Towards Semantic 3D City Modeling and Visual Explorations

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Abstract In recent years, the integration of semantics into 3D city models has become a consensus. The CityGML standard laid the foundation for the storage and application of semantics, which boosts the progress of semantic 3D city modeling. This paper reports an extended semantic model based on CityGML and its visual applications under the content of a three-dimensional GIS project of China. Firstly, concepts Room, Corridor and Stair are derived from concept Space which represents the similar concept of Room in CityGML. These concepts will benefit the application of indoor navigation. Geological model is also supported by this model, which enables the underground analysis. Secondly, a semi-automatic data integration tool is developed. The types of semantic concept are defined based on the Technical Specification for Three-Dimensional City Modeling of China which leads to an adaptive way to assign semantics into pure geometry. In order to better visualize the models enriched by semantics, two fundamental techniques, data reduction and selective representation are then introduced. It shows that semantics could not only help improve the performance of exploration tasks but also enhance the efficiency of spatial cognition. Finally, two exploration cases are presented, one is indoor navigation, the semantic model is used to extract the geometric path and a semantics enhanced navigation routine is used, which greatly enriches the connotation of ordinary navigation applications; the other is a unified profiler, in order to fill up the cross-section correctly, semantics are incorporated, which help ensure the topological and semantic consistency.

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1 Introduction

1.1 Semantics in 3D Modeling and Exploration

The accessibility of 3D city models (3DCMs) has grown unprecedentedly, success of Google Earth and Bing Map 3D brings us a new time with 3D Geo-information (Butler 2006). However, increasing professional applications give rise to needs of conceptual meanings beyond geometry since the pure appearance representation mainly focus on the photorealistic visualization while ignore a full comprehension of the data. Numbers of applications like urban planning and facility management, disaster management and personal navigation require additional information, i.e. classification and relationship of components, about the city objects given in a standardized representation (Kwan and Lee 2005). Therefore, the 3DCMs must incorporate the geometry and the semantics.

CityGML is an international standard for the representation and exchange of semantic 3D city and landscape models, which not only represents the shape and graphical appearance of city models but specifically addresses the object semantics and the representation of the thematic properties, taxonomies and aggregations (Gröger and Plümer 2009). However, the current version of CityGML does not include underground features like geological model and underground infrastructures (Emgård and Zlatanova 2008a). Moreover, implicit definition of Room in CityGML is not enough for the accurate geometrical path extraction in the indoor navigation. On the other hand, existing datasets are often produced lacking of semantics by using photogrammetric approach or CAD tools. An efficient way should be proposed to complement the thematic meanings of the geometry.

This paper aims at the improvement of the CityGML model in the visual exploration practice of large urban scenes. The main contributions lie in following aspects: Firstly, geology model is supported in the thematic model; Secondly, Space is introduced in our building semantics and Room, Corridor, Stair that derived from Space are employed to facilitate indoor navigation; Thirdly, a semi-automatic semantic enrichment tool is developed to help enrich semantics to existing geometric models; Then, two basic visual exploration techniques in our platform are illustrated which utilize semantics to enhance the exploration performance; At last, two exploration cases are demonstrated to show the application of semantic model and visual exploration techniques. Our test bed is the digitalized 3D city models of the Wuhan city, China, which covers 8,600 km^2, is consist of 119,051 buildings.

1.2 Related Work

Increasing 3D city modeling projects have been carried out in recent years. As one of the pioneers, the 3D Berlin project firstly integrates semantics into the 3DCMs produced by traditional photogrammetric procedures in order to facilitate the information querying and spatial analysis (Döllner et al. 2006). At the same time, fundamental issues such as the consistency of geometry and topology as well as the coherent of geometry and semantics were extensively studied (Kolbe 2008; Kwan and Lee 2005), which laid the basis of CityGML and semantic modeling. Recently, several extensions of CityGML are also proposed, such as the integration of both above and underground features as well as temporal semantics of house properties (Emgård and Zlatanova 2008a, b; Zhu and Hu 2010).

On the other hand, visual exploration has been approved to be the most powerful tool to present and use the 3D spatial data. LandXplore in 3D Berlin project has become a standard package to visually interact with CityGML datasets (Döllner et al. 2006), and many other researches on city visualization have proposed advanced features to better present 3DCMs (Fabritius et al. 2009). However, the full use of semantics is still lack in existing visual applications.

2 Semantic Modeling

An "integrated 3D semantic model" is brought forward here, based on which an approach of "semantic enrichment" is discussed.

2.1 Integrated Model Based on CityGML

The integrated 3D semantic model adopts several concepts presented in CityGML but also comprise new developments which the current version of CityGML does not include. Figure 1 shows the structure of the thematic model, which is defined based on the Technical Specification for Three-Dimensional City Modeling of China (Nagel et al. 2009). An extended class Geology is added to support geological analysis applications, similar to (Emgård and Zlatanova 2008a). The transportation here is specialized into express way, main road etc. Such subdivision makes the semantic enriching process more adaptive. In the following, the building model will be discussed in more detail to illustrate the general principle which is different from the definition in CityGML.

A Building is described by optional attributes and constituents; optional attributes contain: function, usage, and class, measured height, number and so on. It is aggregated by two classes: IntBuilding and ExtBuilding, which facilitates the extracting of LOD3 model from the detailed model. Specifically, we borrow the abstract concept Space from IFC (Industry Foundation Classes) to represent the conceptual bounded space in a building (buildingSMART International 2010). Subclasses of Room, Stair, ElevatorRoom, and Corridor are derived from Space, which further define specified Spaces with typical composite pattern of Openings (Openings can be interpreted as doors, windows or entrances) This model is more appropriate to the application of indoor navigation because sometimes it is ambiguous to automatically extract

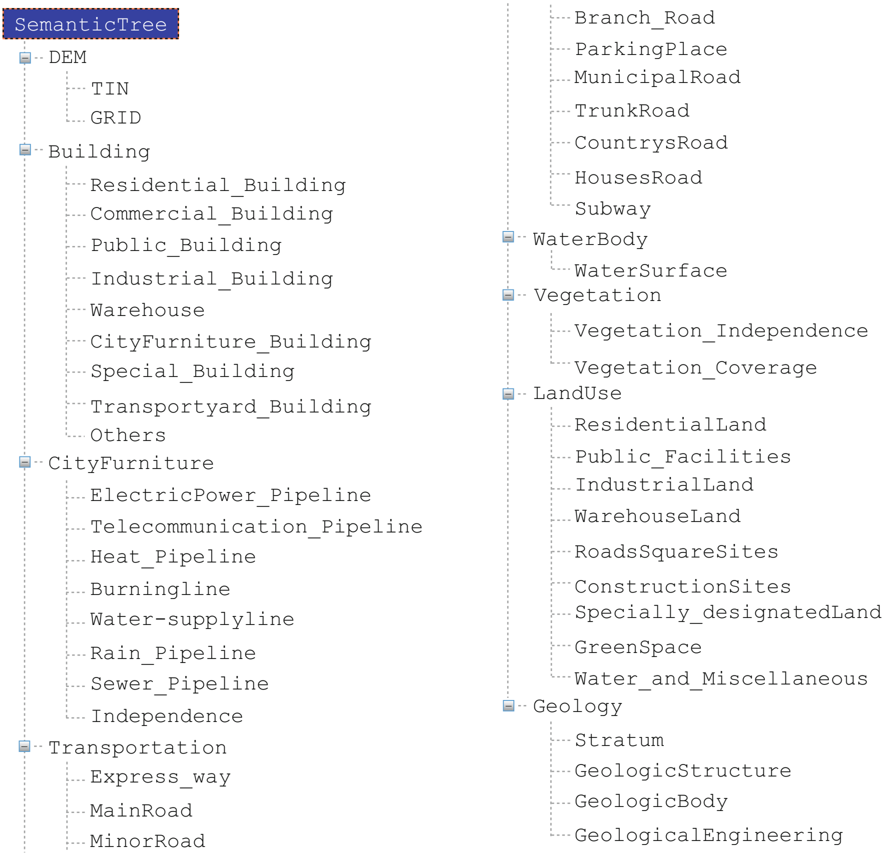

Fig. 1 The thematic model

geometric path directly from the topological accessibility graph derived from Room and Opening of CityGML. For example, a stair with two entrances at the two ends clearly defines a path. However, a path extracted from the Stair in CityGML would be probably a vertical line segment as shown in Lee (2001), which is obviously not suitable for more precise navigation applications.

In the following, definitions of the derived concepts are shown:

- Room:
  A Room is a specified Space which should have functions other than passing through, such as resting, working or entertaining etc. It should be bounded by WallSurfaces (Similar to the BoundarySurface in CityGML) like interior wall surfaces, ground surfaces, roof surfaces, Openings, and Furniture as well as other IntBuildingInstallations. A Room contains a label to record the WallSurfaces, by which the adjacent Space is connected through Openings. In the topological network, a Room is represented as a node.

- Stair:
  A Stair is a specified Space which contains a Stair and is bounded by WallSurfaces with at least two Openings, as shown in Fig. 2. A Stair contains a label to record the bounded WallSurfaces as well as Openings, by which the adjacent Space is connected. In the topological network, a Stair is represented by a node.
- Corridor:
  A Corridor is a specified Space which contains a passageway and is bounded by WallSurfaces with at least two Openings, as shown in Fig. 3. A Corridor contains a label to record the bounded WallSurfaces as well as Openings, by which the adjacent Space is connected. In the topological network, a Corridor is represented by a node.

The UML diagram of the building model is shown in Fig. 4. Via the definition, the model is more convenient and precise for constructing the geometrical route network automatically.

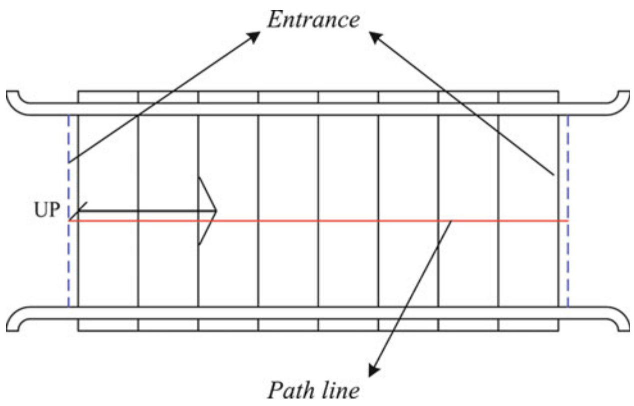

Fig. 2 A Stair

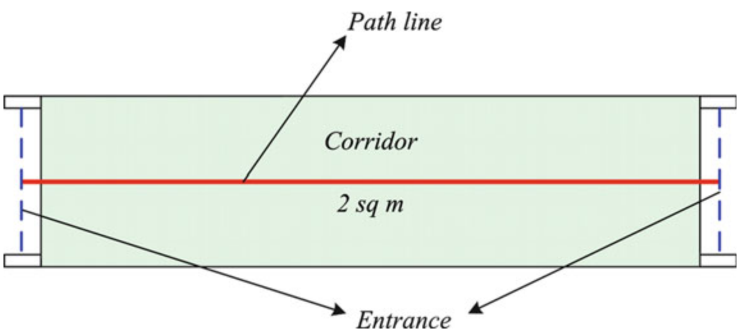

Fig. 3 A Corridor

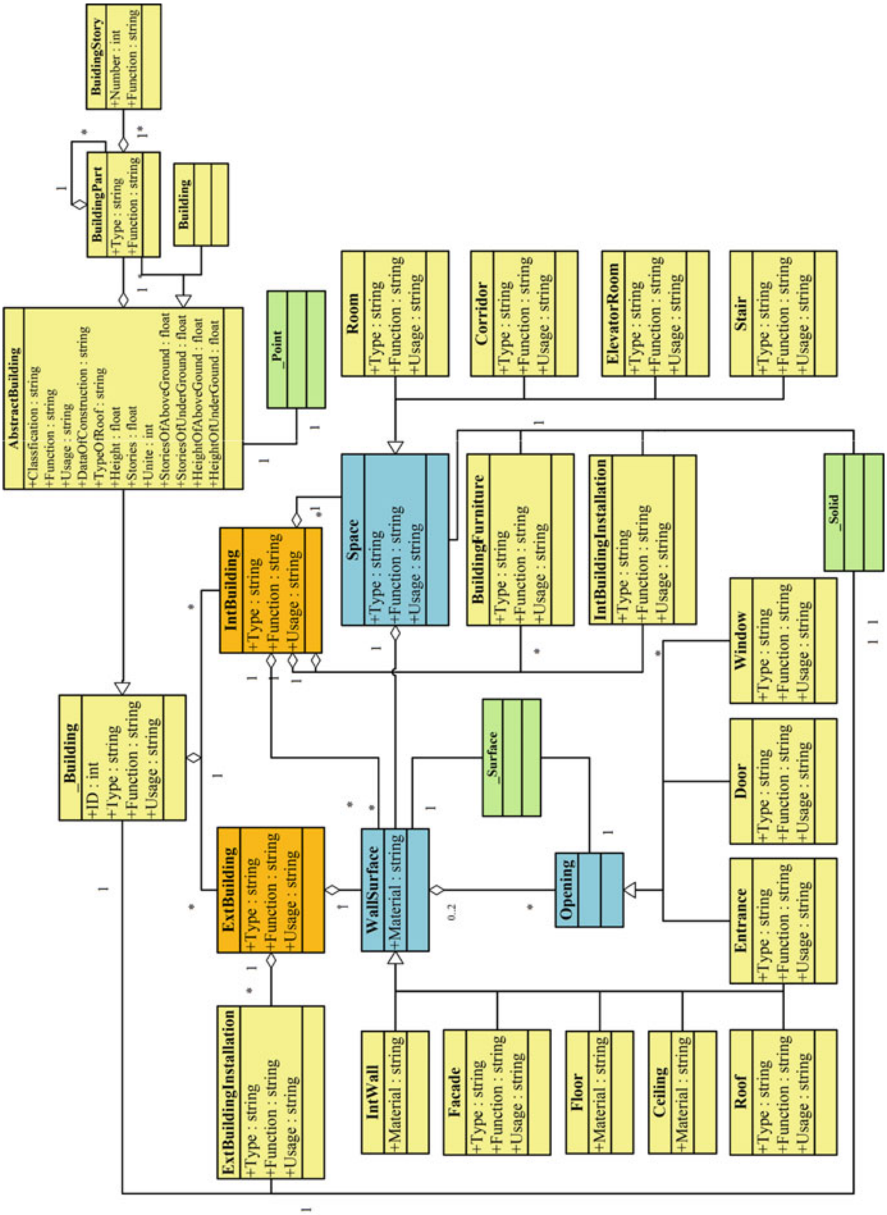

Fig. 4 The UML diagram of building

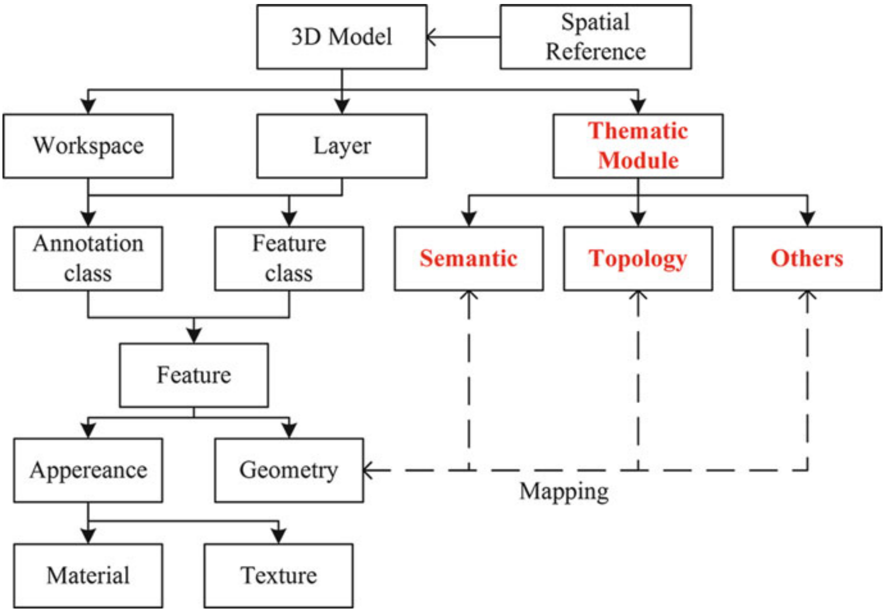

Fig. 5 The Geometry-Semantic coherent mapping

To record the Geometry-Semantic coherence, a flexible and extendable structure is needed, as illustrated in Fig. 5. Firstly, abstract thematic module is defined, from which hierarchy of semantics as well as topology could be derived. Then, semantic information is mapping to its corresponding geometrical objects like a solid or a surface. Under this framework, the geometry and appearance structure could be compactly designed for high performance visualization purpose and different domains of semantics can be mapped to the geometry model and be utilized in different applications in the meanwhile.

2.2 *Semantic Enrichment*

To seamlessly integrate heterogeneous data (particularly those without semantic information), it is necessary to incorporate or enrich the semantics for the geometries. While existing CityGML models could be imported and support well, for other models, however, it is hard to extract semantics from pure geometric models automatically. Therefore, a semi-automate tool is developed.

As discussed in Sect. 2.1, the semantic concepts were already defined in thematic model. The assigning of semantic information and the building of semantic hierarchy turns out to be simply choosing the geometric components in top-down order (from exterior to interior) and indicating the corresponding semantic concepts. To improve the efficiency, an adaptive way is employed which could automatically refine the

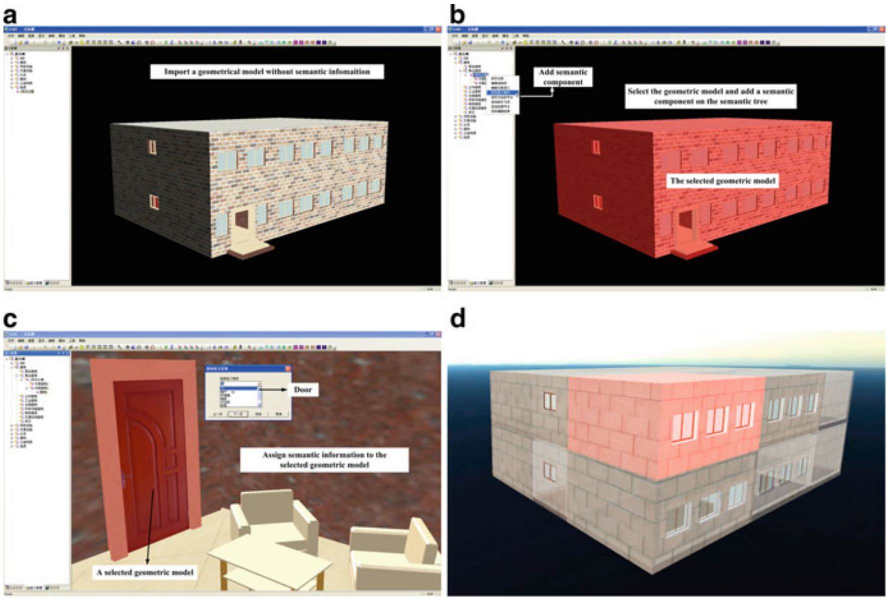

Fig. 6 (**a**) The imported geometric model; (**b**) mapping the entire building; (**c**) the component editing; (**d**) the component aggregation

selection range of semantic concepts according to the thematic model. After all the components are mapped, the semantic hierarchy is built at the same time.

The integration procedure is illustrated in Fig. 6. Firstly, the entire model is mapped to its conceptual node of the thematic model, for example, Fig. 6b shows the building is mapped to the commercial building. Then, in the step termed component editing, the geometry-semantic coherence is built up by grouping geometry surfaces like wall and door etc. and mapping them to the semantic concepts derived from the abstract building, as illustrated in Fig. 6c. Finally, in the step of component aggregation, the mapped components are aggregated based on the thematic hierarchy, such as a closed Space bounded by Wallsurface would be aggregated into a Room or a Corridor, as illustrated in Fig. 6d.

After the semantic enrichment, a semantic model is acquired, based on which various applications like conceptual querying and emergency path searching can be implemented.

3 Fundamental Approaches for Visual Exploration

Three-dimensional visual exploration is one of the most important applications of 3D GIS, which not only help user investigate the highly detailed spatial data sets but also achieve an unexpected discovery of the hidden spatial knowledge

(MOHURD 2010). However, as the increasing of the accessibility of detailed 3D city models, real-time visualization of a complex city scene is still extremely challenging. On the other hand, users' attention might be frequently diverted due to the unfocused representation, which would greatly decrease the efficiency of the spatial cognition. Given these reasons, we present two fundamental approaches for visual exploration: data reduction and selective representation.

3.1 Data Reduction Based on Semantics

A number of output sensitive technologies for visualization of massive scene had been proposed in recent years, which combine simplification, levels of detail, image-based rendering, visibility culling, as well as cache coherent layout methods. A good review is given in Gobbetti et al. (2008).

However, researches on cognition and psychophysics suggest that human beings will always tend to neglect objects in the view fields which have little correlation with certain tasks, such as in navigation scenarios (Canosa 2009). Therefore, discarding or simplifying meaningless objects during exploration would further improve the performance of rendering but affect little of the cognition.

In order to decide what to show and what to discard, criteria need to be set up to measure the importance of objects. For example, during indoor navigation, fine interior structures and surrounding components of the building are of great importance while terrain and outside buildings, which contribute little to the task, could be discarded; for fly over application, geology model and interior building parts could be discarded, and so forth.

Figure 7 illustrates the contribution composition of a building. We provide several semantics related criteria to calculate the contribution value such as visual importance represented by the number of projection pixels, task correlation represented by the distance to the active camera path, etc.

Vital semantics based tags are assigned to components in order to ensure that important components will not be discarded easily. These tags are integrated into the data dispatching and rendering pipeline, as shown in Fig. 8.

3.2 Selective Representation

Rendering of places of interest and analysis results must be given prominence in visual exploration of complex scenes. Selective representation we proposed emphasizes essential objects which users may pay more attention to while fading out others. The potential advantages would be that users will take considerable less time to complete a search and recognition task in comparison to normal representation.

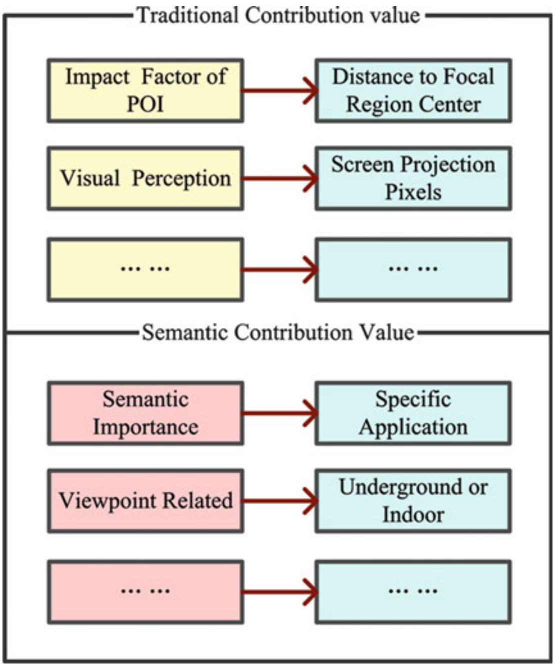

Fig. 7 Illustration of the contribution composition

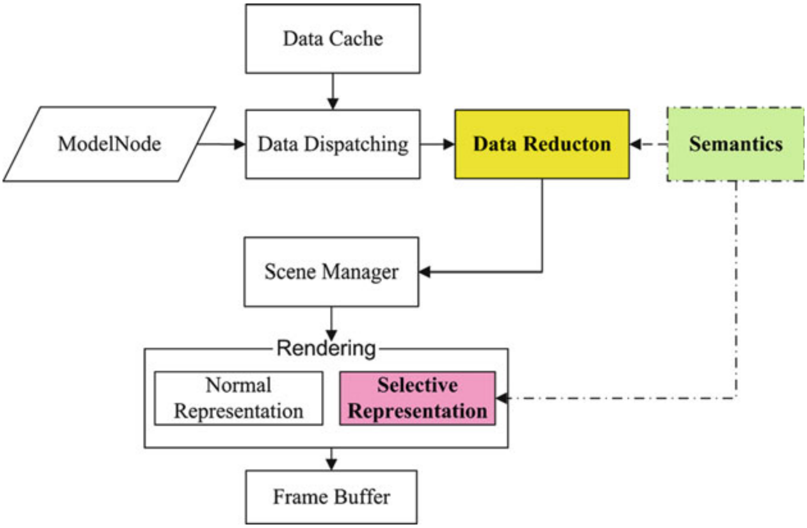

Fig. 8 The flow chart of data dispatching and rendering

Since visual properties like color, light and transparency are some of the crucial factors influencing the visual perception of city scenes, a multi-mode visualization framework is employed, in which single object or a group of objects can be assigned with various draw model including hidden, wire-frame, highlight as well as different levels of transparence. The configuration of render modes are set up based on properties of certain tasks.

Screenshots of underground utilities query application are shown in Fig. 9, for an example. In Fig. 9d, buildings above ground remain texture-mode, while the terrain surface is drawn in translucent-mode. High-lighted pipes perform significantly well in drawing users' gaze. Therefore it could be easy to locate the corresponding position of pipes on the ground.

In the implementation, we found that data reduction could successfully improve the performance of rendering and selective representation leads to easier interacting with complex city scenes. In some sense, our approach can be interpreted as a practical way to create an efficient representation of an urban environment, and, as a way of finding unique knowledge of a large cityscape. Possible areas of utilization of this technology are applications such as route finding, and spatial analysis applications.

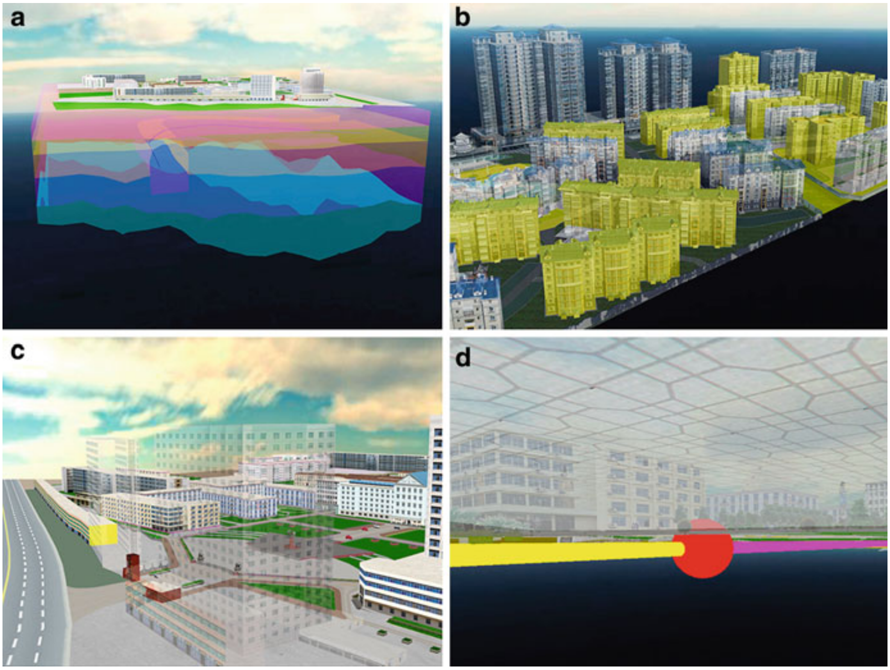

Fig. 9 (**a**) The stratum and tunnel below ground; (**b**) the highlight of meaningful buildings; (**c**) alleviating occlusion by translucent; (**d**) revealing the relationship between pipes and above ground features

4 Exploration Case 1: Semantics Enhanced Indoor Navigation

4.1 Overview

Almost all of the city emergency response scenarios need indoor navigation. However, it is always a labor intensive work to build path network inside a building manually. Fortunately, Lee proposed a method to extract the indoor road network based on connectivity graph of the building parts (MacEachren and Kraak 2001). We transmit his idea to our semantic models and improve the results by using pre-discussed Stair and Corridor concepts. A semantics enhanced navigation interface is also introduced.

4.2 Route Deducing: Automatic Extraction of Path Network

The automatic extraction of path network can be divided into two steps: network topology construction and geometric network construction.

Network topology is a pure graph that represents the adjacency, connectivity and hierarchical relationships among the semantic nodes. Based on the definitions of the semantic model of the building, the network topology can be constructed automatically (Gröger and Plümer 2009). A connection will be built between two Spaces if they can be connected by the Opening.

In order to implement network-based analysis such as shortest path algorithms, the network topology needs to be complemented by geometric properties, which accurately represent the cost of connection. Lee presented a well-developed method, "Straight-MAT", to identify line segments from a simple polygon based on combinatorial data model (CDM) which describes the topological relationships between 3D geographic entities (MacEachren and Kraak 2001), as shown in Fig. 10.

However, Stairs in this method are represented as vertical lines, which might lead to unconvincing routing results. Moreover, the existing method will face difficulty in dealing with a square Corridor because the direction of the path line could not be uniquely defined. To partly solve this problem, we employ different routines to extract path lines from different derived Spaces. For example, "Straight-MAT" method is used to extract path inside a Room while we directly extract path of a Stair or a Corridor by connecting Entrances, based on our semantic model. Results are shown in Fig. 11 by green lines.

4.3 Enhanced Route Navigation

Unlike the ordinary navigation applications, it's important for indoor navigation to emphasis the key features for the user during navigation. With the help of semantic model, we could extract information such as the Room number and the name of the

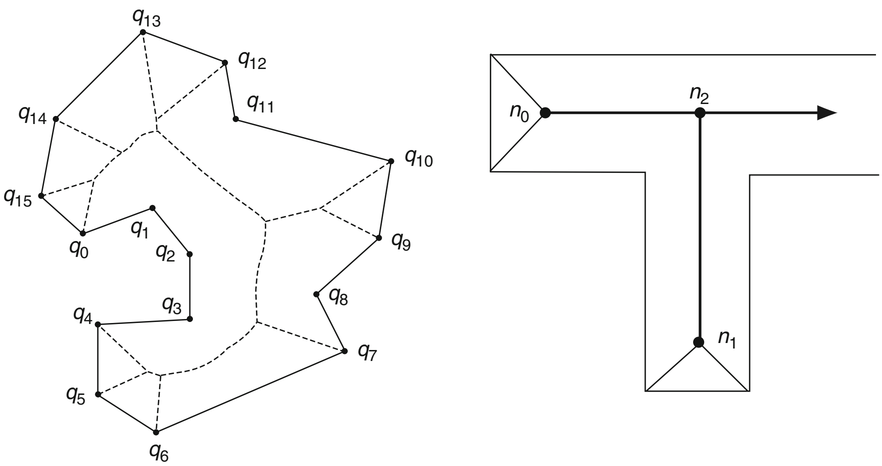

Fig. 10 Lee's "Straight-MAT" method

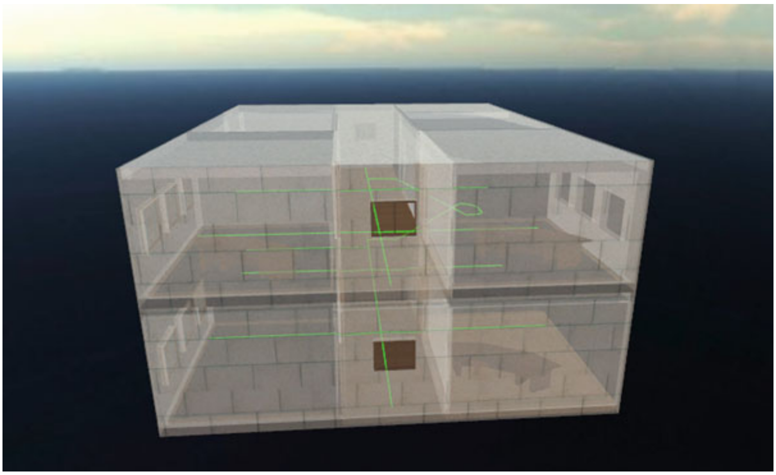

Fig. 11 Constructed geometry path

building part passing by. Selective representation routines are also adopted to highlight the important features such as doors, Stairs and fade out the unrelated features such as other Building parts and Furniture.

Some of the results are show as follows. Figure 12a and b shows the calculated shortest path, represented, from outside and inside the building. In Fig 12b, the important features such as Stairs, Corridors and Doors are highlighted while other Building parts are shown transparent. Figure 12c and d show the semantic tags for notifying features during navigation, which would enhance the impression of the route.

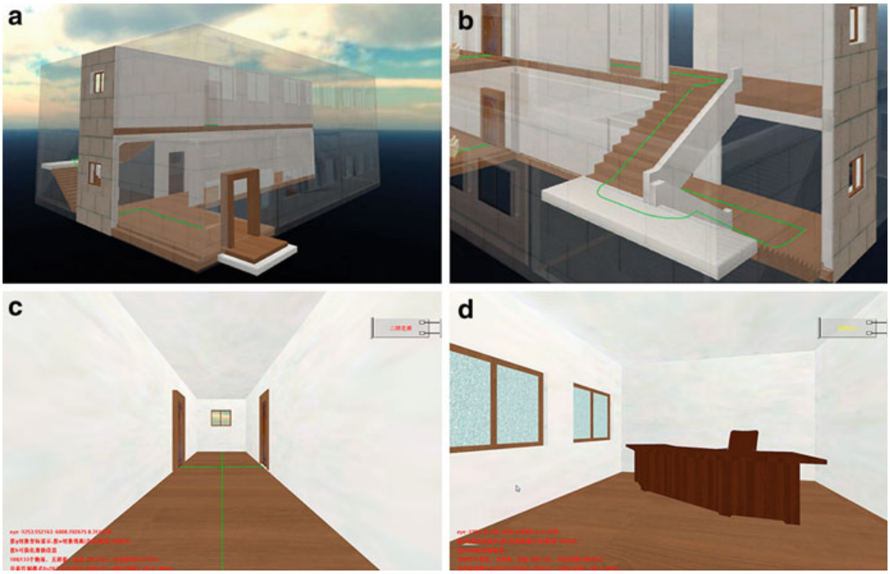

Fig. 12 (**a**) The calculated path observed from outside; (**b**) the calculated path observed from inside; (**c**) the semantic tag indicates the Corridor on the second floor; (**d**) the semantic tag indicates the Room 204

5 Exploration Case 2: A Unified 3D Profiler

5.1 Overview

The unified 3D profiler, which could help users make good sense of urban architecture, underground infrastructure, internal structure and interrelationship of stratum, is an effective tool in providing visual hints and revealing the context and spatial relation of objects.

However, since features in 3D city scene vary largely depending on geometry, topology and semantics. The need to ensure the topological and semantic consistency has a strong impact on the validity of profiling explorations and the analysis results.

5.2 Achieve Consistency for Topology and Semantics

Standard languages for 3DCMs such as CityGML provide "Solid" as the most important type to represent buildings, rooms, public infrastructure or other volumetric object in geometrical modeling. "Solid" here is described mathematically by rigid body, which is a bounded, regular and semi-analytical subset of R^3 (Kolbe 2008). In boundary representation schemes, which are widely used in Geometrical Modeling,

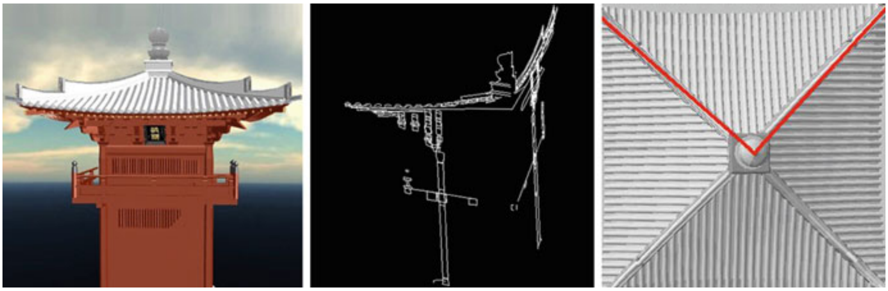

Fig. 13 The extracted intersecting-line set of a geometrical model

CAD and GIS, solids are represented by their bounding surfaces, or topologically, a single, closed two-manifold. During profiling, each solid should be rebuilt in accordance with topology consistency. Otherwise, the ill-structured cross-section would prohibit not only the successive spatial analysis, but also the clear cognition of objects.

On the other hand, for 3DCMs, marking, identification and affiliation descriptions of object type should be implemented with semantic consistency, which is the essential difference that distinguishes 3D city models from general geometrical models. In profiling, we cannot tell the meaning of cross sections in a reconstruction with inconsistent semantics. And it is also difficult to ensure query accuracy and descriptive validity of relationships among objects in this case.

An example of profiling without considering topological and semantic consistency is given in Fig. 13. The intricate and complicated intersecting-lines are difficult to be handled in other applications.

As a result, in order to ensure consistency of topology and semantics, implementation of profiling for buildings requires containing different semantic information derived from original semantic property as well as avoiding topological mistakes such as degeneration and punctuation. In addition, during profiling, whether to fill up cross-sections or just extracting cross-section lines should be judged according to the original semantic and topological information. Then, the generated surfaces should be mapped to semantic node in semantic hierarchy.

5.3 Profiling with Semantics

In the profiling analysis, objects in a city scene can be divided into three categories according to their topological descriptions, namely, models represented by open surfaces, models represented by strictly closed surfaces and models represented by a mixture of both open surfaces and closed surfaces.

The first category contains terrain surface, which is the LOD0 model of CityGML. The second category consists of stratum in geology and models from LOD1 to LOD3 of CityGML as well as architecture components in BIM models, which are described by rigid bodies. The third category is mainly the LOD4 models of CityGML, in which building components such as walls, floors are expressed by open surfaces and rooms, IntBuildingInstallations and Furniture are expressed by solids, a good illustration of the differences between models of LOD4 and BIM models can be found in Gröger et al. (2008).

During profiling, cross-sections should be treated separately, models belong to the first category only produce cross-section lines, and therefore, post processing is needless. For models belongs to the second category, cross-section must be filled by surfaces which can be determined based on the topology of the original model directly. However, to cope with Spaces in BIM models, inner features behind the cross-section such as bounding walls should be revealed so the generated surface should therefore be shown in translucent mode. For the models belong to the third category, which is the most complicated, different classes of surfaces should be

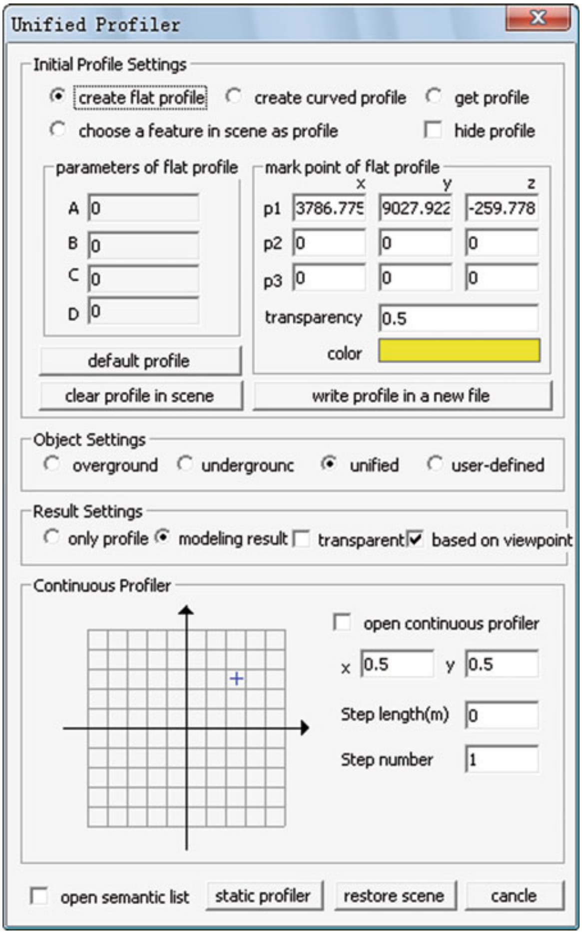

Fig. 14 The configuration of a unified profiler

distinguished based on the semantics so that we could fill the cross-section of a Space with translucent surfaces which contain the semantic information associated to the Space, while treat other cross sections as WallSurfaces which are filled by solid surfaces in order to close the gap between Spaces. The IntBuildingInstallations as well as Furniture are dealt with employing the same method used for the second category.

The main steps of the profiling are as following:

- Firstly, objects in the scene are classified into different categories according to the criteria discussed above.
- Then, intersection lines are extracted between the cross-section surface and intersected surfaces. Delaunay triangulation routine is adopted to re-mesh the cross-section.
- Thirdly, a BSP tree is built and semantic information, especially the Space, is employed to classify the new faces.
- At last, the cross-section is filled up according to semantics and is mapped to the semantic hierarchy which ensures that new elements inheriting semantic information correctly from the original model.

5.4 Results

Figure 14 shows the configuration of a profiler and Fig. 15 shows a built cross-section surface. Different types of cross-section surface including planes and curved surfaces are supported. And what is the most important, the participants of

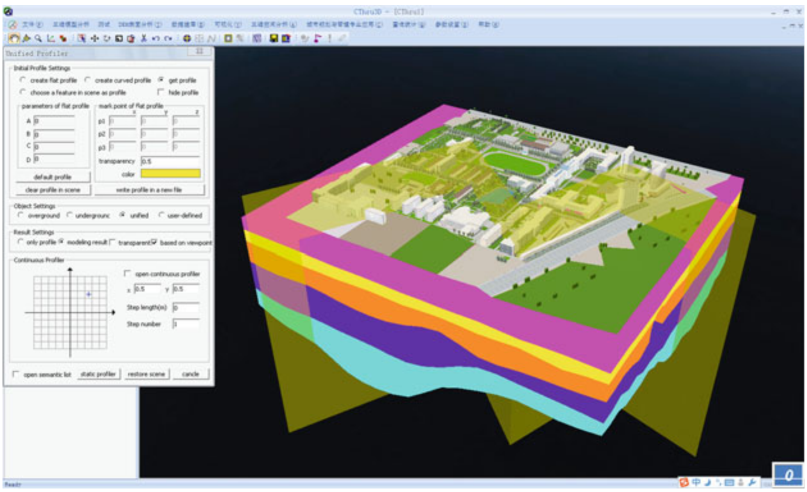

Fig. 15 A threefold cross-section surface generated by the profiler

the profiling application, such as which kind of feature should be profiled, could also be defined.

Examples of profiling with typical types of models in city scene are given in Fig. 16. The top shows a LOD4 model, with geometry and texture profiled correspondingly. The restored cross-section is displayed transparently so as to show inner features. The middle shows a detailed architecture model without Space. All the components are filled up by solid surface with the same material after profiling. For example, the gray part on the first floor shows a cross-section of a Buddha statue, which was filled up by the right texture. The bottom shows a geology model

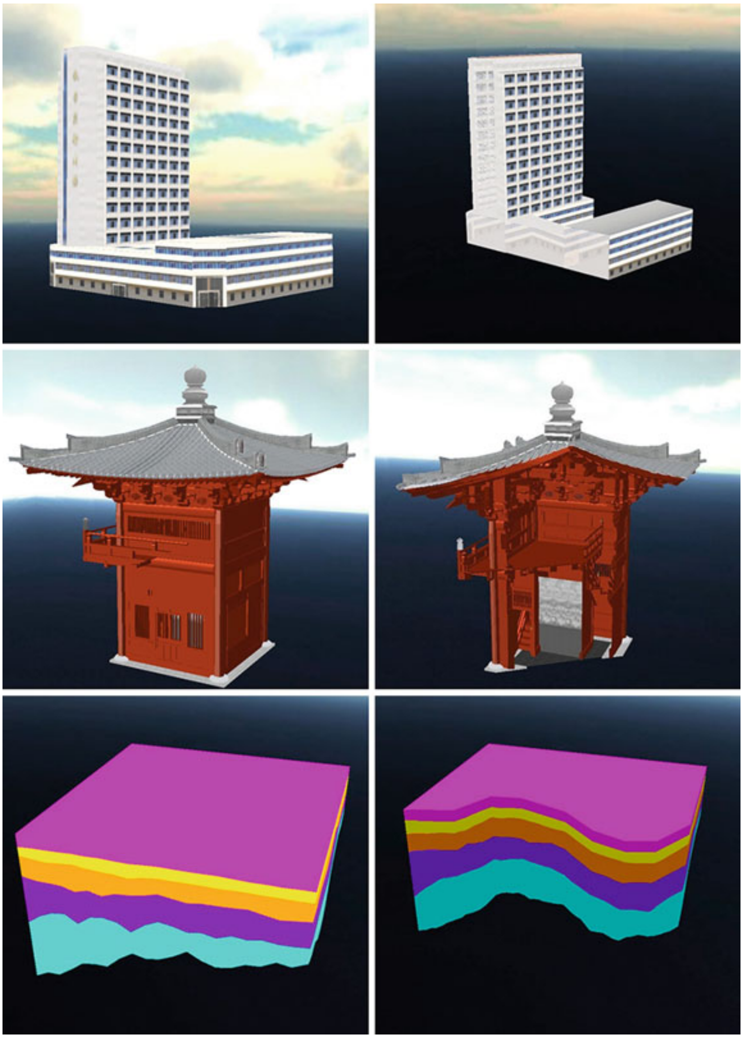

Fig. 16 Profiling results. *Top*: a LOD3 building; *middle*: an IFC building; *bottom*: geology model

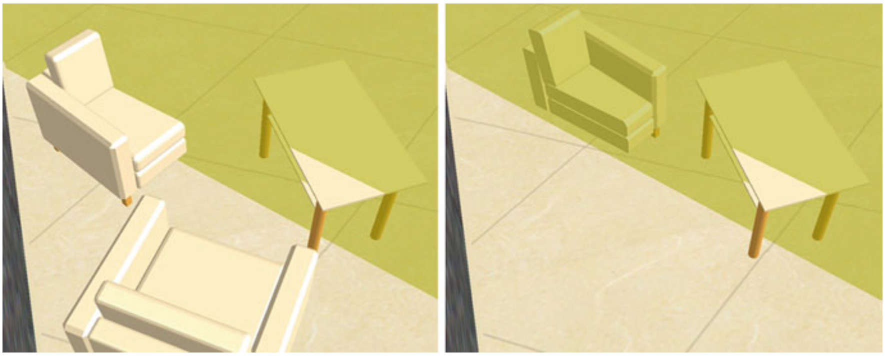

Fig. 17 An example of user-defined profiler based on semantics

represented as a layer-cake. The profiling is executed in each stratum, which is properly filled up.

An example of user-defined profiler is depicted in Fig. 17, in which Furniture "sofa" is set to be included in the analysis, while floor and Furniture "table" are excluded.

In this exploration case, it is demonstrated that the unified profiler based on the topological and semantic consistency could provide a dimensional reduction technique, which would probably be one of the basic analyzing technologies in 3D GIS.

6 Conclusion

This paper presents a semantic model based on CityGML, which is extended to support geological model and specified Spaces such as Stair and Corridor for indoor navigation. An integration tool is also proposed for enriching existing geometric models with semantics. Besides, two visualization techniques based on semantics are introduced which aim at improving the performance of visual exploration. All the above laid the foundation of our 3DGIS platform, in which the geometry and material data structure is designed mainly for high performance visualization but can be flexibly mapped to the semantic hierarchy. Based on the platform, we achieved the semantics enhanced indoor routing and unified profiling of the complex city scenes.

Currently the ongoing project is developed to support most of the commonly used data types and extend the storage of the massive city dataset to the commercial database. Moreover, dynamic features like fluid and clouds are expected to integrate in the future.

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