Computers, Environment and Urban Systems 41 (2013) 309–317

Contents lists available at SciVerse ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/compenvurbsys

A semantics-constrained profiling approach to complex 3D city models

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ARTICLE INFO

Article history:
Received 6 December 2011
Received in revised form 4 July 2012
Accepted 4 July 2012
Available online 3 August 2012

Keywords:
3D city models
Profiling
Semantic constraints
Consistency
CityGML

ABSTRACT

A complex 3D city model contains detailed descriptions of both its appearance and its internal structure, including architectural components. Because of the topological complexity and the large volumes of data in such models, profiling is an effective method to present the internal structure, the distributed characteristics, and the hierarchical relationships of the model to provide intuitive visual information to the viewer and to reveal the relationships between the elements of the model and the whole. However, with commonly used boundary descriptions, it is difficult to comprehensively preserve the consistency of three-dimensional profiling using existing algorithms based on geometric constraints. This paper proposes a novel semantics-constrained profiling approach to ensure the consistency of the geometrical, topological, and semantic relationships when profiling complex 3D city models. The approach transforms the 3D model's boundary description, defined using the CityGML standard of the Open Geospatial Consortium (OGC), into a set of unified volumetric features described as solids. This approach is characterized by (1) the use of the concepts of semantic relationships, virtual edges, and virtual surfaces; (2) the semantic analysis of 3D models and the extraction of volumetric features as basic geometric analytic units; (3) the completion of structural connectivity and space coverage for each volumetric feature, which is represented as a solid model; and (4) the use of a reliable 3D Boolean operation for efficient and accurate profiling. A typical detailed 3D museum model is used as an example to illustrate the profiling principle, and the experimental results demonstrate the correctness and effectiveness of this approach.

1. Introduction

As the increasing complexity of a 3D city model makes the perception and understanding of the model more difficult (Glander & Döllner, 2009), profiling is an effective exploratory method used to present the internal structure, the distributed characteristics and the hierarchical relationships of the model to provide intuitive visual information to the viewer and to reveal the relationships between the elements of the model and the whole. Both geometrical and topological consistencies are important concerns when evaluating the effectiveness of profiling analysis. Consistency is not only an important aspect of spatial data quality (Gröger & Plümer, 2011a) but also a crucial prerequisite for many relevant applications of 3D city modeling (Gröger & Plümer, 2009). However, 3D city models that satisfy the CityGML standard are characterized by a unified multi-level representation of the geometrical, topological and semantic relationships (Zhao, Zhu, Du, Feng, & Zhang, 2012) with high coherence. The complexity of this coherence is greater at higher levels of detail (Stadler & Kolbe, 2007). For example, a 3D city model specified at the LoD4 level of detail of CityGML contains a detailed description of both the appearance and the internal structure, including the architectural components (Zhao et al., 2012). The profiling of such enriched 3D city models requires an integrative updating of the outer hull and the interior structures as well as the interior space; additionally, the profiling involves the joint updating of the geometry and its associated semantics as well as their relationships. Consequently, achieving consistent profiling is a basic and critical requirement for applications of complex 3D city models because the results produced by consistent profiling can support further analysis such as thematic queries and volume measurements.

CityGML provides three options for LoD4 models to represent the interior volumetric features: solids, independent discrete thematic boundary surfaces, and both solids and thematic boundary surfaces. The second option, termed as the 'boundary description' in this paper and typically obtained from CAD models, is most often used when a high degree of detail is needed in a model. The boundary description is commonly used not only because CAD models are an important data source for cyber GIS (Kofler, Rehatschek, & Gruber, 1996) but also because, compared to other modeling approaches using accurate measurement techniques, CAD models have advantages when displaying complex internal structures (Zhu & Lin, 2004). However, because this discrete representation is topologically complex, it is difficult to comprehensively preserve

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http://dx.doi.org/10.1016/j.compenvurbsys.2012.07.003

the consistency of the 3D profile when using existing profiling algorithms based on geometrical constraints, which are derived using computational geometry from vector models such as polygonal meshes and solids (Herring, 2001). Inconsistency in open structures (Fig. 1b) and insufficient topological connectivity between related elements (in this paper, complete topological connectivity means that a volumetric feature is represented by complete closed and continuous boundaries) (Fig. 1c) result in the computational problems of incomplete and inconsistent geometry and topology. These factors influence the completeness of the profiling of volumetric features such as rooms with openings for windows and doors.

Existing profiling algorithms based on vector models can be divided into two broad categories: cutting algorithms for polygonal meshes with open borders and profiling algorithms for solid models bounded by closed surfaces.

The first category, cutting algorithms for polygonal meshes with open borders, typically includes incremental algorithms based on edge swapping (Anglada, 1997), classic marching cubes (MC) algorithms (Hoppe, 1996; Lorensen & Cline, 1987; Zhou, Chen, & Tang, 1995), double-edge cutting algorithms (Tang, 1999) and active-points cutting algorithms (Nienhuys & Frank Van Der Stappen, 2004). These algorithms use a single continuous mesh with open borders as the main calculation unit and result in cross sections or split meshes. To calculate profiles, such algorithms require a consistency check of the outlines according to the geometrical topology of the cross sections. The drawbacks of these methods are their high computing cost, which results from the large volume of data, and the potential for topological ambiguity in the intersecting lines produced by complex models and scenes with a wide range of features, aggregate elements, complex topological relationships and mixed graphic element types. These methods are especially likely to produce logical errors because of their incomplete topological connectivity when highly detailed features composed of aggregating elements are profiled. Even when semi-automatic processing is used, degraded or approximately degraded intersecting lines are difficult to identify.

The second category of algorithms, which are always represented as 3D Boolean intersection predicates, addresses two key problems: spatial intersection and geometrical reconstruction. The related research focuses primarily on improving the efficiency of the intersection computation by providing collision detection through a special index (Gottschalk, 2000; Sun, Li, Tian, & Li, 2009; Yang, 2010); this approach has been used to reduce the dimension using projection (Zhang & Zhang, 2010), to simplify the intersecting objects using space partitioning (Yang, 2010) and to design a topological data structure to improve efficiency and stability (Granados et al., 2003). Although these methods can produce profiles with regular mathematical rules and clear topological relationships, they perform well only in cases in which a single model or model element is rigorously 2-manifold, and they cannot handle the diverse geometrical types in complex 3D city models, especially in complex building models such as LoD4 models. Consequently, the methods usually result in a series of discrete surfaces, and the methods have difficulty preserving volumetric features. Additionally, some effective algorithms used in mainstream modeling software, such as the Computational Geometry Algorithms Library (CGAL, 2010), are dependent on additional topological conditions that are not included in the records of general 3D city models.

As mentioned above, because of the complexity of 3D city models, the critical issue when using existing geometrical profiling algorithms is how to preserve the consistency of coherent geometrical, topological, and semantic relationships. Consistency refers not only to the coherent semantic-geometric representation designed using the principles of CityGML (Stadler & Kolbe, 2007) but also to complete space coverage using semantics with a specific demarcation of the geometry in 3D space (Gröger & Plümer, 2011b). Furthermore, consistency requires topological completeness in the 3D space, including a seamless topological connection within the closed boundary surfaces of each volumetric feature and all aggregating elements. However, each spatial element of a 3D city model can be defined as a corresponding volumetric feature, such as a wall or a room, in the semantic description, and also have a coherent and valid geometrical description for the purpose of modeling continuous and closed boundaries with specific demarcations. Therefore, the key problem in consistent profiling is to completely calculate correct profiles with specific and proper semantics and to preserve the correct model structures of all of the volumetric features, specifically avoiding the reduced dimensionality of geometric models resulting from incomplete boundaries. In this way, the ability to support further analyses, such as thematic queries, is maintained.

This paper proposes a novel semantics-constrained profiling approach to ensure the consistency of the geometrical, topological,

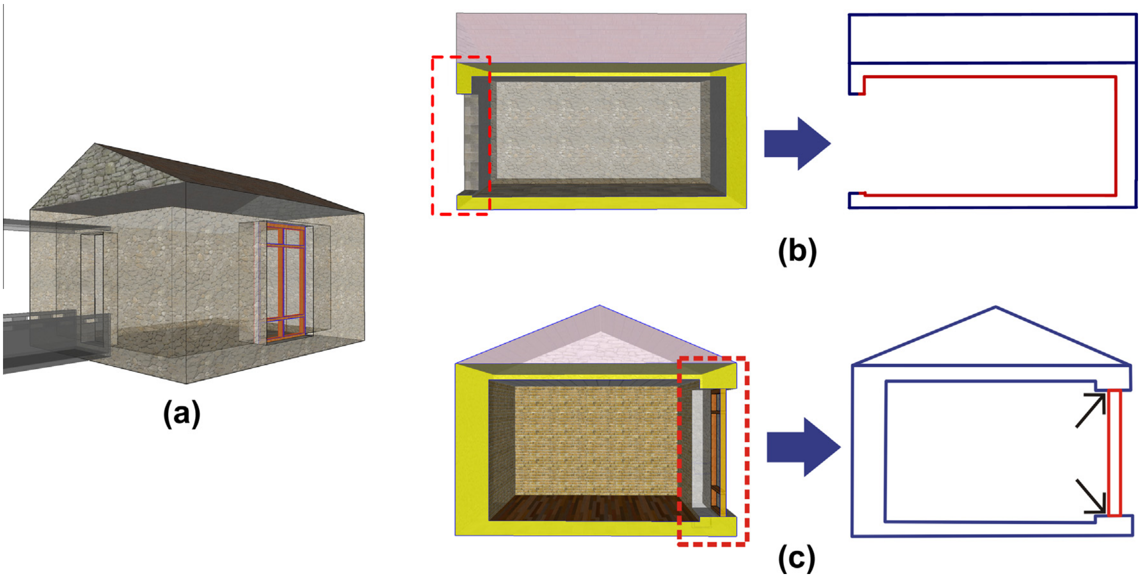


Fig. 1. Inconsistency problems in 3D building model profiling.

and semantic relationships in the profiling commonly used in complex 3D city models. The remainder of this paper is organized as follows. In Section 2, the concepts of semantic relationships, virtual edges and virtual surfaces are introduced to support the description of the transformation from a boundary to a solid. Section 3 presents the principles and describes the implementation of the proposed algorithm. The experimental results and further analysis are outlined in Section 4. Finally, concluding remarks are presented in Section 5.

2. Transforming a boundary description into a solid description

The key strategy of our method is to reorganize the independent thematic boundary surface elements of the existing CityGML LoD4 model to extract a complete set of volumetric features using solid descriptions as the basic units of geometric analysis and to perform unified profiling. The following sub-sections introduce the basic definitions and the conditions used in the transformation process.

2.1. Basic definitions

Volumetric features require a valid geometric solid description that is an aggregation of continuous and closed boundaries with additional topology. To describe the open and discontinuous boundary created by an open structure and the topologically disconnected elements in a complex 3D city model, semantic relationships as well as the concepts of virtual edges and virtual surfaces are introduced to complete the solid description of the volumetric features extracted from aggregated boundary features.

2.1.1. Semantic relationship

The framework of existing topological spatial relations has been well defined by Egenhofer and Franzosa (1991). However, some semantic relationships, such as the is-part-of relationship between features, can be derived only at the semantic level (Gröger, Kolbe, Czerwinski, & Nagel, 2008) and can effectively reduce the geometrical ambiguities (Stadler & Kolbe, 2007). Therefore, semantic relationships should be considered to be essential constraint factors in complex 3D city models and can be formally described as follows:

$$M = \{G, S, T, SR\};$$

where M represents the complex 3D city model, G represents the geometry of the elements in the model, S represents the semantics associated with the elements in the model (e.g., a wall surface or an opening), T represents the topological relationships of the elements, and SR represents the semantic relationships of the elements.

Similar relationships, such as the "is-part-of" relationship in navigation (Hu, 2008; Zhu & Hu, 2010; Zhu et al., 2010) and the "mortise-and-tenon-like" and "masonry-like" relationships in generalization (Zhao et al., 2012), have been successfully introduced in professional GIS applications. For volumetric features extracted from boundary descriptions, there are two types of semantic relationships. A *composite relationship* describes the structural composition of a volumetric object, in which the connected boundary surfaces are aggregated to the outer hull of the volumetric object; for example, a room is the composite of the wall surfaces and the ceiling surfaces. A composite relationship can effectively determine the correct connectivity and distinguish the role of a boundary connection within intricate structural joints between elements. A *membership relationship* describes the hierarchical relationship between volumetric objects, such as between a room and the related windows. These relationships in the semantic model should be recognized and properly handled during the extraction of volumetric features; they indicate the correct structural connectivity and semantic hierarchy between model elements and avoid violating the rules of the valid model structure that prohibit the arbitrary combination of connective boundary surfaces or elements in profiling.

2.1.2. Virtual edges

Virtual edges are introduced to complete the topological connectivity, in the sense of the topological "meet" relationship (Egenhofer & Franzosa, 1991), between two volumetric features with a membership relationship. When two volumetric features do not meet in their respective edge collections, a virtual edge should be created in the edge collections of both volumetric features, as shown in Fig. 2a.

If a virtual edge is not introduced, some volumetric features, such as a room with doors and windows, cannot be extracted from a closed structure with a continuous boundary. Based on such a disjoint structure, it is difficult to calculate the correct cross sections. Therefore, the virtual edges must be modeled before executing the cutting calculation.

2.1.3. Virtual surfaces

Compared with a normal boundary surface (here termed a real surface), a virtual surface is introduced to achieve the closure of a structure, to complete space coverage and to accomplish the space demarcation of a volumetric feature, which is composed of the boundary surfaces defined by a composite semantic relationship. A virtual surface requires the complete cohesion of the boundaries of the virtual surface with the corresponding open structure. The volume of an open volumetric object is computed in a manner similar to the concept of a closure surface in CityGML, as shown in Fig. 2b.

If a virtual surface is not introduced, some volumetric elements in LoD4 models, such as tunnels, corridors and rooms with unsealed openings, cannot be modeled with closed surfaces. This unbounded space demarcation not only results in incomplete models but also leads to inconsistent descriptions of the geometry and the semantics. It is thus difficult to preserve closed boundaries in the model elements resulting from the original semantic-volumetric features, such as certain complete rooms. Additionally, the incompleteness of the original models will increase after profiling and separate some features from their semantically defined relationships.

2.2. Volumetric features with solid descriptions

With the introduction of virtual edges and virtual surfaces, we can achieve consistent 3D city models. Instead of using discrete processing on unclosed boundary surfaces, any 3D city model can be decomposed into a set of volumetric features according to their semantic relationships. Therefore, we can directly extract such volumetric features from the boundary surfaces with the correct structural connectivity determined from the composite relationship from the semantic model. These volumetric features are described as a geometric solid bounded by a closed composite surface (Herring, 2001; Mäntylä, 1988) and can be directly employed as basic analytic units to calculate the cross section in an arbitrary direction.

It is important to note that to ensure that each profile inherits the unique spatial and semantic relationships of the model, the set of volumetric features comprising a 3D city model should satisfy the following two conditions: (1) each volumetric feature should be an atomistic-level representation that cannot be subdivided into a more detailed description of the feature, and (2) the set of volumetric features must completely cover the entire inner space bounded by the outer shell of the 3D city model with no overlapping. This requirement ensures that any region of any section of such a space can be completely defined using closed-boundary polygons with

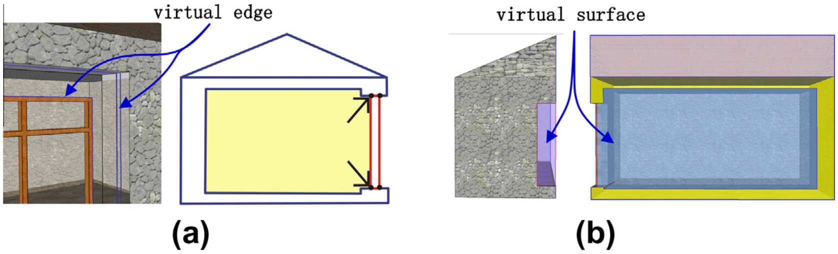


Fig. 2. Virtual edge and virtual surface.

semantically defined relationships and can support further visual schemes, inquiries and analysis.

3. Algorithm description

3.1. Overview

To overcome the drawbacks of purely geometrical approaches, and based on the concepts introduced above, this paper presents a novel semantics-constrained approach for profiling complex 3D city models. The approach considers the semantic relationships between the elements and treats the analyzed model as an integrated hierarchical description in 3D space, based on a corresponding consistent expression, to perform a hierarchical analysis with semantic constraints and to achieve consistent profiling of the geometrical, topological and semantic relationships. The flowchart of the algorithm is shown in Fig. 3 and described below.

Step 1: Based on the semantic analysis approach, semantic themes in CityGML LoD4 models are analyzed to extract the volumetric features according to semantic relationships.

Step 2: Virtual edges are introduced to complete the topological connectivity between relative structures; additionally, virtual surfaces are introduced to seal open spaces to achieve the complete space coverage of the semantic tree with specific geometric space demarcations.

Step 3: The solid elements are used as the primary computational units to calculate the profiles, employing a vector Boolean operation based on a binary space partitioning (BSP) tree.

Step 4: Reconstruction is executed from top to bottom according to the hierarchical relationships, and the profiled models are created.

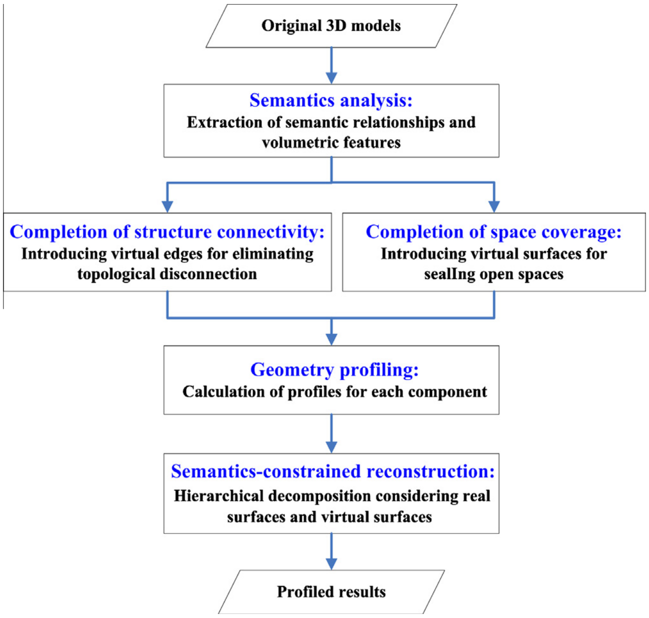


Fig. 3. Flowchart of the semantics-constrained profiling algorithm.

3.2. Semantic analysis

Although CityGML allows the definition of volumetric features, such as rooms, in 3D city models, directly executing profiling on a LoD4 model does not achieve consistency because volumetric features are not mandatorily required to have solid descriptions in CityGML. In detailed models, volumetric features are often modeled using a discrete wall surface, floor surface or other independent thematic boundary surface. These volumetric features are empty structures. Therefore, the extraction of a complete set of volumetric features corresponding to the original model is an essential step to achieve a complete and consistent profiling result.

We realize the extraction by analyzing the semantic model. Fig. 4 shows the flowchart for extracting volumetric features from LoD4 models while considering the semantic relationships.

First, the semantic model and the semantic relationships are extracted. Second, the atomistic-level volumetric features, including walls, rooms, elevators, corridors, staircases and other structural solids and spaces, are selected according to the membership relationship while satisfying condition 1 from Section 2.2 to prevent any space overlap between the extracted volumetric features. Third, the geometry of each selected feature is extracted according to the composite relationship of the subfeature boundary surfaces. Finally, the complete coverage of the inner space bounded by the

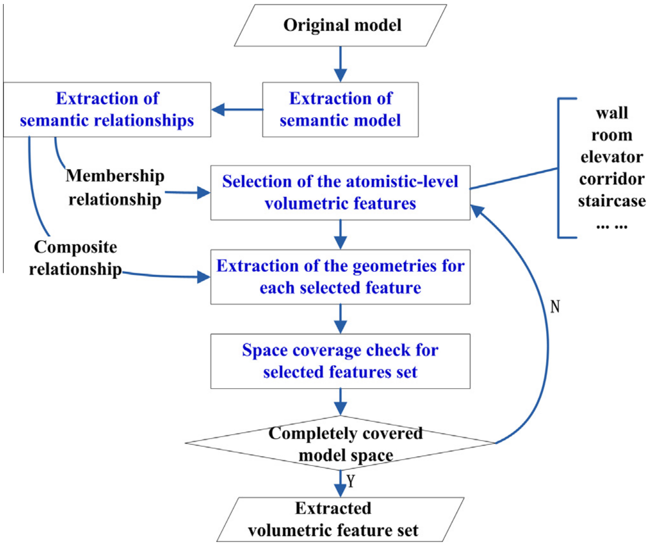


Fig. 4. Flowchart of the extraction of the volumetric features from the LoD4 model.

outer shell of the original model is verified according to condition 2 from Section 2.2 to ensure the integrity of the profile.

An example of an LoD4 building model with boundary organization is shown in Fig. 5 to illustrate the extraction of volumetric features.

In the example model, the original boundaries are divided into three volumetric features: an attic, a room and a wall. The room volume has the window as a member and contains an open entrance connected with a passageway. Therefore, it is not a solid bounded by closed and continuous geometric surfaces, and these elements must be completed after the extraction process to satisfy topological connectivity and geometrical closure.

An illustration of the hierarchical structure of the feature organization corresponding to the example model in Fig. 5 is shown in Fig. 6.

In Fig. 6, $\{Gi|i \in \mathbb{N}\}$ and $\{Si|i \in \mathbb{N}\}$ represent the basic geometrical elements and the associated semantic elements, respectively, of the original model based on the boundary organization. The solid outlines indicate the semantic nodes in the original model, and the dotted outlines indicate the virtual surfaces created during the analysis. $\{mj|j \in \mathbb{N}\}$ represents the geometrical models of the Gi. $\{Sx \mid x \in a,\ldots,z\}$ represents the volumetric features extracted from $\{Si|i \in \mathbb{N}\}$.

To achieve a concise diagram, in Fig. 6b, we use only three nodes (S1, S2 and S3) to represent the multiple semantic elements, such as the roof surface, ceiling surface and floor surface, shown in Fig. 5b. Sa, Sb, and Sc represent the attic, room and wall volumetric features, respectively, shown in Fig. 5c.

To produce the units of geometric analysis in the proposed algorithm, the geometry of the volumetric features (G12, G23, and G34 in Fig. 6b) is aggregated from $\{Gi|i \in \mathbb{N}\}$ (G1, G2, G3, and G4 in Fig. 6b according to the extraction of the volumetric features. After the solid description of the volumetric features is generated, G12, G23, and G34 satisfy geometrical closure and constitute analytic units for the purpose of geometric profiling.

3.3. Completion of the solid description of volumetric features

Each extracted volumetric feature must be described as a solid to satisfy the unified geometric calculation conditions. The following sub-sections describe the process used to achieve complete structural connectivity and space coverage from the original models consisting of inconsistent open structures with insufficient topological connectivity (as shown in Fig. 1) using the concepts of virtual edges and virtual surfaces.

3.3.1. Completion of structural connectivity

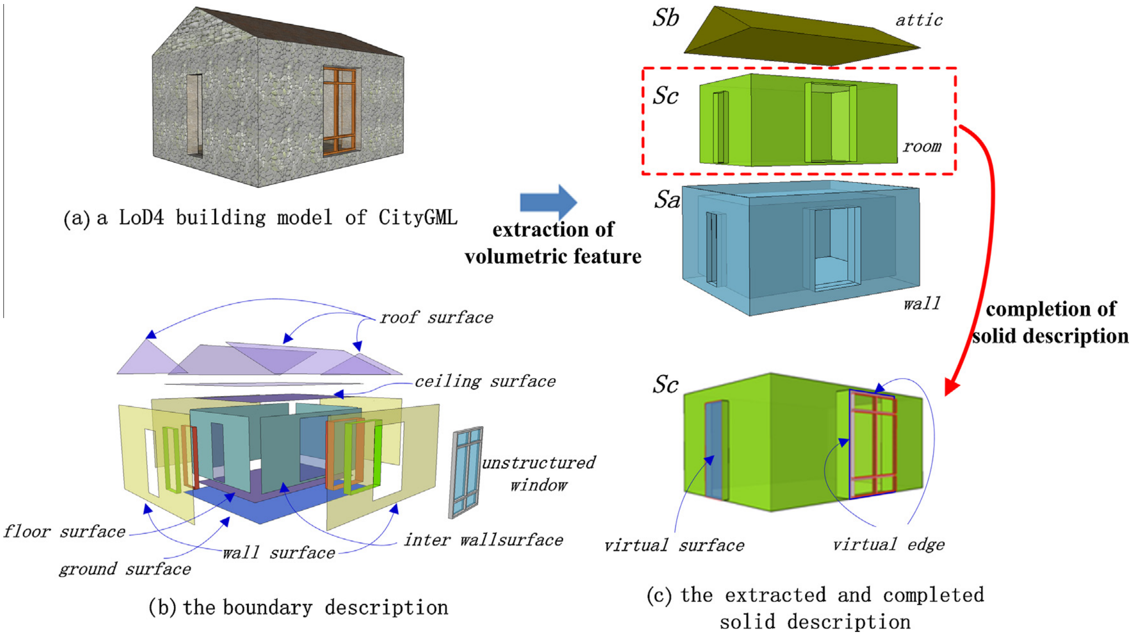
To achieve the complete structural connectivity necessary for valid solid descriptions of the volumetric features, we must ensure complete topological connectivity by creating virtual edges where two volumetric features in a membership relationship meet. The volumetric feature and the member feature are determined from the semantic model. The algorithm for calculating the virtual edges is as follows:

Step 1: Extract the coplanar surface pair within the volumetric feature and its member feature, using edges and faces to create the index for each edge of the target feature.
Step 2: Calculate the intersecting line segments and the boundary line segments of the intersection area.
Step 3: Traverse each line segment and determine whether it is an existing edge on both the volumetric feature and the member feature.
Step 4: Extract the line segments that are not in either the volumetric feature or the member feature, insert the segments into the edge sets of the features and update the joint topological relationships among the points, edges and surfaces.
Step 5: Eliminate the repeated surfaces in each feature.

3.3.2. Completion of space coverage

To achieve the space demarcation of the volumetric features, we must verify the closure of each feature and create virtual surfaces with coherent geometry when the extracted volumetric features are not geometrically closed.

Because each extracted feature is an atomistic-level volumetric feature, the geometry of the feature's boundary can be treated as a whole or as a part of a solid. Therefore, we can verify the closure of each feature and then automatically calculate the coherent geomet-

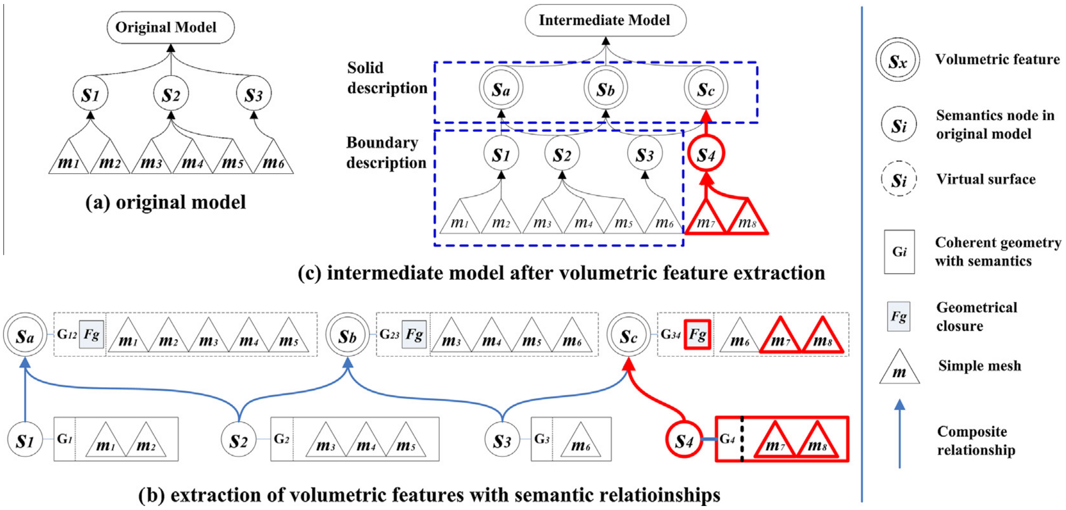


(a) a LoD4 building model of CityGML

(b) the boundary description

(c) the extracted and completed solid description

Fig. 5. Extracting a solid description from a boundary description based on the semantic relationship.



(a) original model

(c) intermediate model after volumetric feature extraction

(b) extraction of volumetric features with semantic relatioinships

Fig. 6. The hierarchical structure of feature organization.

rical model for the virtual surfaces created using the following algorithm:

Step 1: Extract the topologic relationships among the points, edges and faces to create the index for each edge of a target feature.
Step 2: Traverse the index and record the cited count for each edge.
Step 3: Determine whether the edge is cited only once. If it is not, the feature is closed; otherwise, the feature is not closed, which eliminates the need to go to step 4.
Step 4: Extract the edges that are cited only once and search the closed contour until all of the extracted edges are processed. The closed contours are then extracted as the geometrical border of the virtual surface.

We can verify the validity of the composite surfaces in each solid description of a volumetric feature using Gröger and Plümer's axioms (2009). If the validity is not complete, the topological relationships extracted in step 1 are reevaluated and the algorithm is repeated. After semantic analysis and completion, the volumetric features are extracted, with explicit descriptions of the valid solid objects with continuous and closed boundaries. We can next simply perform unified geometric profiling of the solid descriptions of each volumetric feature using a reliable 3D Boolean operation to preserve the correctness and completeness of the volumetric features and thus directly achieve consistency. This procedure represents the main feature of the proposed method that differs from existing geometrical algorithms.

3.4. Geometric profiling

Geometric profiling is a basic sub-step in profiling a 3D city model. After the semantics-constrained extraction and the completion of the volumetric features that will serve as the analytic units, the 3D space within the outer shell of the analyzed model is divided into a set of complete and unified volumetric features in a valid solid description with hierarchical relationships according to the original model. One of the main factors influencing the efficacy of the process of profiling complex models is the ability to quickly locate the profiled elements. Therefore, we first employ a prior intersection detection method combined with a multi-scale 3D spatial index. Next, drawing from research on solid profiling, a more general and stable vector Boolean operation approach based on the BSP division of 3D space is used to perform the calculation. The main idea of this method is to divide the space into positive parts and negative parts based on the boundary surfaces of the model and their normal directions. The method meets the classification requirement for subdivided surfaces. In particular, it is common for the subdivided surfaces to be coplanar with the reference plane in the BSP tree in the profiling process; consequently, it is difficult to determine the classification of the subdivided surfaces. We transform the problem into a 2D solution that establishes child 2D BSP trees based on the border line segments of the coplanar surface and then determines the positive and negative spaces according to the direction of the line segments. Additionally, to achieve a balance of efficiency and performance in the building tree, we obtain the surfaces from the boundary array in a random order. The proposed approach supports model profiling with an arbitrary orientation and position only if the profiler, which is a continuous surface without any holes or gaps, completely cuts through the original model.

3.5. Semantics-constrained reconstruction

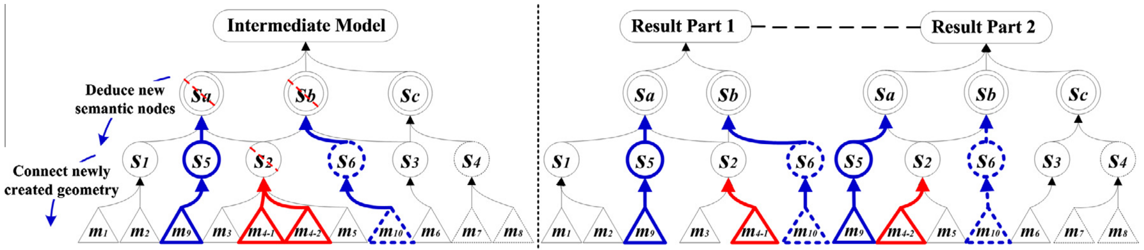
3.5.1. Updating the semantic hierarchy for newly created profiles

After obtaining the newly created geometrical profilers for each volumetric feature, we first need to deduce their coherent semantics. However, our analytic units are the atomistic-level volumetric features, and the boundaries of an analytic unit are its equivalent connections. Therefore, the semantics of the profilers describe the composition of the corresponding analytic units and can be deduced from the semantics of the analytic units. The semantic tree is updated by the insertion of these new semantic nodes in the parent nodes of the corresponding analytic units, as shown in Fig. 7a.

3.5.2. Decomposition based on the semantic hierarchy

We can next rebuild the entire model by considering the semantic relationships in the hierarchical decomposition of the updated semantic tree. A semantics-constrained process with decomposition rules is defined as follows, and an example is shown in Fig. 7b:

(a) Traverse the nodes of the volumetric features. The profiled nodes are copied to multiple split models, whereas the unprofiled nodes are inserted into only one model result according to their geometrical locations relative to the profiler. The nodes are checked in the resulting models. If semantic topologies originally existed between the nodes, these relationships are restored in the model results.



(a) deduce semantic nodes for the newly created profiles **(b) split semantic tree**

Fig. 7. The semantic hierarchy updated for newly created profiles.

(b) Traverse all child nodes associated with the unprofiled features. The semantic sub-nodes and their geometrical models and topologies are successively inserted into the newly built semantic tree.
(c) Traverse the unprofiled child nodes associated with the profiled features. The semantic sub-nodes and their geometrical models and topologies are successively inserted into the newly built semantic tree.
(d) Traverse the profiled child nodes associated with the profiled features. The semantic sub-nodes and their topologies are successively inserted into the newly built semantic tree. The geometrical models of the unprofiled nodes are inserted into only one model result according to their geometrical locations relative to the profiler, whereas the newly created nodes, which form the split surfaces, are copied to new trees.
(e) Traverse the newly created semantic nodes. Their geometrical models and topologies are inserted into the newly built semantic tree.

During the process, the semantics of the original model are used in creating the new geometry and deducing the semantic nodes, ensuring that the new semantic relationships directly correspond to the original semantics. The original model is thus separated into two parts with correlated topologies and semantics by the profiler; the parts are assigned two new object IDs for their geometric models but share the feature ID of the original model. Additionally, each part has its own complete geometrical, topological, and semantic relationships, which can be independently visualized to support further analysis. Consequently, consistency is achieved.

4. Experimental analysis

To validate the correctness and effectiveness of the proposed approach, a detailed museum model is used as an example (Fig. 8). This is a typical complex 3D model with interior structures that is based on boundary descriptions and satisfies the CityGML standard. The main section of this museum is modeled using 314,908 aggregated boundary surfaces and has affiliated elements, such as doors, stents for the show windows, and suspended ceilings, with membership relationships to certain parts of the main section.

In applications such as surveying, mapping and architecture, a meaningful profiler is usually a plane that is parallel or perpendicular to the principal axis of the profiled model. Therefore, we use a plane profiler that is perpendicular to the footprint of the museum model and cuts through the center of the hall in the main section, which is relatively detailed. Fig. 9a provides a top view of the museum model with the profiler.

The cross-sectional line set computed using geometrical cutting algorithms for open meshes is shown in Fig. 9b. This cross section contains 12,519 line segments. The cost of searching the closed boundary and the topological reconstruction increases exponentially with the number of lines. Furthermore, the unclosed area created by the open structures and the topological disconnection created by insufficient topological connectivity between related features produces an incomplete profile and the loss of volumetric features; consequently, consistency cannot be achieved. These ill-structured results prohibit not only a clear understanding but also the correct spatial analysis of the model. The results can be used only for temporal visualization, which has extremely limited utility and is inadequate for further analysis (Paliou, Wheatley, & Earl, 2011).

There are 63 volumetric features of the main section extracted from the aggregated boundaries based on their composite relationships and 296 affiliated volumetric features related to the main section through the membership relationship. Geometrical profiling is performed on the 359 total solid elements, and complete profiles are newly created. Decompositions are performed based on the semantic hierarchy to create consistency in the new model, as shown in Fig. 10a. The result preserves the volumetric features well and can effectively support the further analysis required in professional 3D GIS applications. The Hall of Chu Culture volumetric feature is highlighted to illustrate the final result, as shown in Fig. 10b. The shaded surfaces are extracted from the completed structural connectivity based on the virtual edges and created from the completed spatial coverage using virtual surfaces. The profile of the Hall of Chu Culture is also completed using virtual surfaces.

Because a complete solid description is obtained of the volumetric features, a 3D Boolean operation can be used to directly

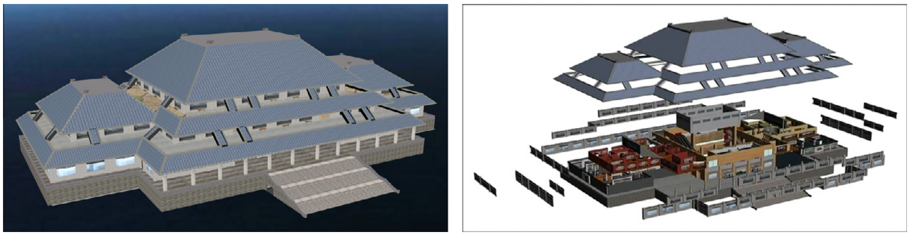


Fig. 8. The detailed boundary model of the main section of the museum building.

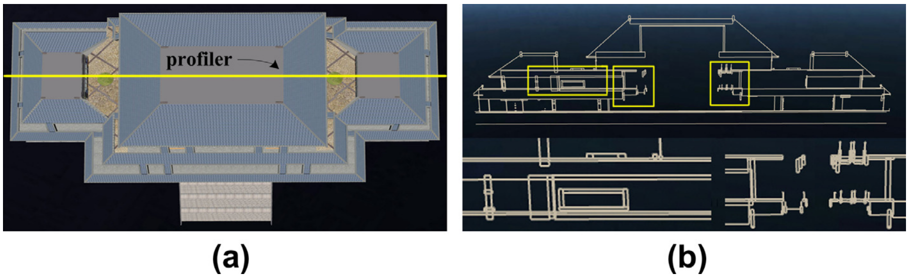
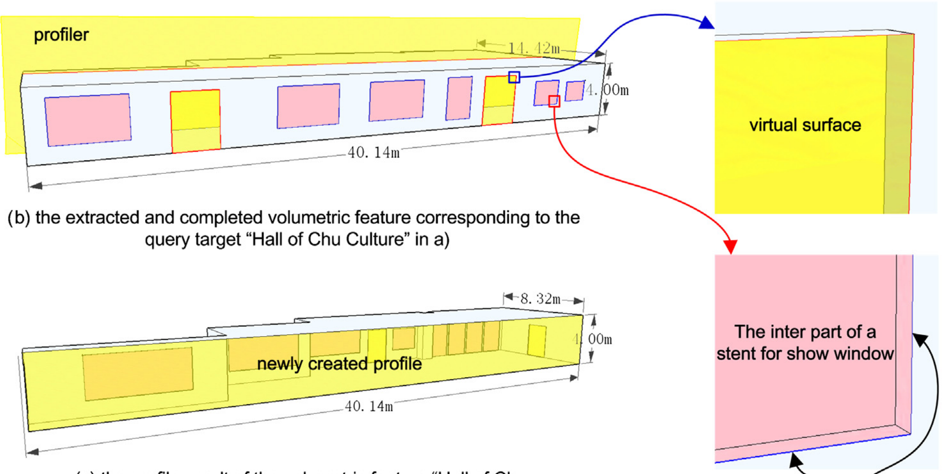


Fig. 9. Cross-sectional line set of a detailed model of the museum building.

(a) the profiling results of interior museum structure



(b) the extracted and completed volumetric feature corresponding to the query target “Hall of Chu Culture” in a)

(c) the profile result of the volumetric feature “Hall of Chu Culture” corresponding to b)

Fig. 10. Semantics-constrained profiling performance of the detailed museum model.

calculate the profiles, avoiding the ambiguous judgments and complex computation required to create the profiles of complex features from discrete lines and surfaces using the traditional process. Additionally, the computational cost increases approximately linearly with the data volume. High-performance computing techniques such as parallel computing can also be easily used to improve the computational efficiency, taking advantage of the unified organization resulting from the approach. Consequently, the proposed approach is well suited for large-scale scenes.

5. Conclusion

Three-dimensional profiling analysis is one of the basic functions of 3D GIS. Addressing the coherent complexity of commonly used 3D city models at LoD4 of CityGML based on boundary description, this paper presents a new method for three-dimensional profiling that makes full use of the semantic relationships as well as the geometrical topology between aggregating elements, transforming the complex 3D model into a set of unified volumetric features described as solids with continuous and closed boundaries. This method effectively simplifies the complexity of the consistency check of traditional cross-sectional segments and facilitates reliable 3D Boolean operations. The proposed approach also guarantees geometrical and topological consistency when profiling complex 3D city models such as buildings with rooms, interior structures and underground spaces. The experimental results from a typical 3D building model demonstrate the effectiveness of the approach in supporting thematic queries, volume measurements and further 3D spatial analysis. Of course, an accurate and reliable three-dimensional profiling process depends on the quality of the 3D city model data, which requires satisfying the requirements of the standard CityGML model and ensuring topologically seamless connections among all of the aggregating elements. Our future work includes implementing data structure optimization and real-time parallel computing as well as applying the profiling operator in 3D spatial analysis and 3D spatial data mining.

Acknowledgments

The valuable comments and suggestions provided by three anonymous reviewers are gratefully acknowledged. The work described was financially supported by the National Basic Research Program of China (973 Programs), No. 2010CB731801 and the National Natural Science Foundation of China, Nos. 41171311 and 41001222.

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