SEMANTIC BASED LOD MODELS OF 3D HOUSE PROPERTY

Mingyuan Hu [a, *]

[a] State Key Laboratory of Information Engineering in Surveying Mapping and Remote Sensing, Wuhan University, 430079, P.R.China - humingyuan@gmail.com

Commission 2, WG II/1

KEY WORDS: Semantic Description, Levels of Detail, Hierarchical Events, 3D House Property Model, Integrated Representation of Indoor and Outdoor Objects, Dynamic Representation

ABSTRACT:

Based on comprehensive analysis of 3D property right objects and various application characteristics, in this paper, a novel conceptual model is proposed for solving the problems of integrated management and registration of overlapping and interlocking buildings and their interior property situations in real 3D environment, as well as the asynchronous change feature within building in more microscopic and partial level, which consists of three key aspects: the semantic description of spatial entity and related property right, and 3D hierarchical framework (Levels of Detail: LOD) for the integrated representation of indoor and outdoor property right objects, and hierarchical events for dynamic representation. The conceptual model can describe the actual relationships among property right objects especially the integrated management of indoor and outdoor objects, and represent complex interior space of real 3D property right for the increasing complex buildings and related microcosmic and dynamic characteristics. Theoretical analysis proves this model provides an insight in the vertical dimension of property rights, and plays an important role in improving real 3D dynamic house property management research.

1. INTRODUCTION

Modern cadastre registration and house property management are becoming multi-dimensional and dynamic as urban physical spaces are continuously expanding upwardly and downwardly. This important trend can be summarized from three main aspects:

- With the rapid process of urbanization, more and more complicated house property infrastructures are built in the third dimension, both upwards and downwards, such as tunnels, cables and pipelines, underground parking places, shopping malls, buildings above roads/railways and high-rise buildings (for example, tower building, commercial building and building complex etc.) (Stoter, 2005; Oosterom, 2006).
- The design style of residential building has gradually evolved from extensive planar layout to compact 3D solid design, which has been demonstrated by the change process from low-unit housing to compact 'one staircase-two house' buildings, and to building complex with different floor height, springing layer or slope roof.
- The relationship between residents and houses (or land) is dynamic (Oosterom, 2006), and dynamic changes in real 3D space of buildings and related complex interior property situations are evolving from outdoor to indoor, macroscopic to microcosmic, as well as whole to partial.

Consequently, people's recognition of cadastre registration and house property registration is no longer constrained to the 2D static and planar world. However, there are big gaps between the macroscopic 2D representation and the comprehensive understanding of the real 3D dynamic phenomena. Several reasons contribute to the big gaps : (1) the visualization of 3D interior structures and 3D dynamic operations (such as 3D Union) can not be obtained from 2D models (drawings); (2) 3D property objects which are represented as 2D topological and geometrical projections, especially the increasing complex 3D buildings of whom, have limitations in providing an insight in the vertical dimension (e.g. depth, height and interior of buildings) of rights; (3) and the 3D property objects above may lose some of their properties (graphic, height, etc.) and their spatial relationships to other property objects, therefore, they can not guarantee the consistency between the 2D graphic representation and the spatial extent of real property object; (4) the microscopic dynamic change characteristics of real 3D space of buildings and related complex interior property situations can not be described well using the macroscopic dynamic representation method, because 3D dynamic information can only be located, identified and analyzed when the spatial object is treated as a whole level, rather than the object and its interior components are treated as separate levels..

In order to facilitate effective and efficient 3D house property information management, in which more detailed and micro-scale features of the real 3D environment become increasingly important, the key issues are essentially focused on how to describe actual relationships among real property objects especially the relationship for the integrated representation of indoor and outdoor objects, and how to represent complicated interior property situations within a building and related 3D dynamic representation towards indoor and partial changes. In

* Corresponding author. Mingyuan Hu, humingyuan@gmail.com.

addition, the completeness in 3D geometry space of a real property object need to be well guaranteed.

Solving these issues are beyond the ability of the existing 3D/4D spatio-temporal data models. Researches have been carried out to improve spatio-temporal & dynamic representation or 3D city modeling, but few cover the both sides of the aforementionded requirements.

The representation of geometry and topology of 3D objects has been extensively studied and developed by Molenaar (1990; 1998), Zlatanova (2000; 2004), Oosterom (2002), Shi (2003). However, these models do not take into account object aggregation and special semantic information, thus not specialized for 3D house property application. The concept of multi-representations was used to realize levels of detail (LOD) is developed by Coors (2003) and Klobe (2003). To a certain extent, some of models are flexible to partition 3D space which is needed for 3D cadastre. However, being different from 3D cadastre, 3D house property management needs paying more attention to the interior property situations in real 3D environment (such as interior property situations in building). Therefore, more micro-scale LOD representations to the house property application other than the complexity of house buildings have to be defined. Furthermore, efforts have been made on semantic representation in several models, for example, IFC (Adachi, 2003), BIM (NIBS, 2007), CityGML (Open-GIS-Consortium, 2006; Kolbe, (2003; 2005)). However, the semantic description of buildings and their parts (like rooms, interior doors, stairs) does not equal to semantic relationship between the buildings and their interior real property objects such as storey, functional area and unit, and thus not suitable for thematic application of 3D house property management.

For spatio-temporal data modeling in both fields of GIS and cadastre management, more and more data models have been developed such as event-based models (Peuquet, (1995; 2001); Chen, 2000; Worboys, 2005;), state-based models (Armstrong, 1988; Langran, (1988; 1992); Liu, 2006) and object-oriented models (Worboys, (1992; 1994; 2005); Raza, 1999), etc.. However, most of existing models are mainly implemented on a 2D topologically and geometrically described system and represent multidimensional spatio-temporal phenomena in a standardized 2D abstraction. Though the 3D information is also considered in some models, only a certain degree of state changes of house property objects as well as the causes of these changes can be obtained. For example, the 3D house property object such as multi-property building is often considered as a whole, and its interior multi-property entities (units) can not be detailed represented. The real entities which are changing can not be identified well. Therefore, models above are difficult to provide a detailed and microcosmic representation for the asynchronous changes of interior and exterior multi-properties in 3D space.

The rest of this paper is organized as follows. Characteristics of 3D house property are analysed in Section 2. Section 3 discusses a proposed conceptual model by means of a unified modeling language (UML) diagram, and Section 4 describes the experimental results. The paper ends with conclusions in section 5.

2. CHARACTERISTICS OF 3D HOUSE PROPERTY

The vertical dimension for registering the legal status of real property objects is an important factor in 3D cadastre, in which researches have been carried out to study the needs, possibilities and constraints of them and significant progress has been achieved (Stoter, (2003; 2004; 2005)).

However, being different from the existing 3D cadastre research, the 3D house property management needs paying more attention to the interior property situations in the real 3D environment (such as interior property situations in a building), which has some special characteristics, including the semantic description for 3D property information, the management of multi-scale models in different requirement levels, spatial relationships between the shared area of a building and a real property object, the 3D real property partition of a residential building. These characteristics should be specially handled in designing a spatial data model for 3D house property management, since solving these characteristics are beyond the ability of the existing 3D city models. Besides the rich 3D information, the asynchronous change feature within building needs to be paid enough attention to a more microscopic and partial level.

Though significant progress has been achieved in 3D/4D cadastre (Stoter, 2005; Oosterom, 2006), there is still much work to be done before one can reach a satisfactory data model for 3D house property management.

3. SEMAITIC BASED LOD MODELS OF 3D HOUSE PROPERTY

3.1 Conceptual Model

The semantic-based LOD (Levels of Detail: LOD) models of 3D house property, SLODM-3DHP for short, is adopted in order to fully reveal the real three-dimensional features of house property information, and support semantic description of spatial entities and related property right, and provide 3D hierarchical framework (LOD) for the integrated representation of indoor and outdoor property right objects, and offer a particular method corresponding to the dynamic representation.

As shown in figure 1, the conceptual data model of SLODM-3DHP includes four components, which are semantic layer, property layer, event layer, and geometry layer. The basic functionality and characteristics of SLODM-3DHP are illustrated as follows:

Semantic layer: The relationship among the objects is given in the semantic layer, which mainly consists of two basic semantic structures (as discussed in the following sections): the LOD semantic structure and the real property semantic structure. The LOD semantic structure concentrates on the 3D hierarchical framework for the integrated representation of indoor and outdoor property right objects, while the real property semantic structure describes the relationship between spatial entities and related property features. As shown in figure 1, the following characteristics are considered in semantic layer. (1) The LOD framework consists of the following basic entities in different application levels: district/land-block, building, storey, and unit. Different LOD is to ensure that for each object only exactly one application level is considered when performing an analysis or visualizing data. LOD1 corresponds to the land-block (or district), LOD2 corresponds to the building or other infrastructures (such as pipeline, subway etc.), LOD3 corresponds to the storey and LOD4 corresponds to the unit (door). (2) Land-blocks are often managed in a district area, and buildings or other infrastructures are often located at a land-block, so the relationship between the land-block and the district, as well as the building (or other infrastructure) and the land-block is defined as 'located at'. For a building complex (existing complicated property situation), interior geometric structures (such as stories, units) need to be well represented to partition the property space clearly; the semantic relationship between the storey and the building, as well as the unit and the storey is 'composed of'. In addition, (3) the real property semantic structure mainly comprises the 'annexes-of-common' object and the 'annexes-of-exclusive' object. The 'annexes-of-common' object is the public affiliated object used or shared within building, including elevator wells, stair wells, passageways, basements, gatehouses etc. The semantic relationship between the 'annexes-of-common' object and the building is 'shared with'. At the same time, the 'shared with' semantic rule will be conveyed to the storey or the unit according to different spatial levels. The semantic relationship between the 'annexes-of-exclusive' object (such as balcony, overhanging corridor) and the unit is 'attached to'.

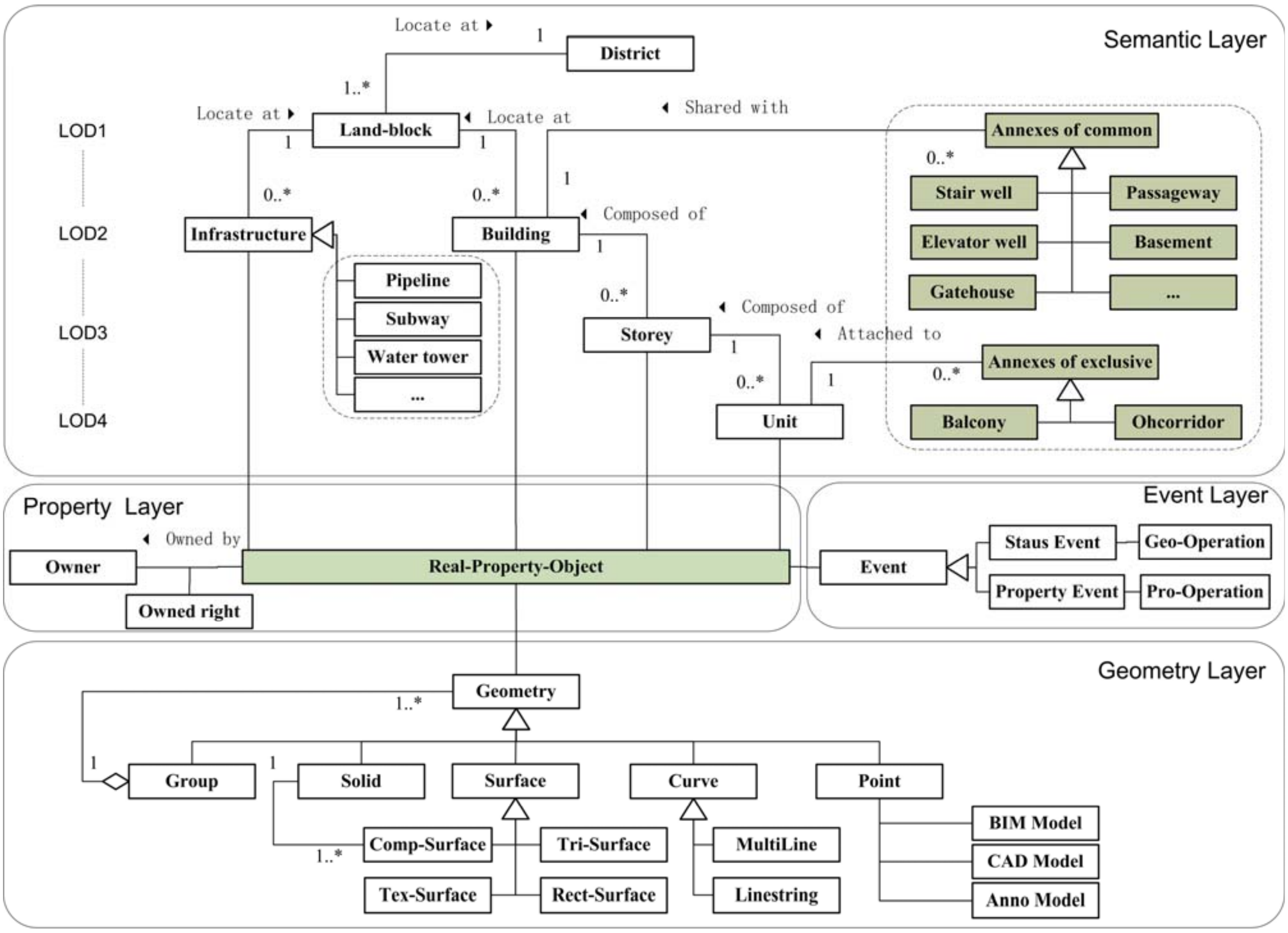


Figure.1 Semantic-based LOD Model of 3D House Property

Property layer: For confirming the unification between the ownership of a real property and the content thereof, the integrated content representation of a specific ownership, which includes main object of housing spatial features (such as building, storey, unit) and their related 'annexes-of-common' objects or 'annexes-of-exclusive' objects, is termed 'real-property-unit'. This layer provides the basic property relationship (defined as 'owned by') between the 'real-property-unit' and its owner, where the concept of 'real-property-unit' is important not only to be the core of property layer, but to link with the semantic layer, the event layer and the geometry layer. In the figure 1, 'real-property-unit' is used to indentify the integrality of 3D property space through establishing one-to-one relationship with building (or other infrastructure), storey, or unit in accordance with different semantic levels. In addition, 'real-property-unit' has the relationship with geometry and event, which satisfies the interior geometric structure description, spatial analysis and dynamic change representation.

Event layer: Considering the remarkable 3D dynamic characteristics in house property objects, hierarchical events concerned with the description of occurrences rather than states, are incorporated into the conceptual model. The hierarchical events representation is developed on the comprehensive consideration of the 3D spatial constraint (land-block, building, storey, unit), semantic description of event. Based on a dynamic correlation of hierarchical events, keeping track of the buildings changes including geometry changes and related property changes, through their whole life cycle from creation to demolition can be obtained.

***Geometry layer*:** This layer provides a solid foundation for achieving the geometry representation, spatial analysis, and dynamic change description in real 3D environment. Figure 1 shows a basic structure, which includes five basic abstract features: point, curve, surface, solid, and group. (1)Beyond the simplest spatial characteristic (such as the 3D position, the azimuth and the box size), a point object may be associated with the complicated and elaborate 3D model, such as BIM (Building Information Model) model, CAD (Computer Aided Design) model and Anno (annotation) model etc., and therefore possesses the ability of integrated representation of indoor and outdoor property objects. (2)The curve object is used to express the linear object (e.g. pipeline, cable), and further the multiline and line-string as basic linear entities can be derived from it. (3)The subclass of surface object comprises the different types of a surface model: 'tri-surface', 'rect-surface', 'tex-surface' and 'comp-surface'. Tri-surface and rect-surface are special surface entities, which specify triangulated irregular networks often used to represent the terrain and regular surface such as rectangle or square surface. Considering the characteristic of 3D visualization, tex-surface is also introduced, which can be assigned materials (colors, shininess, transparency) or simple textures. The comp-surface is a special complex surface feature, elements of which are simple surface entities and must be topologically connected along their boundaries. (4)In addition, the comp-surface is basic element for solid object – building, storey and unit, for example. (5)The group object is mainly used to represent an aggregation of multi-independent geometric objects, which are disconnected in the spatial level. For example, a functional area is a group object, which is aggregated by different stories regarded as the same property right.

3.2 Semantic Structure

The standardization of architectural design enables the house buildings to have a similar style in the physical structure. However, complex multi-semantics are existed in the house property management to indentify the specific real property objects themselves and mutual relations. Based on comprehensive analysis of various characteristics of 3D real property objects, such as shape, size, position, property right attribute and internal 3D structure in building, some semantic rules are extracted to unify and solve these multi-semantics problems. The rules are illustrated from two aspects, which are the semantic rule for spatial relations and the rule for real property relationships, as follows.

(1) Semantic rules for spatial relations. The fundamental task of spatial relations is to distinguish different spatial expressions using mathematical or logical method, and then give a formal description. In the spatial level, there are logical relations among the 3D house property entities, such as the inclusion relation, and correlation relation, and so on. Compared with the other domains, spatial relations for 3D house property management mainly comprise the following rules.

Rule 1 (Locate at).This semantic rule is used to emphasize the hierarchical relations between the 3D house property objects. In this rule, the spatial object is considered as a whole object, and spatial relations between spatial objects are described and determined by the spatial location (or inclusion) between whole bodies (i.e. building or district etc.) of these objects instead of their components (i.e. interior storey or unit etc.). For example, a building as a whole are often located at a district (land-block) area; the semantic relationship is defined as 'locate at'.

Rule 2 (Aggregate).This is an aggregation of real property objects with the same owner, and provides correlative relation between real property objects. The collection of these real property objects ensures the integrality of one property unit. More specifically, multi-independent house buildings (or units) are owned by one owner, which further will be aggregated one building (or unit) cluster in the house property management in order to guarantee the integrality of property right; the relationship between the building and the building cluster is 'aggregate'. In addition, the same goes for the relationship such as several storeys aggregate one functional area, or several units aggregate one storey.

Rule 3 (Composed of).This provides a spatial semantic rule between features and its parts, e.g., a building is composed of its stories or a storey is composed of its units. The whole spatial object (feature) consists of several parts, in which their own geometric representations are different from the whole.

(2) Semantic rules for real property relationships.

Rule 4 (Owned by).This represents a primary link relationship between the property right unit and its owner. The right of ownership can be established by this rule.

Rule 5 (Attached to).This provides the property semantic relationship between the unit (house) and its subsidiary objects (such as balcony, overhanging corridor).The relationship between the unit and its subsidiary object is one to one; balconies or overhanging corridors only belong to this unit, and they are not shared and used by other units.

Rule 6 (Shared with). In order to distinguish the complete extent of the property unit, a special concept, namely the annexes-of-common, is briefly introduced. In some countries e.g. in China, a building area (or annex) that is shared with multi-property units within a building but outside a unit (door), such as elevator well, stair well, passageway, basement and gatehouse etc., is named the annexes-of-common object. In this paper, the semantic rule between the annexes-of-common object and the main body of real-property-unit is defined 'shared with'. Besides, the relative rule is divided into four levels: (1) shared with a building; (2) shared with a functional area; (3) shared with a storey; (4)shared with a unit.

3.3 LOD framework

Establishing reasonable LOD of 3D house property information is necessary for analysis and visualization of indoor and outdoor real property objects. Different from the description of LOD in CityGML, the requirements at different application levels, the complexity of the relationship between real property objects and the complexity of the building (house) in cartographic structure are the key issues to determine advisable contents of LOD models. 3D house property entities are defined as five levels of detail and each LOD has its own application scope with respect to the requirements for house property application as well as the complexity of house buildings (constructions), which are illustrated in table 1.

LOD 1: This level has to be employed to ensure reasonable partition of property right space on a horizontal level, which is the extension from the traditional principle of two-dimensional to three-dimensional space. Two hierarchical representations, i.e. each land-block belongs to exactly one district and each district belongs to exactly one city, are allowed to be contained in one level (view). Furthermore, level 1 figures out the detailed horizontal distribution of property information (buildings) within the district/land-block scope.

LOD 2: This level is a primary vertical description of the 3D house property space, such as a 3D partition of aboveground or underground building, which can solve the problem of mutual overlaps between property entities in the 2D projection, and satisfy the property requirement of the 3D space level. The basic element is the residential building or other independent infrastructure (facilities), which has a single right of ownership and is represented by the well known blocks model.

LOD 3**:** This level is a more micro-level representation in order to distinguish interior property situations in the building, which fixs the boundaries of property right from the vertical structure of buildings, and makes storey as the primary property unit within the residential building.

LOD 4**:** In the house property management, the unit is the least property right level. Therefore, the unit is the basis of this level, which is used to provide detailed and clear 3D geometry expression of property rights.

LOD 5: This level is adopted to model interior geometric structures of a unit, which is used for three-dimensional analysis and the dynamic change expression.

LOD	***application scope***
LOD 1	horizontal level
LOD 2	2.5D vertical partition
LOD 3	3D interior property object
LOD 4	minimal real-property-unit
LOD 5	interior structures and spatial analysis

Table 1: Definition of LODs

3.4 Hierarchical Events

House property information has remarkable 3D dynamic characteristics which are different from the traditional changes in the 2D/3D cadastral field: (1) multi-time-scale features in 3D space-time; (2) diversity and asynchrony of local changes in 3D space; (3) high relevancy between change events in spatial level (structure); (4) microscopic and dynamic change characteristic in the real 3D geometry of house buildings and their complex interior property situations.

Based on the comprehensive consideration of the 3D spatial constraint, the semantic description of event and natural principle of human spatial cognition, the dynamic representation of house property information can also be abstracted as four hierarchies, i.e. land-block, building, storey and unit. Based on the discoveries, a novel dynamic description framework (hierarchical events including land-block event, building event, storey event, unit event and property right event) for modeling the spatio-temporal changes of 3D residential building and property features is discussed. The framework of hierarchical events is illustrated in the figure 2.

(1)Land-block event: Beyond the traditional cadastral parcel alternation event (for example, land subdivision, land amalgamation and boundary adjustment), land-block event (or the regional composite event, such as the removal or reconstruction of district, residential area planning and old-town renewal etc.) reflects a more comprehensive alternation to emphasize the influences on buildings located on the land, as well as to stimulate more micro-level events in the aspect of the semantic level.

(2)Building event: When changes of the whole building are driven, the change events are defined as a building event, the acted object of which is building itself. The event which stimulates the changes, such as construction of newly-built and expansion in a building area, is used as this concept.

(3)Storey event: The building is composed of several natural stories in the vertical level. The aimed unit of the storey change event is the storey， the elements of which have the synchronization change process. The storey of this concept, besides the traditional knowledge of the storey, also consists of the functional area which includes different stories regarded as the same property right. The typical changes of the storey in this innovative concept include storey demolition caused by the height limitation, storey subdivision and stories extension and reconstruction.

(4)Unit event: The acting object of the unit event, which is the minimal spatial partition of real-property-unit in the house property management, is a special room or unit with individual and complete property right. The change events are defined as the unit event, such as room expansion, structure change of room and so on.

(5)Property right event: It means the attribute change event aiming at the changes of ownership right owned by real-property-unit.

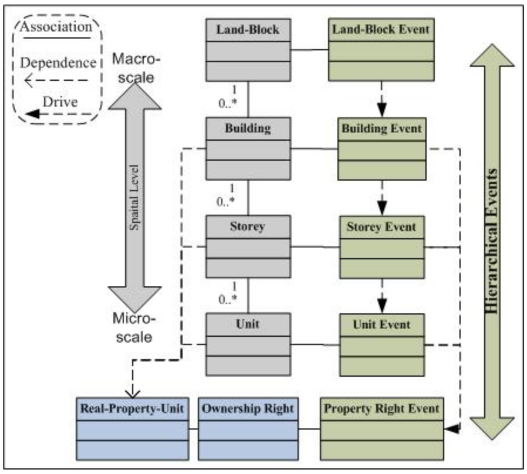


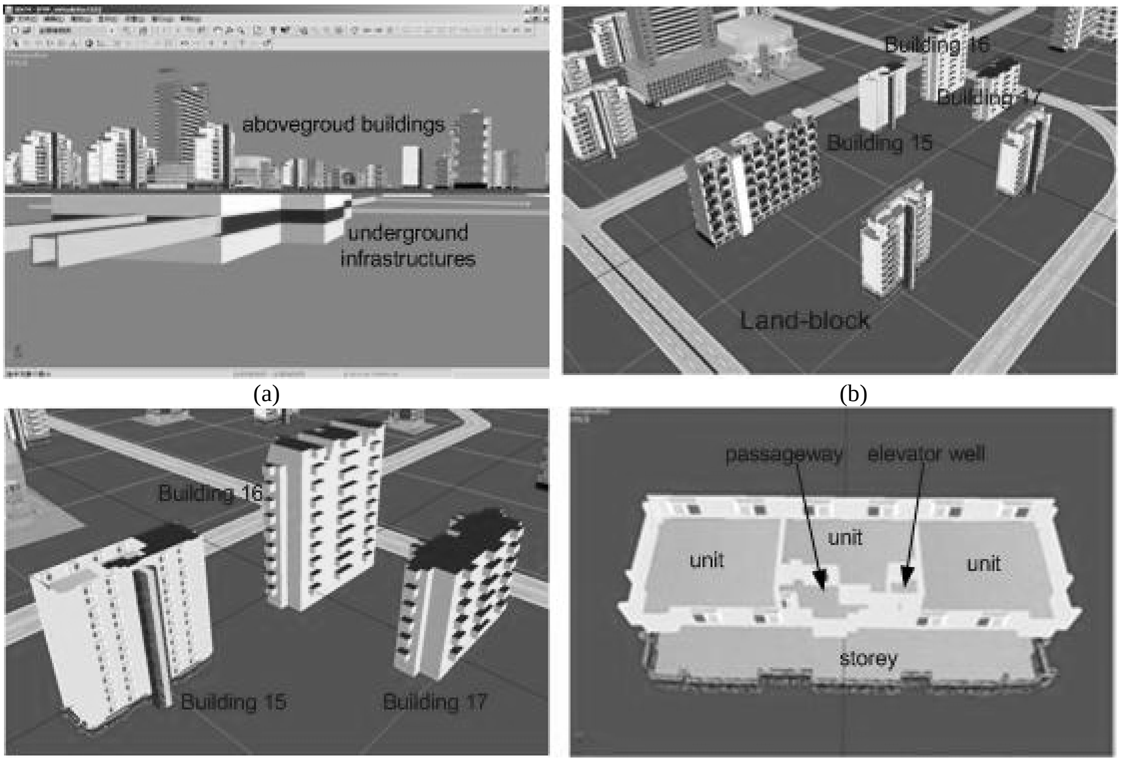
Figure.2 Framework of Hierarchical events

4. EXPERIMENTAL RESULTS

Based on the conceptual model and the semantic, LOD and hierarchical events structure of SLODM-3DHP, the implementations were accomplished on a Component-Oriented 3D GIS software VGEGIS 6.0 (developed by Wuhan University in China). The full 3D real property space partition and related dynamic changes in practical house property management are discussed by the two applications: partition 3D space for real property and dynamic representation.

4.1 Partition 3D Space for Real Property

Figures 3 shows a 3D hierarchical framework for the integrated representation of indoor and outdoor property right objects, which includes some important features mentioned above.



(a) (b)

(c) (d)

Figure.3 Illustrations of 3D Partition

(1)Figure 3 (a) shows the integrated expression and registration of aboveground and underground infrastructures or buildings. The semantic description of 'located at' is supported, and the coarsest property requirement to partition 3D solid space is satisfied.

(2)Figure 3 (b) illustrates the level of land-block, which contains the practical property right distribution in horizontal level. Representations responding to different real-property-units are provided in an integrated land-block according to the real-property-unit interpretation (e.g. building as a real-property-unit, storey as a real-property-unit).

(3)The building 16 with single property right is represented by external appearance of 3D visualization (LOD 2) in figure 3 (c), and figure 3 (d) explains the storey (using LOD 3) and units (using LOD 4) to distinguish interior property rights in a multi-property building (the 15th building) with the aid of geometric and semantic information.

(4)In figure 3 (d), in order to clear interior property situation of the commercial-residential building (the 15th building) in 3D geometry space, more refined representations using storey or unit as a real-property-unit are provided.①The first storey is a super-market with single property right. Based on the semantic rule for spatial relations, the spatial link between the story and the building is represented by 'composed of'. To distinguish the property situation of the super-market, storey is the basic element of the 3D geometry representation and has the characteristic of individual property right in property layer (If the function area includes many stories, it will be related to the semantic rule of 'aggregate', and forms a integrated real-property-unit); the related semantic rules are: 'shared with a building' and 'shared with a functional area'.②The second storey and above are residential space with the multi-property right, and every storey contains 3 units and 2 shared building area objects (i.e. passageway and elevator well). The spatial relations between the unit and story, or building are defined by the semantic description of 'composed of'. The spatial adjacency relationship between two units in the same storey is built by the important geometric feature 'common wall'.③By analyzing the relationship between real property objects and their affiliated shared objects, the passageway connecting every unit in the same storey is only shared by 3 units, the elevator well is shared by the whole building, so the correlative semantic relationship contains: 'shared with a storey', 'shared with a building' and 'attached to'.

4.2 Dynamic Representation

Based on the 3D hierarchical framework above and the hierarchical events, dynamic change representations towards 3D real-property-unit changes including geometry changes and related property changes are illustrated as follows:

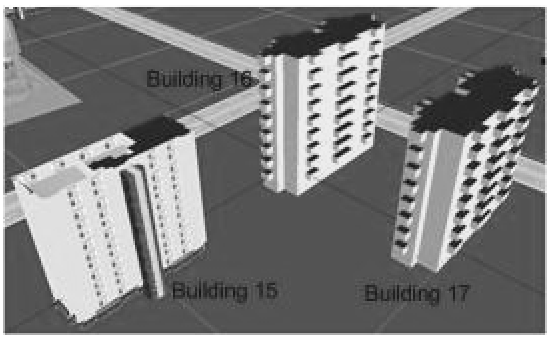


Figure.4 A Result of Spatial Changes over Time

The screenshots (figure 3(c) and figure 4) show the geometry changes of the building 16 and 17 in a special district reconstruction project. In the environment, the building 16 which is a single property right body needs to be partially dismounted due to the height restriction. Two stories need to be added an extension to the building 17 which is a multi-property body. Therefore, the role of partial demolition of the building 16 is an atomic event (identifier is ‘building event1’ in figure 5), and further drive the occurrence of property right event (right event1); The role of expansion of the building 17 is a composite event (building event2) which needs to be further divided into two storey events (i.e. storey event1 and storey event2) furthermore, each storey event which is a composite event is also divided into two unit events. Finally, the unit event as the atomic event directly drives the property right event, the geometric and property changes of the whole building are terminated. The dynamic changes and links above are shown in Figure 5.

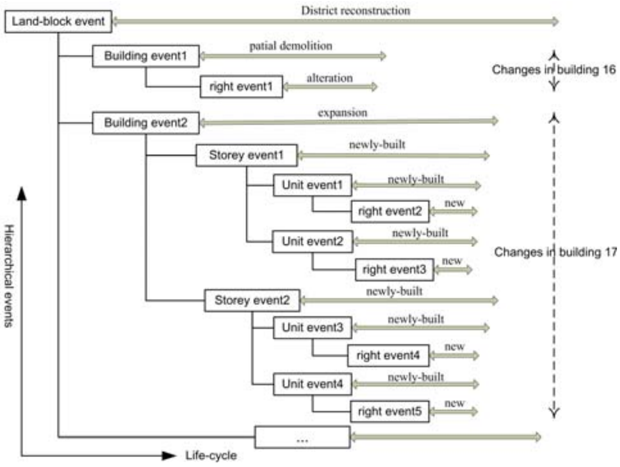


Figure.5 An Application Illustration of Hierarchical Events

5. CONCLUSION

In this paper, a novel conceptual model is proposed for solving the problems of increasing complicated urban house property management, by means of this model both the geometric and semantic information of house property can be represented in full three dimensional space and then used for more flexible and dynamic registration and management. Further development of this model is about the design and implementation of event-driven operators as well as proper database structure.

REFERENCES

Adachi, Y., Forester, J., Hyvarinen, J., Karstila, K., Liebich, T.W., 2003. Industry Foundation Classes IFC2x Edition 2. International Alliance for Interoperability. http://www.iai-international.org/Model/files/20030630_Ifc2x_ModelImplGuide_V1-6.pdf (accessed 25 Dec. 2007).

Armstrong, M P., 1988. Temporality in spatial databases. In: *Peoceedings of GIS/LIS'88*, (2), pp. 880-889.

Chen, Jun. and Jiang, Jie., 2000, An event-based approach to spatio-temporal data modeling in land subdivision systems. *Geoinformatica*, 4(4), pp. 387-402.

Coors, V., 2003. 3D-GIS in networking environments. Computers, Environment and Urban Systems, 27(4), pp.345-357.

Kolbe, T.H., Gröger, G., Plümer, L., 2005. CityGML: Interoperable Access to 3D City Models. In Geo-information for Disaster Management, pp. 883-899.

Kolbe, T.H., Gröger, G., 2003. Towards unified 3D city models. *In:* Proceedings of the ISPRS Commission IV Joint Workshop on Challenges in Geospatial Analysis, Integration and Visualization II, Stuttgart, Germany.

Langran, G., Chrisman, N.R., 1988. A Framework for Temporal Geographic Information. *Cartographica*, 25(3), pp. 1-14.

Langran, G., 1992. *Time in Geographic Information Systems*, Taylor and Francis, London.

Liu, Nan., Liu, R. Y., Zhu, G. L., Xie, J., 2006. A spatial-temporal system for dynamic cadastral management. *Journal of Environmental Management*, 78(4), pp. 373-381.

Molenaar, M., 1990. A formal data structure for 3D vector maps. In: *Proceedings of EGIS’90*, Amsterdam, The Netherlands, 2, pp. 770–781.

Molenaar, M., 1998. *An Introduction to the Theory of Spatial Objects Modelling.* Taylor & Francis, London.

NIBS, 2007. The National Building Information Modeling Standard: Version 1.0-Part 1 Overview, Principles, and Methodologies,http://www.facilityinformationcouncil.org/bim/pdfs/NBIMSv1_p1.pdf (accessed 26 Dec. 2007).

Open-GIS-Consortium, 2006. Candidate OpenGIS CityGML Implementation Specification: OGC 06-057r1, Version: 0.3.0, http://www.citygml.org/1522/ (accessed 29 Dec. 2007).

Peuquet, D.J. and Duan, N., 1995. An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. *International Journal of Geographical Information Systems*, 19(1), pp. 7-24.

Peuquet, D.J., 2001. Making Space for Time: Issues in Space-Time Data Representation. *Geoinformatica*, 5(1), pp. 11-32.

Raza, A., Kainz, W., 1999. Cell Tuple Based Spatio-Temporal Data Model: An Object Oriented Approach. In: *Proceedings of ACM-GIS'99*, 2(4), pp.20-25.

Shi, Wen-zhong., Yang, Bi-sheng., Li, Qing-quan., 2003. An object-oriented data model for complex objects in 3D geographic information systems. International Journal of Geographic Information Science, 17(5), pp. 411-430.

Stoter, J.E., Ploeger, H.D., 2003, Property in 3D-registration of multiple use of space: current practice in Holland and the need for a 3D cadastre. *Computers, Environment and Urban Systems*, 27, pp. 553-570.

Stoter, J.E., Van Oosterom, P.J.M., 2003. Cadastral registration of real estate objects in three dimensions. *URISA Journal*, 15, pp. 51–60.

Stoter, J.E., 2004. 3D Cadastre. PhD thesis, *TU Delft*, the Netherlands.

Stoter, J.E., Van Oosterom, P.J.M., 2005. Technological aspects of a full 3D cadastral registration. *International Journal of Geographical Information Science*, 19(6), pp. 669-696.

Van Oosterom, P.J.M., Stoter, J.E., Quak, W., Zlatanova, S., 2002. The balance between geometry and topology. In: *Proceedings of Advances in Spatial Data Handlin, 10th Int. Symp, Springer, Berlin*.

Van Oosterom, P.J.M., Ploeger, H.D., Stoter, J.E., Thompson, R., Lemmen, C.H.J., 2006. Aspects of a 4D cadastre: a first exploration. *In: Peoceedings of Shaping the Change, XXIII international FIG congress,* pp. 1/23-23/23.

Worboys, M.F., 1992. Object-oriented models of spatio-temporal information. In: *Proceedings of GIS/LIS '92,* San Joes, California, pp. 825-834.

Worboys, M.F., 1994. A Unified Model of Spatial and Temporal Informaiton. The *Computer Journal*, 37(1), pp. 26-34.
Worboys, M.F., 2005. Event-oriented approaches to geographic phenomena. *International Journal of Geographical Information Science*, 19(1), pp. 1-28.

Zlatanova, S., 2000. 3D GIS for Urban Development. PhD Thesis, ITC Dissertation Series no 69. The International Institute for Aerospace Survey and Earth Sciences (ITC), the Netherlands.

Zlatanova, S., Rahman, A.A., Shi, W.Z., 2004. Topological models and frameworks for 3D spatial objects. *Computers & Geosciences*, 30(4), pp. 419-428.

ACKNOLEDGEMENT

Special thanks to Prof. Dr Qing Zhu from Wuhan University, Dr Donna J. Peuquet from the Pennsylvania State University, Dr Hong Shu from Wuhan University, and Dr Michael Worboys from University of Maine, for their critical comments and constant source of help. The work described in this paper is supported by the National Natural Science Foundation of China (40671158) and the National High Technology Research and Development Program of China (2006AA12Z224 and 2004CB318206).