedings of ISPRS Technical Commission II Symposium*, 2006, pp. 49–54.

[21] M. Zhang, L. Zhang, P. T. Mathiopoulos, W. Xie, Y. Ding, and H. Wang, "A geometry and texture coupled flexible generalization of urban building models," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 70, pp. 1–14, 2012.

[22] S. He, G. Besuievsky, V. Tourre, G. Patow, and G. Moreau, "All range and heterogeneous multi-scale 3d city models," in *Proceedings of Usage, Usability, and Utility of 3D City Models.*, 2012.

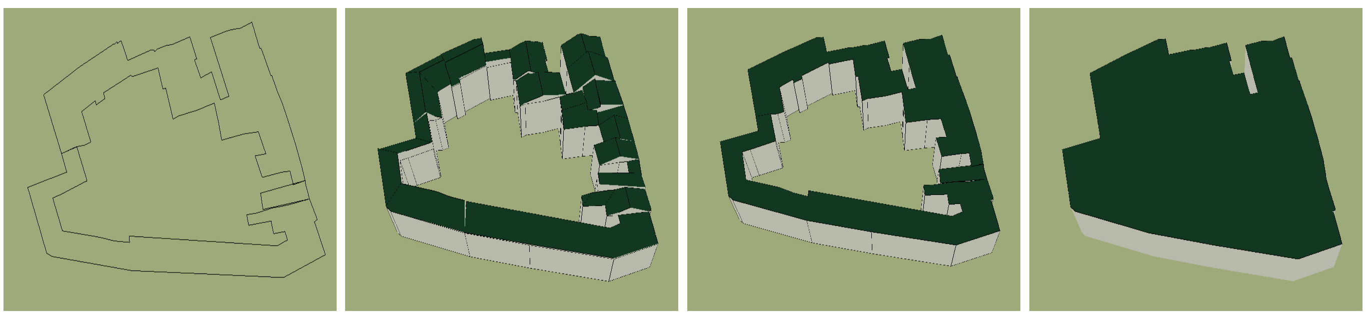
[23] A. Stadler and T. H. Kolbe, "Spatio-semantic coherence in the integration of 3d city models," in *Proceedings of the 5th International Symposium on Spatial Data Quality*, 2007.

[24] G. Gröger and L. Plümer, "Citygml – interoperable semantic 3d city models," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 71, pp. 12–33, 2012.

Table I: Statistics for Test 1.

Group LoD	Fig.	Footprint		3D model	
		Vertex	Polygon	Vertex	Polygon
Group LoD2	10a	361	44	1565 (100%)	381 (100%)
Group LoD1C	10d	186	18	843 (53.9%)	203 (53.3%)
Group LoD1B	10f	121	3	679 (43.3%)	153 (40.2%)
Group LoD1A	10g	121	3	590 (37.7%)	121 (31.8%)
Group LoD1	10h	70	1	345 (22.0%)	70 (18.4%)

(a) Original models (©IGN BATI 3D) (b) Projected footprints (c) Footprints of outer units (d) Group LoD1C model

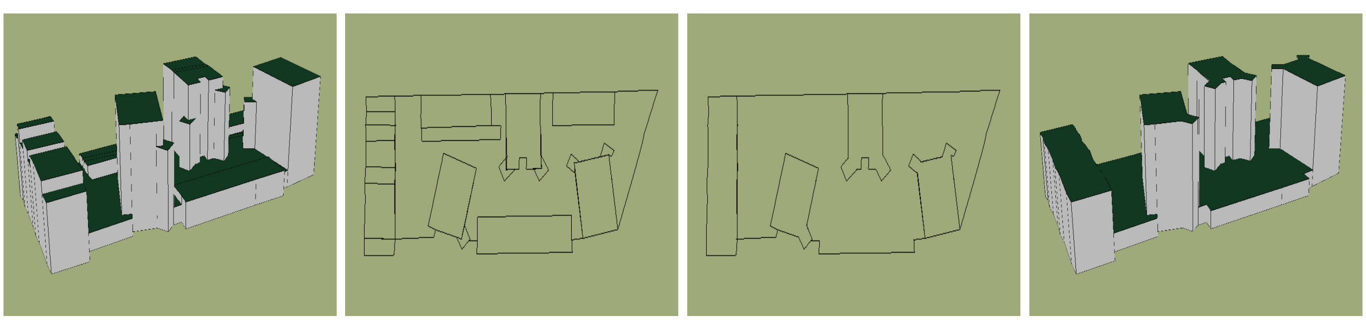


(e) Footprints of merged outer units (f) Group LoD1B model (g) Group LoD1A model (h) Group LoD1 model

Figure 10: Generalization results of Test 1.

Table II: Statistics for Test 2.

Group LoD	Fig.	Footprint		3D model	
		Vertex	Polygon	Vertex	Polygon
Group LoD2	11a	193	19	879 (100%)	211 (100%)
Generalized	11d	118	5	565 (64.3%)	116 (55%)

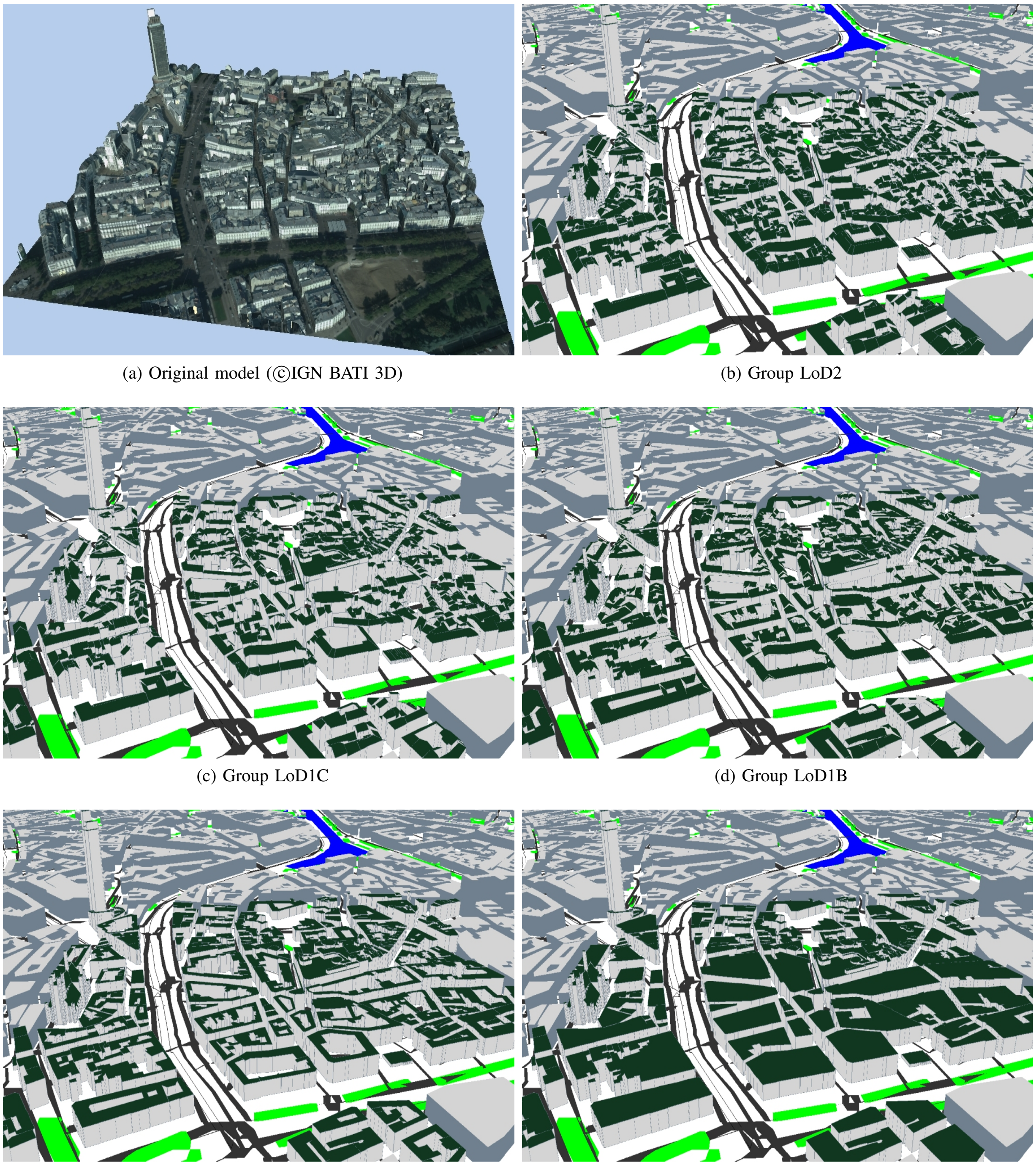


(a) Original models (©IGN BATI 3D) (b) Projected footprints (c) Generalized footprints (d) Generalized model

Figure 11: Generalization results of Test 2.

Table III: Statistics for Test 3.

	Group LoD2	Group LoD1C	Group LoD1B	Group LoD1A	Group LoD1
Figure	12b	12c	12d	12e	12f
Polygons	52247 (100%)	37348 (71%)	35592 (68%)	28023 (54%)	20338 (39%)
Buildings	290	213	213	213	213
Units	1421	949	321	312	213



(a) Original model (©IGN BATI 3D) (b) Group LoD2

(c) Group LoD1C (d) Group LoD1B

(e) Group LoD1A (f) Group LoD1

Figure 12: Generalization results of Test 3. Three landmark buildings are marked and excluded from each generalization.