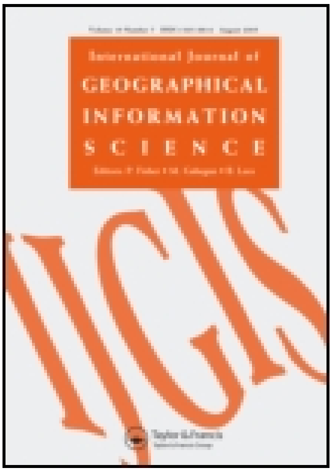

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Semantics-based 3D dynamic hierarchical house property model

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Research Article

Semantics-based 3D dynamic hierarchical house property model

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Aiming at the increasing critical issues of existing 2D plans and map-based methodology for integrated management of advanced buildings and related dynamic property rights in complicated 3D built environments, a novel semantics-based 3D dynamic house property model with hierarchical levels of detail is proposed in this paper, based on comprehensive analysis of 3D house property objects and various application requirements. This model is characterized by: (1) 3D geometric semantics: a 3D geometry hierarchy of exterior and interior of buildings is defined; (2) thematic semantics, comprehensive house property object and related property right relationships are illustrated; (3) temporal semantics, dynamic representation of house property driven by both geometric events and property right events is involved. This model facilitates comprehensive data mining to analyze spatial relationships and dynamic change of property rights in real 3D built environments and can also support the sale and lease of real estate, facility management, house planning and so on.

Keywords: Semantic description; Hierarchical levels of detail; Hierarchical events; 3D house property

1. Introduction

Houses and buildings are the most important elements related to urban life. Modern house property management is becoming multi-dimensional and dynamic as urban physical spaces are continuously expanding upwards and downwards. Due to land use limitations, more and more complicated house property facilities are being 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 (Durmisevic 1999, Raper 2000). On the other hand, the modernization of architecture, engineering and construction also encourages compact multi-storey buildings, as well as building complexes with split-level or duplex/compound apartments (Schoenauer 2000). The relationships between residents and houses (e.g. transfer of ownership rights) are changing more frequently than before. Such kinds of 3D house and related property rights are termed ‘3D house property’, which can be summarized from two components: the natural geographic attributes centering on buildings and the legal and social attributes. The geographic objects are mainly composed of districts, parcels, buildings, storeys, units, etc., while the legal and social attributes objects are property rights focusing on ownerships, owners, etc. (ISO/WD-19152 2008).

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1.1 *Semantic issues*

From a juridical point of view, complete and precise house property information is increasingly introduced to the householder or urban planning department, the departments of house property management always attempt to register the valid and accurate information about property right extent in 3D space, especially for the integrated registration of complicated buildings and their interior property situations such as privately owned units and jointly owned parts in 3D built environments (Kaufmann and Steudler 1998, ISO/WD-19152 2008). There are three kinds of semantics to be considered, i.e. spatial semantics for spatial relationships among 3D geometries, thematic semantics for property right relationships and temporal semantics for dynamic changes (see Section 3.4): (1) the spatial relationships among house property objects, based on 2D topological and geometrically described parcels, have shown inadequacy for defining the location and physical boundary of 3D constructions (e.g. pipelines, tunnels, building complexes) and in the vertical and interior dimension (overlapping storeys and units) of rights established for 3D house buildings (Stoter 2004); (2) in addition to the private ownership of individual units, buildings' shared ownership contains a variety of forms: from multi-apartments buildings used only for residential purpose to those containing both residential units and space used for commercial purposes, thus bringing about the complex property registration semantic issues for the identification of the entire property. The loss of information regarding co-owned parts (e.g. elevator wells, staircases, passageways, basements and gatehouses) and related attributes (e.g. shared in a building, in a functional area and in a storey) conceal important property rights allocation details that might cause a dispute over property rights. For the purpose of explicitly defining and depicting the extent as well as the location of each property right object, including the individual units and shared parts, basic property right semantic relationships need to be defined as shown in figure 1 (see details in Section 3.2); (3) house property information has

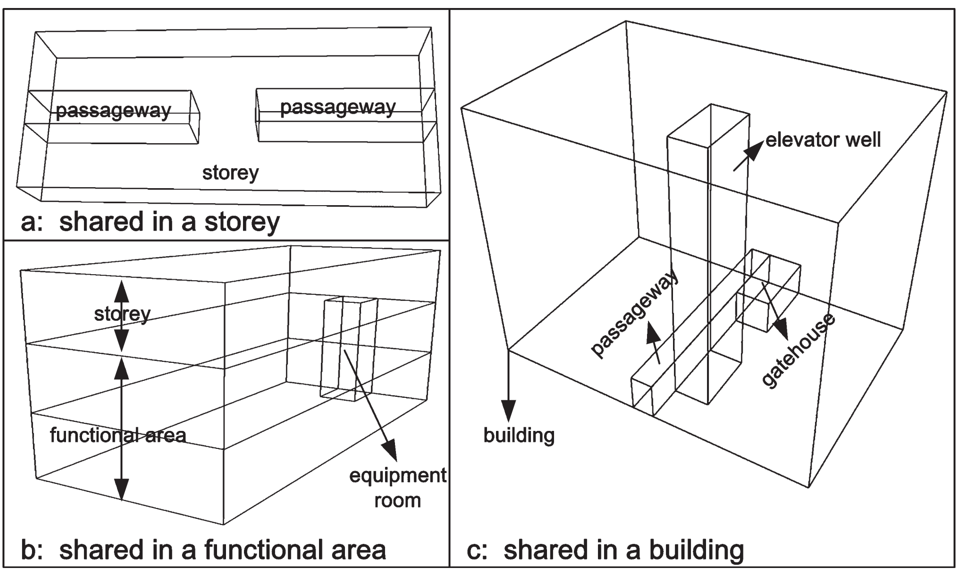

Figure 1. Semantic description of 'Shared' relationship: (a) shared in a storey; (b) shared in a functional area; (c) shared in a building.

remarkable dynamic characteristics with diversity and asynchrony in 3D physical world (van Oosterom *et al.* 2006b). The diversity focuses on both the geometrical changes including storey subdivision, unit expansion, etc., and property rights changes including newly added ownership and transfer of property right, etc. While asynchrony means the changes of house property objects could take place in their own local space at different frequencies, for example, the asynchronous changes between a piece of land and its attached buildings: property rights and geometry of the land can be maintained for many years, but the building's property rights and geometry changes more frequently; the same goes for asynchronous changes occurring between a building and its interior units/storeys. In addition, local changes for property analysis such as the geometric boundary adjustment of a shared wall are usually restricted within its adjacent unit space but the whole building. Consequently, house property objects such as an apartment complex containing multiple interior apartment units should be clearly registered as separate unit parts in 3D space not as the building itself based on the 2D representation, for the sake of providing precise registration for the changing property unit and exact analysis for specific change processes of house property.

1.2 *From 2D to 3D*

People's recognition of house property registration is no longer constrained to the 2D static world, because the shape of the 3D building-storey-unit is explicitly built in the real world. There are big gaps between the abstract 2D representation and the real 3D house property information because of several reasons: (1) 3D house property objects are currently registered as 2D topological and geometrical maps, lacking an insight in the vertical dimension of property rights. For example, storeys with different heights are represented as an identical flat 2D plan in the house property management system, and cannot illustrate the actual height of each storey and which storey lies on top of the other; (2) based on 2D representation, the 3D house property objects may lose appearance and height properties, as well as the spatial relationships. As shown in figure 2, the special parts of a sloping roof with height of less than 2.1 m will be ignored partially in 2D representations according to the standards in the legal sense (GB/T50353-2005 2005). This results in the incorrect registration of the property right space; (3) it is too difficult to register and to manage the increasingly complicated houses and their 3D interior ownership situations completely by employing 2D models, especially for registering multi-functional building complexes, split-level apartments and duplex apartments combined with very complex spatial property structures and relationships.

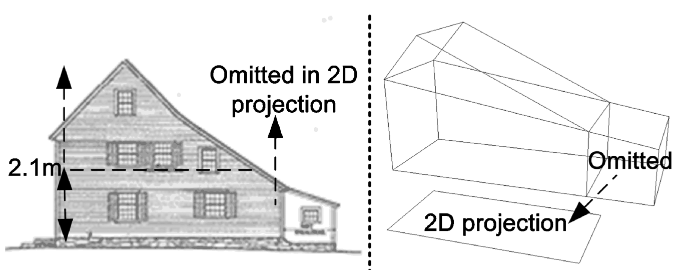

Figure 2. A case of typical features with restricted heights.

Table 1 gives a comparison between 2D and 3D representations of different features in house property management. Compared with a flat 2D map, more detailed 3D house property object representation with accurate spatial boundary and position under the existing legal framework of house property registration is demanded in a unified real 3D environment. Existing 2D floor/unit plan representation is only a logical concept to access the ownership of house buildings, which is not adequate for registering detailed 3D features such as the spatial position, shape, interior structure and their mutual relationships.

1.3 *Hierarchical levels of detail*

The simple external appearance is not adequate for representing and registering complicated houses, especially their corresponding interior property situations. In fact, real 3D buildings may have different spatial structures inside them (Stoter *et al.* 2004). On the other hand, it is usually not necessary to fully register the complex 3D interior structures of each house building; the preference for property registration depends on the level of complexity of the property rights of the building. In reality, a building complex can be used as several self-owned apartment units, in which case it is better to register each of them in detail, or as a one-person-owned property, when it can be registered as a whole. These two situations having different property registration units attached to their own ownerships motivate the accurate registration representation of 3D house property objects with hierarchical structures (building-storey-unit), which can supply distinct levels of detail (LOD) of a building to illustrate different property features and dynamics as required.

House property management urges more detailed and integrated 3D house property information, and the key issues are essentially focused on how to describe actual relationships among house property objects, especially the relationship for the integrated representation of multi-hierarchical 3D house property objects, and how to represent complicated interior property situations within a building and related 3D dynamic representation towards interior and partial changes.

The remainder of this paper is organized as follows. The related work on 3D house property model is reviewed in Section 2. Section 3 introduces the semantics-based 3D dynamic hierarchical house property models and Section 4 discusses the implementation issues. Finally, the conclusions are presented in Section 5.

2. Related work

Currently, house property management is by means of 2D graphic representation of the floor plan and individual household planar graphs of the apartment or building complex. However, it is difficult to pinpoint the location of a 'vertical physical boundary' from 2D floor plans, and one also cannot clearly identify the extent and

Table 1. Comparison of 2D and 3D representation.

Managed objects(features)	*2D Representation*	*3D Representation*
Parcel	Parcel map	3D land-block based on DEM
Building	House plan	3D building model
Storey	Floor plan	3D volume of interior storey/ functional area
Unit	Unit plan	3D room model
Affiliated facility	Attribute	3D solid/attribute

adjacent details of the property rights, especially three levels of typical building and dwelling registration (BDR), property level, building level and unit level, a property rights overview of an apartment complex (Hansen 2001, Stoter *et al.* 2004). The 3D geometry of both the interior structures of buildings and the boundaries of apartments is not directly addressed in the BDR, which still remains at the conceptual level for 3D house property registration. In addition, the storey, which can be used to establish a link between the building and its interior units and to provide dynamic representation, is also ignored in BDR.

For the legal and social attributes, Cadastre 2014 describes the complete legal situation of the land parcel, including public rights and restrictions (Kaufmann and Steudler 1998). Furthermore, an ISO standard of the land administration domain model (LADM) has concluded the legal/administrative issues into 'Rights', 'Restrictions' and 'Responsibilities' based on the legal documents, where restrictions and responsibilities are often related to some additional non-ownership rights such as right of easement. Rights, especially the ownership rights, are compulsory association between registered objects and persons (ISO/WD-19152 2008). Theoretically, the registered land ownership right is related to the land parcel and applies to the whole space above and below the parcel. However, it is necessary to consider the house property situation where the land and its attached house have different owners, for example, the land belongs to the state and the buildings belong to the citizens. Therefore, to register the ownership right of 3D property unit is becoming increasingly important (Stoter 2004) to support the complete transfer, inheritance, mortgage and sale of the property. This paper thus focuses on the ownership right of house property unit.

The registration of land and attached objects in the vertical dimension in 3D cadastre research is an important basis for the house property registration management. However, there is a difference between registering the house/building itself and its interior units related to a specific ownership, while registering the interior property unit within a house building is the core task in the house property registration. The current 3D cadastre research supporting volume parcels has extended traditional cadastral registration into the third dimension, especially for solving the registration problem in overlapping and interlocking constructions in urban business centers (ISO/WD-19152 2008). For example, airspace parcels have been introduced in Victoria, British Columbia and Canada (British-Columba-Government 1996, Stoter 2004); multilayer representation to 3D characteristics of properties has been promoted in Israel (Benhamu and Doytsher 2003); 3D properties with footprints (which relate to built constructions) have been described in Sweden (Julstad and Ericsson 2001); the 3D built construction property has been applied in Norway (Onsrud 2002) and 3D volumetric parcels created on the plan have been established in Queensland, Australia (Queensland-Government 2008). Although buildings can generally be considered as separate properties within existing juridical frameworks in some countries, the 3D building representation above such as built constructions or building parcels (which are generally defined as floors, walls and ceilings) in the cadastral registration is only suited for whole buildings and dwelling registration because no detailed interior structures and semantics information are represented. In the Netherlands, the 3D cadastre model with three different forms, 3D administrative tags and warnings, hybrid cadastre and full 3D cadastre, and the LADM (ISO/WD 19152) have been proposed to solve problems, such as: the 3D geometries could not be interactively visualized and queried in an integrated view to obtain a complete 3D situation, and the lack of 3D data exchange among different systems in the cadastral domain (Stoter 2004, Stoter and van Oosterom 2005, van Oosterom *et al.* 2006a, ISO/WD-19152 2008). However, when the model is used to identify the interior 3D property situations in a building complex, it still rests on the conceptual level for 3D space partition; the detailed interior structures and relationships of the house property management cannot yet be well represented. Besides, the semantic information, which is very important in efficient house property applications especially in shared ownerships, is insufficiently considered in these models.

The development of 3D building model in GIS area is largely influenced by the '3D FDS' model, which combines the basic geometry and topology of 3D geo-data and allows one to keep track of multiple topological properties (Molenaar 1990; 1998). Subsequently, in the field of CAD and urban GIS, the representation of geometry and topology of 3D objects has been extensively studied and developed in the models of 'SSM' (Zlatanova 2000, Zlatanova *et al.* 2004), 'multi-topology' (van Oosterom *et al.* 2002), 'OO3D' (Shi *et al.* 2003), 'TEN' (Pilouk 1996, Penninga and van Oosterom 2008) and 'HL-3DRNM' (ZHU and LI 2008). These models focus on issues such as space partitioning, supported objects and primitives and modeling rules, and also on some thematic and semantic constraints, for example, 'TEN' was built for geological applications, 'SSM' was applied in web diffusion and 'HL-3DRNM' was focused on road network, but they are not specifically for registering 3D house property rights.

In order to support the management and visualization of multi-scale models, a concept of multi-representations was introduced by Flick (1996) to store different presentations for each geo-object (feature). Furthermore, for realizing complex buildings' multi-representations, the concept of levels of detail representation was developed by Coors (2003) and Kolbe and Gröger (2003), also aiming to automatically manage the requirements of different planning levels and the visualization application. To a certain extent, these models are flexible enough to partition 3D space, which is a basic requirement for 3D house property management. However, there are still some inadequacies for the representation of interior 3D property situations within a building, such as the representation of jointly owned parts and the coexistence of multiple property rights.

Driven by the increasing demand for spatial data sharing and semantic interoperability, several models have been attempted to address buildings' semantic representation such as: IFC, a common building model to facilitate interoperability within the building and facility management industry sector (Adachi *et al.* 2003); BIM, a digital representation of physical and functional characteristics of a facility during its lifecycle in the built environment (NIBS 2007); and CityGML, an official OpenGIS standard of semantic information model for three-dimensional, multi-purpose and multi-scale representation of cities and regions (Kolbe and Gröger 2003, Kolbe *et al.* 2005, Open-GIS-Consortium 2008). The building model is the most detailed thematic concept of CityGML, and this OGC standard provides a very good abstract framework of 3D geometry hierarchy. However, its semantic information is confined within structural components (e.g. rooms, doors, floors and walls in a building), and is not explicit for the semantic subdivision of a building into its interior/local real property objects such as storeys, functional areas and units.

Besides the rich 3D geometry, house property information has aforementioned dynamic characteristics including geometric changes and related property right changes in 3D house property space. However, most of the existing dynamic representation models in the fields of GIS and house property management, such as event-based models (Peuquet and Duan 1995, Chen and Jiang 2000, Peuquet 2001, Worboys 2005) and state-based models (Armstrong 1988, Langran and Chrisman 1988, Langran 1992, Liu *et al.* 2006), are mainly implemented and oriented to a 2D topologically and geometrically described system and have limited capabilities in representing complex multidimensional spatio-temporal phenomena (Goodchild *et al.* 2007), which are important factors in house property issues. The existing models have no detailed representation for the asynchronous changes of interior multi-properties in 3D space. For example, a 3D building complex with multiple property rights is often considered as a whole object, which makes it difficult to represent the coexistence of multiple property rights within the building and thus identify the real/actual changing entity. In order to express the change of multiple property rights precisely, critical issues are focused on establishing dynamic linkage relationships between the whole space and the local object in three dimensions, which could help to identify the actual scope of house property change.

Since the dynamic thematic information of property rights is crucial for 3D house property registration, problems arise when the existing research mainly aims at the 3D geometry and topology for the static information of whole buildings. The following sections will focus on the semantic representation of the interior property objects of buildings, as well as the integrated representation of property rights in 3D space for more comprehensive dynamic house property management.

3. Semantics-based 3D dynamic hierarchical house property model

3.1 *Conceptual model*

The semantics-based 3D dynamic hierarchical house property model (3DHP for short) is adopted in order to reveal the three-dimensional features of real house property information and to support the semantic description of spatial entities and related property rights, which provides a 3D information foundation for the integrated representation of dynamic multi-hierarchical property right objects. The basic functionality and characteristics of 3DHP, which support different semantics of 3D geometry, topology, property right, as well as the event-driven dynamics, are as follows:

(1) **3D geometry semantics**: by means of the absolute georeferenced 3D coordinates for position and shape, provides a solid foundation for the integrated management of property right objects from a 2.5D horizontal level to a vertical level and 3D interior level (see Section 3.3), and also for spatial analysis and dynamic change description in the real 3D environment. To keep the consistency with the standard ISO 19107 (2003) and make full use of 3D database management such as Oracle 11g (Kothuri *et al.* 2007), basic 3D geometry representation based on the CityGML model is employed and developed. As a kind of Boundary Representation, the 3D coordinates of every point constituting the object boundary can be imported and managed (Kothuri *et al.* 2007). Figure 3 shows four basic geometrical features: point, curve, surface and solid. Beyond the simplest spatial characteristic (3D position, orientation and shape), an extended point object to the CityGML geometry is proposed to introduce the complicated and elaborate 3D models, especially from the building information models

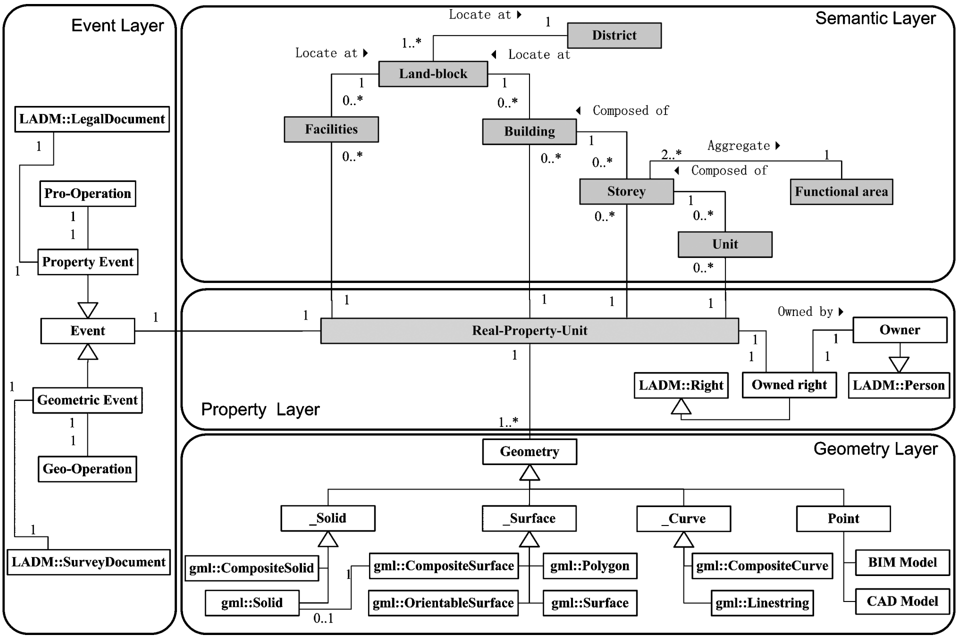

Figure 3. UML diagram of 3DHP conceptual model.

(BIM) for the finest level of detail information about equipment, structure, usage and so on, and the CAD models for architectural design of buildings, sites and environments (van Oosterom *et al.* 2005). For the sake of interoperability, the CAD or BIM model data can be accessed as a special file in their own local coordinate system, which is located in the 3D scene with its absolute central coordinate attached to the point object. The curve object is used to express linear objects (e.g. pipeline, cable), and thus the CompositeCurve and LineString as basic linear entities can be derived from it. The subclass of surface object comprises the different types of surface entities: 'Surface', 'Polygon', 'OrientableSurface' and 'CompositeSurface'. Surface and Polygon are two basic surface entities, corresponding to the representation of the 2.5D land-block and its boundary. Considering the characteristic of 3D rendering, OrientableSurface is also introduced, which can be assigned to simple textures or materials. The CompositeSurface is some kind of complex surface feature, elements of which are simple surface entities and must be topologically connected along their boundaries. A solid object such as a unit is bounded by surfaces and a CompositeSolid is topologically formed from multiple solids connected by their shared parts. For example, a building geometry (compositesolid) can be composed of the individual unit geometry and the shared areas geometry, and their shared parts are common walls. For 3D house property management purpose, the topology focuses on 3D topological description among spatial objects such as location of 3D constructions (e.g. above or below the ground) and in the interior space of rights established for 3D buildings (e.g. adjacent units shared one common wall), while it demands the relationship in semantic levels and non-overlapping unit objects can be defined clearly. In addition, for representing multi-independent solid objects, the model also allows the aggregation.

(2) **Spatial relationship semantics**: provides the most detailed description of house property features, including the integrated management of the relationships between house property objects such as district, land-block, building, facility, functional area, storey and unit. The land-block and the district correspond to the 2.5D horizontal level for insight and analysis of properties; the building or other facilities are related to a vertical level that will contribute to the identification of a one-person-owned-property object from aboveground to underground, while the third hierarchy is composed of storey, functional area and unit, which correspond to the 3D interior level for property partition. The spatial relationships among house property objects are also illustrated in figure 3: land-blocks are often managed in a district area, and buildings or other facilities are often located at a land-block, so the relationships between the land-block and the district, as well as the building and the land-block, are defined as 'located at'. In a similar way, for a building complex, the semantic relationships between the storey and the building, as well as the unit and the storey, are described as 'composed of', because interior geometric structures need to be well represented to partition the property space clearly.

(3) **Property right semantics**: to keep the consistency between the ownership of property and the content thereof, the individually owned content of a house property is termed 'real-property-unit', which corresponds to the main object of building-storey-unit hierarchy. As shown in figure 3, 'real-property-unit' is set to identify the 3D property space through establishing a one-to-one relationship with building, storey or unit in accordance with different semantic levels from one-person-owned building and a storey or a functional area used as one real property, to self-owned apartments units. This also provides the basic property relationship 'owned by' between the 'real-property-unit' and its owner.

(4) **Event-driven dynamic semantics**: there are two kinds of events, i.e. the geometry events and property right events (figure 3), which all together provide the explicit dynamic changes representation when they are related to the SurveyDocument and the LegalDocument of the LADM (ISO/WD-19152 2008), respectively. Considering the before-mentioned 3D dynamic characteristics of house property objects, geometric events and property events are subdivided into hierarchical events (see details in Section 3.4), developed in view of the 3D spatial constraint and semantic descriptions of events, which focuses on the description of occurrences rather than states. Based on hierarchical events and versioned objects, the spatio-temporal information can be obtained from the model, in which dynamic events directly bring about the creation of new versions for an object and the correlation among them is automatically established by their own IDs. It is clearly known that the whole life cycle of an object can be regarded as the combination of versions and each of them gets two valid dates (start time and end time: temporal change scale). In addition, by keeping track of one house property object's chain of events which have caused its changes including geometric changes and related right changes, it is possible to reconstruct every state during its lifespan from creation to demolition.

3.2 *Semantic structure*

Compared with the traditional 2D representations (see details in Table 1), the semantics of 3D house property objects are described as the following 12 kinds of objects (ISO/WD-19152 2008):

(1) real-property-unit object, oriented to the registration of the house property object and corresponding to the main object of housing spatial features (such as building, storey, unit) at different property levels;
(2) district object, regional managed object;
(3) land-block object, managed in a district area and figuring out the detailed horizontal distribution of property information;
(4) building object, the whole 3D building when it can be registered as a one-person-owned property;
(5) storey object, using the 3D volume of interior storey to partition a building vertically for stratified properties, representing the whole interior property right extent between floors;
(6) unit object, usually means a apartment unit, which is the smallest real-property-unit of a 3D house property;
(7) functional area object, a virtual (abstract) object considering the different functional uses rather than the physical structures in building complexes. It consists of a number of storeys with the same functional use, such as commercial-use and residential-use areas existing in the high-rise building complex. In addition, if the functional area object is an individual owned body, it also can be considered as a storey object (named as 'virtual' storey);
(8) accessories-of-exclusive object, each unit's subsidiary facilities such as balcony and overhanging corridor;
(9) accessories-of-communal object, the communal service areas and equipment, such as elevator wells, staircases, passageways, basements and gatehouses, which are used and jointly owned by all/part of the owners in the building;
(10) other facility object, like municipal and urban transportation facilities, including underground garage, subway, water tower, etc.;
(11) owned (ownership) right object, focusing on the description of the house ownership in terms of civil legal relationship, which is a subclass of 'Right' in LADM;
(12) owner object, who owns the house properties including natural person or non-natural person like organizations and companies, which is related to 'Person' in LADM.

The diversity and complexity of 3D house property objects enable the house buildings to have complex semantics regarding the property rights information; it is thus possible for the register/owner to identify the specific property right objects themselves and their mutual relations. Based on comprehensive analysis of various characteristics of 3D house property objects, such as shape, size, position, internal 3D structure in building, privately owned units and jointly owned parts, some semantic relationships are extracted to unify and solve the spatial and property right problems. The semantic relationships are illustrated from two aspects: semantic description for spatial relationships among 3D objects (spatial semantics) and the description for property right relationships (thematic semantics).

◆ **Semantic descriptions for spatial relationships.** In the spatial level, there are logical relations among the 3D house property entities, such as the inclusion relationship and the correlation relationship. Compared to general topological relationships, spatial topological relationships for 3D house property management mainly comprise the following semantic descriptions:

Locate at. This is used to emphasize the hierarchical relationships between 3D house property objects. For example, a building as a whole is often located in a district (land-block) area, and the semantic relationship is defined as 'locate at'.

Aggregate. Separate property objects owned by the same owner become one semantic entity through aggregation. This aggregation ensures the integrality of a real-property-unit and provides correlative relationships among them. For example, several storeys aggregate to a functional area, or several units aggregate to a storey.

Composed of. This provides a spatial semantic rule between an object and its components, e.g. a building is composed of its interior storeys or a storey may consist of several units.

◆ **Semantic descriptions for property right relationships.** In order to find out and thereby confirm the complicated relationships and the multi-semantics between privately owned units and jointly owned parts in house buildings, some important semantic descriptions of property right relationships are defined as below:

Owned by. The main attribute represents a basic link relationship between the owned right and its owner. The full ownership rights of real-property-unit can be established by this semantic description.

Attached to. This is used for confirming the property right semantic relationship between the unit (house) and its subsidiary objects (such as balcony, overhanging corridor), which is a one-to-one relationship, e.g. balcony cannot be separated from the ownership of one unit.

Shared. To identify the integrality and validity of the 3D property space, an important step is to register the accessories-of-communal objects (such as elevator wells, staircases, passageways, basements and gatehouses) for a legal protection of them. The semantic rule between the accessories-of-communal object and the real-property-unit, used in effective house property management, is defined as 'shared'. Furthermore, according to the different application levels, the related semantics are subdivided into four levels (see the UML model in figure 4): (1) 'shared in' a building: from the roughest view describing the relationship between the accessories-of-communal object and the real-property-unit object, it mainly considers communal service areas and equipment that is used or shared in the whole spatial scope of the building, such as the passageway, the gatehouse and the elevator well in figure 1(c); (2) 'shared in' a functional area: it is the further 'high-level' semantic description to classify the accessories-of-communal objects, which correspond to and serve their own functional areas. In figure 1(b), an equipment room as one type of accessories-of-communal object provides service only for its functional area instead of the storey on top of it; (3) 'shared in' a storey: some public affiliated objects belong to a specific storey and its range of use is limited to that storey. Therefore, their rights are only shared by multiple different units inside that storey. As is shown in figure 1(a), the passageway can only be involved in connecting the units and thus be shared with them within the corresponding storey instead of other stories; (4) 'shared with' units: in this semantic rule, access to an accessories-of-communal object is merely confined to adjacent units in a more local space, for example, a common hall between two households is only shared by these two households.

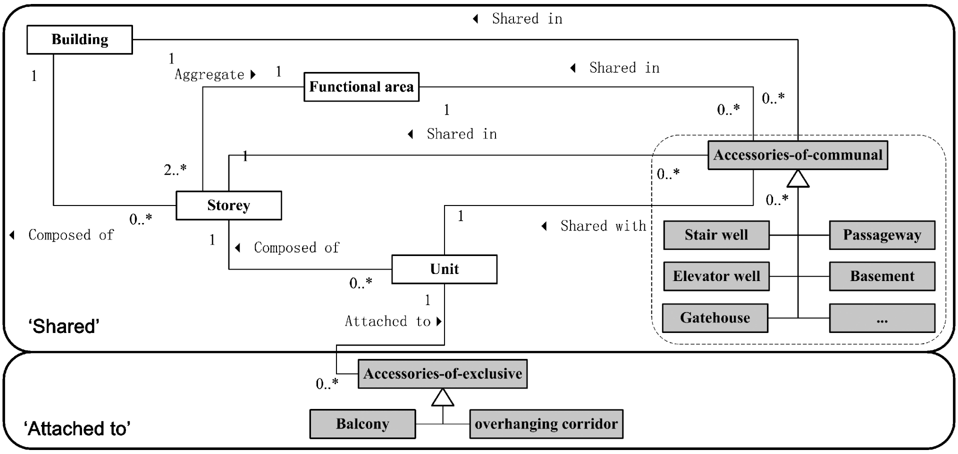

Figure 4. UML diagram of semantic relationships.

3.3 *Hierarchical LOD geometric framework*

Establishing a reasonable hierarchical geometric framework of 3D house property information is necessary for pinpointing physical boundaries, topological analysis and integrated management of property right objects. Hierarchical LOD, a new hierarchical structure, is proposed in order to avoid overlaps or gaps in property right space via providing geometrical and topological representation in three different hierarchies from 2.5D horizontal level to the vertical level and 3D interior level, and five LODs with their own distinct application scopes. Hierarchy 1 explicitly covers a complete 2.5D parcel partition without overlaps and gaps, while hierarchy 2 is flexible to partition 3D space in the vertical level such as aboveground and underground utilities or buildings, and hierarchy 3 represents topological relationships among 3D spatial objects within a building in semantic levels. The characteristics of each hierarchical structure and the advisable contents of LOD representations are illustrated in figure 5.

Hierarchy 1: this provides essentially a 2.5D terrain surface representation of parcels and is adopted to ensure reasonable partition of real property space on a horizontal level. The first hierarchy is composed of LOD 1 representations used for districts or land-blocks, commonly used to figure out the detailed horizontal distribution of property information within a specific region. Two typical representations are allowed to be contained in this hierarchy: each land-block belongs to exactly one district and each district belongs to exactly one city.

Hierarchy 2: this is a primary vertical description of the 3D house property space, such as a 3D partition of aboveground or underground buildings with different owners, 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 (LOD 2) is the residential building or other independent facilities, which is a one-person-owned-property object and is represented by the external appearance such as a 2.5D block model.

Hierarchy 3: in order to distinguish interior property situations in the building, 3D space within a building is semantically subdivided into non-overlapping storeys and units objects, which includes three levels of detail, i.e. LOD 3, LOD 4 and LOD 5. LOD 3 fixes the boundaries of property rights from the vertical structure inside

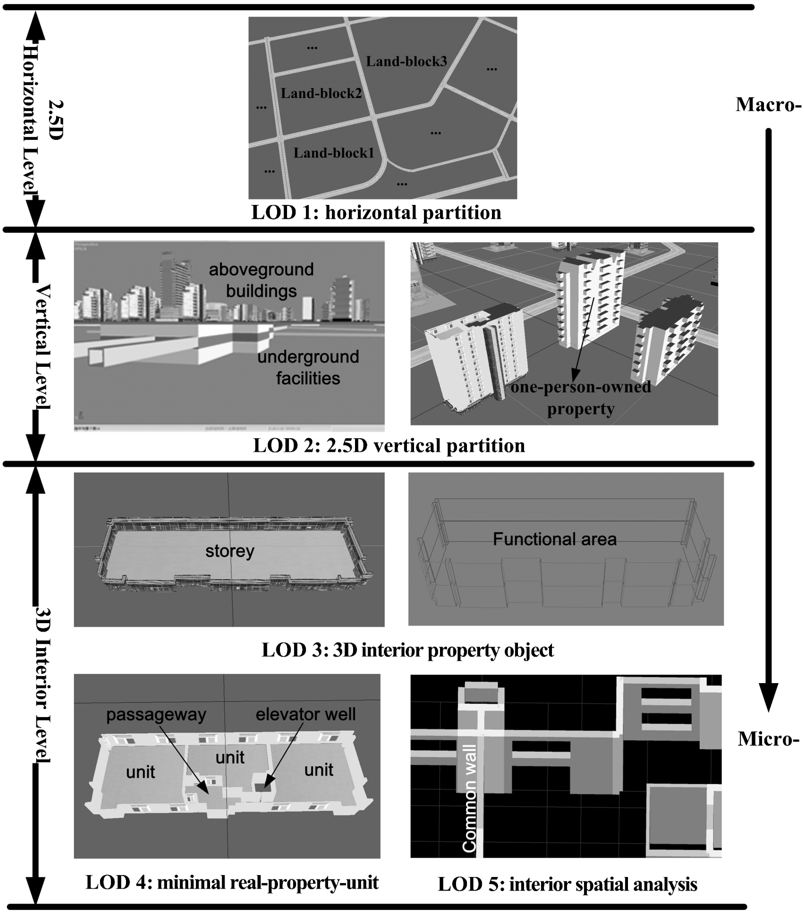

Figure 5. Description of hierarchical levels of detail.

buildings, and makes the storey (when used as one real property) the primary property unit within the residential building. LOD 4 depicts the minimal spatial partition of the real-property-unit in house property management, i.e. the individual unit. LOD 5 comprises detailed component objects of wall, roof and floor, explicitly expressing the spatial adjacency relationship between units and supporting the dynamic change operation.

3.4 *Hierarchical structure of events*

Based on the comprehensive consideration of the 3D spatial level, the semantic description of house property changes and the natural principle of human spatial cognition, the dynamic changes of house property information can also be abstracted into five hierarchies according to the events: land-block event, building event, storey event, unit event and property right event, all of which are related to geometric changes except the last event which is related to the property right. An event-driven dynamic description framework is proposed to model the spatio-temporal changes of 3D residential buildings and their property right features. The structure of hierarchical events is illustrated in figure 6.

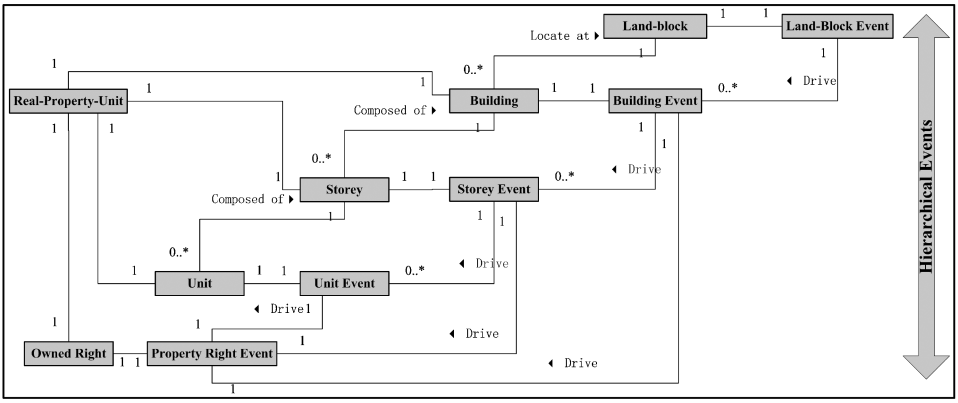

Figure 6. Relationships among hierarchical events.

(1) ***Land-block event***: beyond the traditional cadastral parcel alteration event (e.g. land subdivision, land amalgamation and boundary adjustment), the land-block event (such as district removal or reconstruction, residential area planning and old-town renewal) reflects a more comprehensive/complicated alteration to emphasize the influences on its attached buildings, as well as to stimulate the events in the aspect of semantic level.

(2) ***Building event***: defined as a change event of the whole building. The events stimulate the construction of a building (newly-built) and expansion of the original building height/area;

(3) ***Storey event***: a building consists of several stories in the vertical space. The operation unit of the storey change event is the storey; the change process in space and property rights of the same storey is synchronization. In addition to the individual storey, a functional area including a number of storeys that have the same property right is also considered as a virtual storey. The change events of the storey include storey demolition due to its height limitation, story subdivision, extension or reconstruction and so on;

(4) ***Unit event***: the unit event can be understood as the further subdivision of the storey event. The direct operation object of the unit event, which is the minimal spatial partition of the real-property-unit in the house property management, is a special unit with individual and complete property rights, including unit expansion, structure change of room and so on;

(5) ***Property right event***: the property attribute events concern the ownership right changes of the real-property-unit (e.g. alternation: the property right has been changed, new: newly added ownership).

To build the linkage and the trigger relationship among the events, several general constraint rules of hierarchical events are introduced:

Constraint rules of the land-block event: it is mainly used to represent the whole evolution processes of geographic spatio-temporal phenomenon occurring between a given land-block (or district) and its house buildings. In the spatial level, the land-block event, which is treated as a composite event consisting of two or more atomic events, can often downwards restrict the spatial distribution of buildings (located on this land-block) and drive the changes of house property information, including geometry and property right changes.

Constraint rules of the building event: it covers the representation of geometric changes to a building. According to the different property ownerships of the building, the building event may be interpreted as an atomic event or a composite event. If the building is a single property right body (i.e. one person owns the entire building), the building event will be an atomic event that will restrict the changes of its interior stories or units downwards and relate to the land-block event upwards in the spatial level. In addition, as an atomic event, it drives the changes of correlative property right events directly. Otherwise, the building is a multi-property rights body, and then the building event is treated as a composite event, driving its interior change events of storeys or units.

Constraint rules of the storey event: it covers the representation of geometric changes of a storey or a functional area inside a building. It is similar to the constraint rules of the building event: when a storey or functional area is a single property right body, the storey event is treated as an atomic event, which can drive the changes of correlative property right events directly, restrict the changes of its interior units downwards and relate the building event upwards in the spatial level. Otherwise, the storey event is considered as a composite event, which can further drive change events of its interior units.

Constraint rules of the unit event: the unit event, which relates to the storey or building events upwards in the spatial level, is considered as an atomic event, because the operating object (individual unit) refers to the minimal spatial partition of a real-property-unit; therefore, it can directly drive the changes of correlative property right events.

Constraint rules of the property right event: the property right change, which is restricted by the real-property-unit rather than the spatial level, establishes a one-to-one relationship with a changing object. Most of the property right events are driven directly by spatial events (i.e. land-block event, building event, storey event, unit event) when they are identified as atomic events separately.

4. Implementation issues

The implementation issues of 3DHP are analyzed based on the 3D GIS software VGEGIS6.0 developed by Wuhan University, Wuhan, China. The development and implementation environments are:

Intel(R) Pentium(R)4, CPU 2.00 GHz 1.99 GHz, 512 MB RAM
Operation System: MS Windows XP; Software: VGEGIS6.0
Programming Tool: Visual C++6.0; Graphical Interfaces: OpenGL
Database Management: Oracle 11g

The management of real 3D house property and related dynamic changes are introduced and followed by a discussion of the database representation.

4.1 *Database representation*

As the database representation of 3DHP, there are 16 feature tables created to represent the hierarchical structures for integrated management of 3D house property registration and for events-driven dynamic changes. The relationships within the table are illustrated in figure 7.

◆ Geometry hierarchy tables include the district table, the land-block table, the building table, the facility table, the storey table and the unit table, which are built

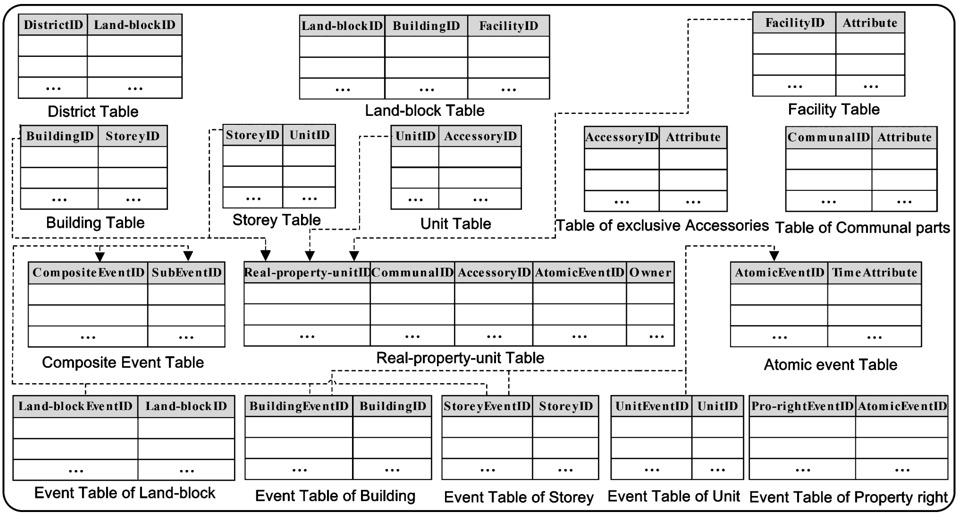

Figure 7. Database representation of 3DHP.

for the hierarchical geometric framework to the practical 3D house property registration. These tables are linked to basic geometric attribute tables for points, curve, surfaces and solids via object ID. Because current Oracle 'SDO_Geometry' can only represent simple 3D geometry (Kothuri *et al.* 2007), then the complicated 3D geometry like curve and extended point object is usually stored as a customized BLOB object. Especially, the elaborate object ID and the possible same footprints can guarantee the consistency between the same objects in different LODs.

◆ Property right semantic tables are made up of the real-property-unit table, the table of exclusive accessories and the table of communal parts. Property right semantic tables are used to identify the integrality of 3D property right space and to establish the immediate relationships between the individually owned units and jointly owned parts.

◆ Event tables include the composite event table, the atomic event table and the event table of land-block, building, storey, unit and property right, which are related to the geometry hierarchy tables and used to set up the dynamic changes process.

4.2 *3D house property space partition*

To evaluate the proposed conceptual model for 3D house property registration and to show the potential of the integrated representation of multiple sources from 3D geometry, semantics, hierarchical levels of detail and property characteristics, the conceptual model is translated into prototype implementations. The 3D information is directly available in the house property registration system, with the ability to improve the consistency between the property right and its scope of physical space.

In this section, a case study from practice will be used to illustrate 3D house property partition. The study area is Wuhan City, China; the sample data are a main district, including 3D land-blocks, 3D buildings, 3D storeys and 3D units. In the experimental region, house property objects are subdivided into four types: residential buildings (multi-storey apartments), office buildings, underground facilities and commercial-residential buildings (multifunctional buildings). The basic description of 3D house property objects and some related characteristics for registration can be seen in Table 2.

Table 2. Description of test data.

Types of house property objects	***Numbers***	***LOD***	***3D Geometric unit***	***Core Associations***
Residential buildings	67	Level 4	Unit	Owned by
Office buildings	23	Level 3	Storey	Shared in a storey
Underground facilities	4	Level 2	Building	Located at
Commercial-residential buildings	14	Level 3,4	Storey, Unit	Aggregate, Shared

From two different visual perspectives, figure 8 shows a typical review of integrated representation of 3D hierarchical house property objects, which includes multi-level representations: (1) 2.5D horizontal level: the level of the district and the land-block, which contains the practical non-overlapping property right distribution (land-block 1, land-block 2, land-block 3, land-block 4) in the horizontal level; (2) vertical level: the integrated expression and registration of underground facilities (facility 1) and aboveground buildings (buildings 16, 17 and 19) in the vertical level, of which the semantic description of 'located at' is supported to attach the spatial position relationships between buildings/facilities and land-blocks, and the coarsest property requirement to partition 3D solid space is satisfied. Furthermore, according to the real-property-unit interpretation (e.g. building as a real-property-unit, storey as a real-property-unit), the building marked 16 with a single property right is represented by the external appearance of 3D building volume (using LOD 2); (3) 3D interior level: the multi-property building (the building marked 19, see details in figure 9) is subdivided into storeys (using LOD 3) and units (using LOD 4) to distinguish interior property situations with the aid of geometric and semantic information.

In order to make clear the interior property situation of commercial-residential buildings (building 19 in figure 8 and 9) in 3D geometry space, more refined representations using storeys or units as a real-property-units are provided (figure 9 and 10): (1) to distinguish the property situation of the first floor, which is a supermarket with a single property right, the storey is used as the basic element of the 3D geometry representation and has the characteristic of an individual property right in a property layer (if the functional area includes many storeys, it will be related to the semantic rule of 'aggregate' and form an integrated real-property-unit.) The related property semantic rules are: 'shared in a building' and 'shared in a

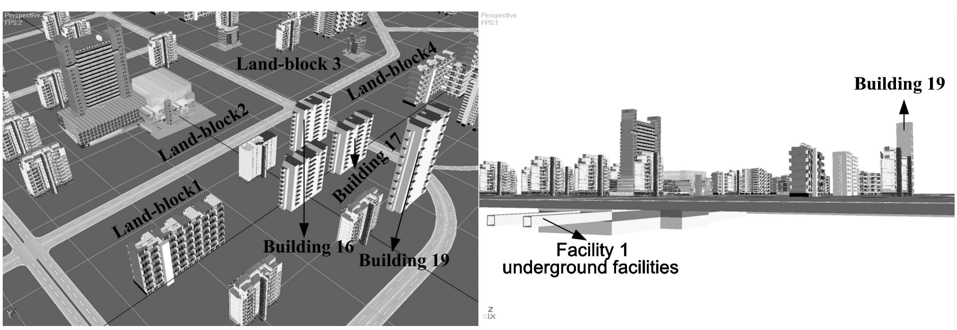

Figure 8. A case of typical 3D hierarchical objects.

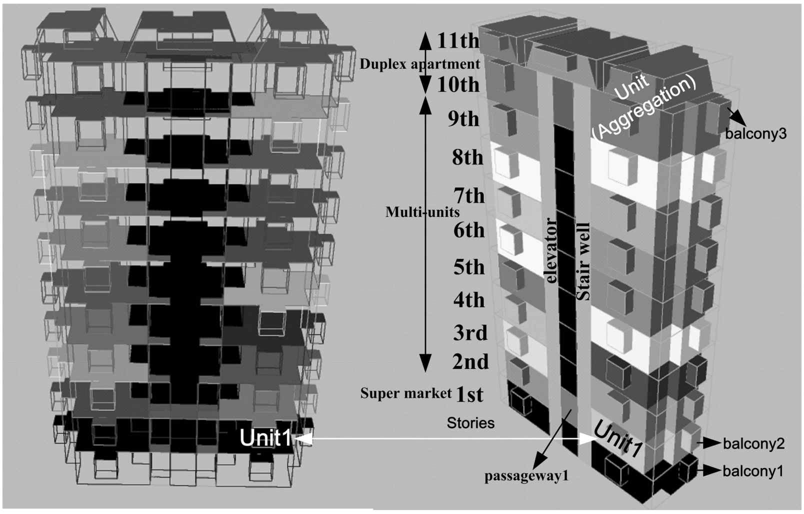

Figure 9. 3D property right partition in the building 19.

storey'. Based on the semantic rule for spatial relationships, the spatial link between the storey and the building is represented by 'composed of'; (2) the second storey and above belong to the residential space with multi-property rights, of which the tenth storey and the eleventh storey (the top storey) form three duplex apartments, and each storey (except the top storey) contains three units and three communal objects (i.e. passageway, stair well and elevator, figure 10). The spatial relationships between the unit and storey, as well as the storey and the building, are defined by the semantic description of 'composed of'. According to the semantic rule 'aggregate', six units inside the tenth storey and the eleventh storey are combined into three real-property-units. The spatial adjacency relationship between two units in the same storey is built by the important geometric feature 'common wall'; (3) by analyzing the relationship between house property objects and their affiliated shared objects, each passageway is only shared by three units in the same storey, the elevator well and the staircase are shared in the whole building, so the correlative semantic relationship contains: 'shared in a storey', 'shared in a building' and 'attached to'.

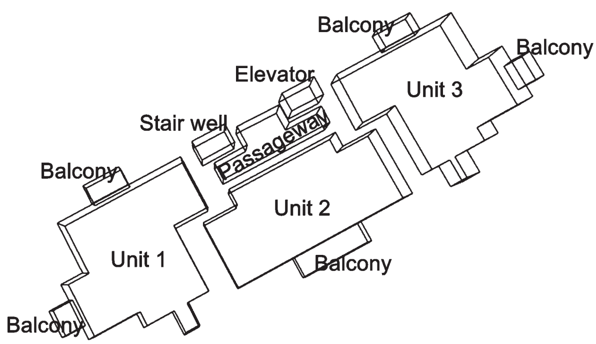

Figure 10. Allocation of property right object within a standard storey.

4.3 *Dynamic representation*

As illustrated in figure 11, the implementation of the hierarchical events-driven dynamic representation consists of three important steps. First, when a change type is detected, it triggers a precise identification of the events types and it is distinguished as the property attribute event or the geometric change event. Second, according to the semantic rules of house property events as well as the constraints in spatial levels, the atomic events of geometric change events are extracted separately to identify actual change objects. Finally, the whole spatio-temporal causality chains are established based on the hierarchical events-driven.

To investigate the effectiveness of the hierarchical events-driven dynamic representation, three groups of hierarchical events were implemented:

(1) District reconstruction: the screenshots (see upper of figure 12) show the geometry changes of the buildings 16 and 17 in a special district (land-block 1), which reflect that the spatial change of land-block have an impact on its attached buildings. In this district, the building 16, which is an individually-owned body, needs to be partially removed due to the height restriction; two storeys need to be added as an extension to the building 17, which is a multi-property body. Therefore, the hierarchical events as shown in the lower of figure 12 are illustrated by the following: district reconstruction is described as a land-block event under the semantic constraints in spatial levels, driving the change event of the building 16 (building event 1) and the change event of the building 17 (building event 2).

(2) Partial demolition of an individually-owned building: based on the semantic constraints of the building event, the partial demolition event of the individually-owned building 16 (as shown in figure 13) is interpreted as an atomic event, and further drives the occurrence of property right events (property right event 1).

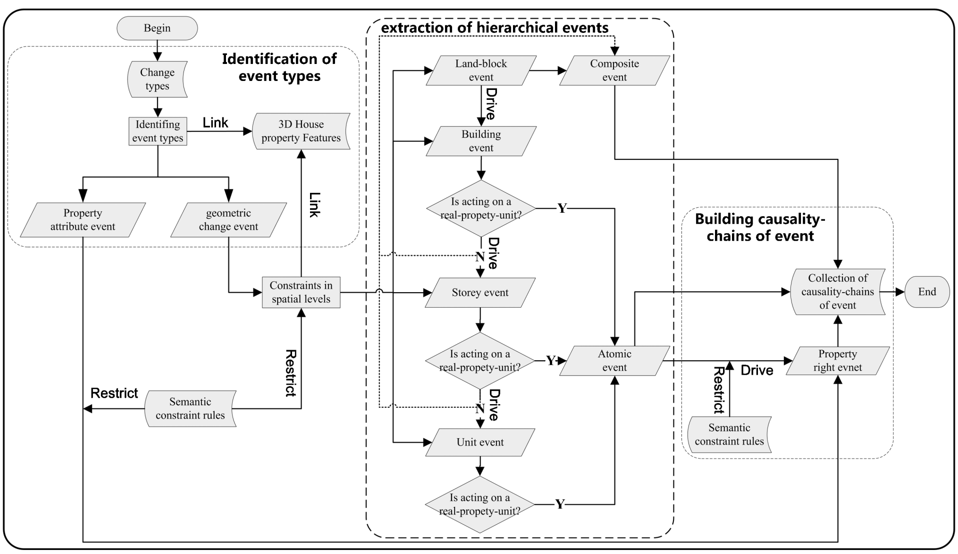

Figure 11. Dynamic representation based on hierarchical events.

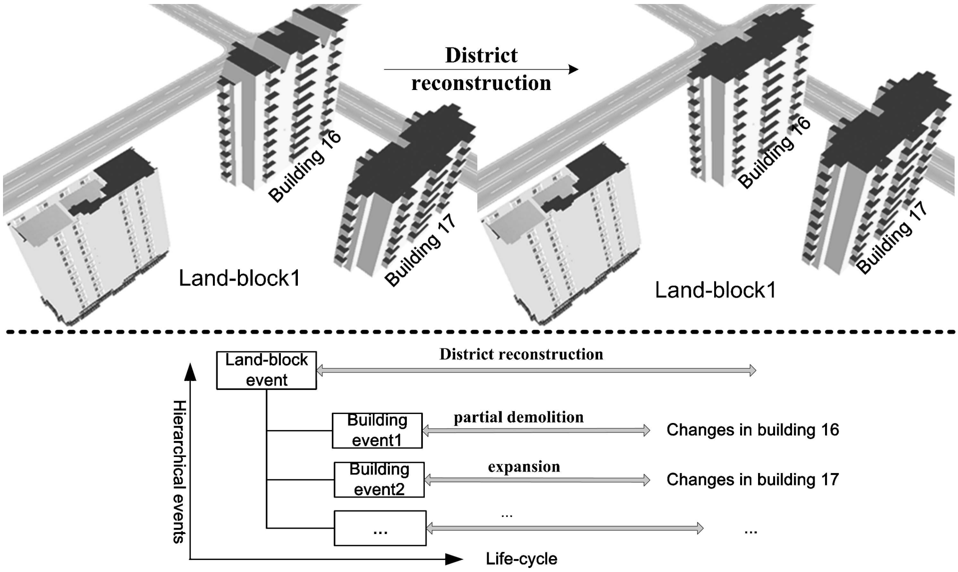

Figure 12. A case of district reconstruction and related hierarchical events.

(3) Expansion of a co-owned building: different from the event of building 16, the expansion of co-owned building 17, regarded as a composite event (building event 2), needs to be further divided into two storey events (i.e. storey event 1 and storey event 2). However, according to the real-property-unit interpretation (e.g. building as a real-property-unit, storey as a real-property-unit), each storey is also a multi-property body and its event is composite. Therefore, each storey event can be also divided into two unit events. Finally, the unit event (which is unit event 1, unit event 2, unit event 3 and unit event 4, respectively) 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 linkages above are shown in figure 14.

In addition, the database representation for the above dynamic representation (from district reconstruction to partial demolition of an individually-owned building and expansion of a co-owned building) can be obtained from the following tables: the composite event table, the atomic event table, the event table of land-block, the event table of building, the event table of storey, the event table of unit and the event table of property right, as shown in figure 15.

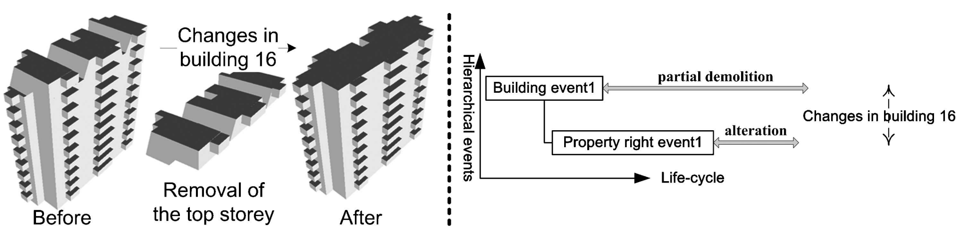

Figure 13. Partial demolition of individually-owned building and related hierarchical events.

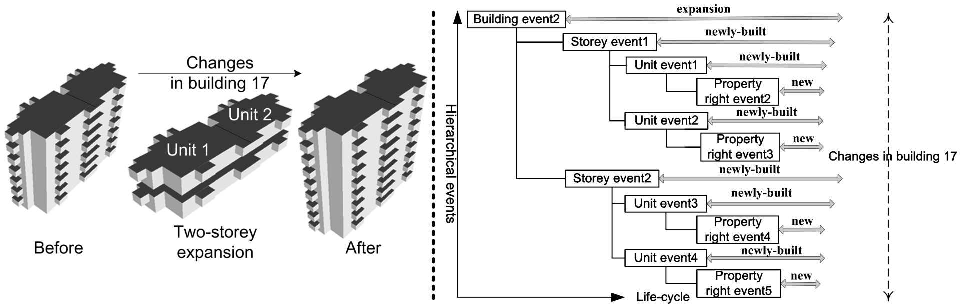

Figure 14. Expansion of co-owned building and related hierarchical events.

5. Conclusions

In this paper, a semantics-based 3D house property model is proposed to integrate the 3D geometry, topology and event-driven dynamics, which has the accurate 3D geometric representation of house property objects with hierarchical building-storey-unit structures, explicit link relationships between house property objects and related property rights, as well as dynamic change representation of 3D house property at multiple spatio-temporal scales.

(1) **Representing an integrated 3D hierarchical LOD framework of property right objects and their topological relationships.** This model provides multiple topological and cartographic representations via three abstraction (thematic) levels, i.e. 2.5D horizontal level, vertical level and 3D interior level. The real 3D representation of house property unit ensures the logical consistency and flexibility of house property registration. The accurate 3D spatial boundary and position enable the explicit and precise definition of property right space, outperforming the traditional 2D floor/unit plan. Moreover, the availability of a hierarchical LOD framework will also facilitate dynamic representation for house or even interior property right changes.

(2) **Supporting uniform semantic descriptions of 3D spatial entities and related property rights allocation.** This model has established a multi-level expression

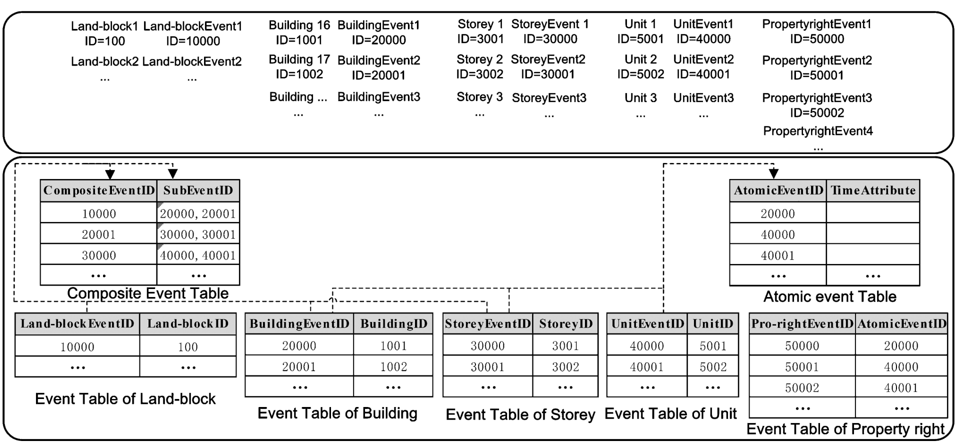

Figure 15. Data table of hierarchical events.

of 3D house property objects with accurate spatial semantic information and clear spatial relationships among different property entities. In addition, all the semantic information of property rights has established a specific connection among property entities, their affiliations and the communal parts for house property registration.

(3) **Providing hierarchical events-driven dynamic representation of house property changes in 3D space.** The integrated connection of hierarchical events from whole changes to partial changes to 3D house property is established. Both the geometry events and right events make it more flexible to identify the actual dynamics of 3D house property at different spatio-temporal change scales. In addition, by the extraction of semantic rules and the trigger for the linkage between the events, the causality representation of events for keeping track of the whole spatio-temporal process can be built efficiently.

The further research of this model will be focused on the integration with the building information model (BIM), for facilities management (FM) during their lifecycle in the built environment and emergency response services. Of course, the fast development of automatic 3D modeling of both exterior and interior geometry of building by making full use of advanced 3D measurement (imaging, LIDAR, GIS, CAD, etc) and the performance improvement of 3D spatial dada management and manipulation based on commercial DBMS such as Oracle Spatial 11g would accelerate the applications of 3D house property management.

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