Logical Design and Implementation of the Data Model for 3D Cadastre in China

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SUMMARY

The establishment of 3D cadastre is imperative and needs support from legal, organizational and technological aspects.

In Shenzhen, China, establishment of 3D cadastre has achievedgreat progress. The joint register mechanism was employedfirstly in Shenzhen, and related research is going on, including definitions, visualization and topological analysis of the property objects(e.g. 2D property objects, 3D property objects), and they are all based on the cadastre-oriented 3D spatial data model which is already proposed. In this data model, both 2D property objects and 3D property objects can be represented.

In this paper, more analysisabout this data model is given, including retrospection of the history of designing the corresponding conceptual model, detailed analysis of the corresponding logical model, explanations about how to design tables based on the relational database, analysis about the normal form(NF), etc.

Finally, taking several 3D parcels in Shenzhen, China as an example, detailed contents of tables stored in Oracle are shown, and comparison between two storage modes(i.e. the implicit mode, the explicit mode) of body information is given.

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1. INTRODUCTION

The establishment of 3D cadastre is imperative. Since the international symposium of 3D cadastre organized in Delft, Netherlands in 2001, issues about 3D cadastre are widely discussed all over the world; in 2002, the united work group for 3D cadastre is built by FIG Commission 3 and Commission 7 who focuses on legal, organizational and technological aspects about 3D cadastre(Stoter and van Oosterom2006). Later, discussions about 3D cadastre are going on at the conferences held in Paris(2003), Athens(2004), Cairo(2005), Munich(2006), Hongkong(2007), Stochholm(2008), Sydney(2010).

"Property Law of the People's Republic of China"becomes effective in 2007. Article 136 in the law says that "The right to use land for construction may be established separately on the surface of, or above, or under the land. The newly-established right to use land for construction shall not damage the usufractuary right that has been already established." It can be seen that, this law provides legal support for establishment of 3D cadastre in China.

The research object in this paper is design of cadastre-oriented 3D spatial data model which has been already proposed (hereinafter referred to as the data model)(Guo, et al. 2011). And core work is laid onanalysis of design ofthe corresponding logical model. This paper is organized as follows: In Section 2, merits and demerits of current approaches in solid modelling and 3D spatial data models when applied into 3D cadastre are analyzed, then definitions and validities of 2D polygons, 3D solids, topological relationships between 3D solids involved in design of 3D spatial data model are elaborated; In Section 3, retrospection of the history of design of the corresponding conceptual model is given,and based on this the design of the corresponding logical model is elaborated, including design of tables based on the relational database, analysis of the normal form(NF), and two specificstorage modes of body information are stated(i.e. the implicit mode, the explicit mode); In Section 4, taking the real space objects of several typical buildings in Shenzhen (China) as an example, the more detailed hierarchical constructing process of body information is shown, and two storage modes of body information are also compared.

2. ANALYSIS OF 3D SPATIAL DATA MODELDESIGNS

2.1 Current 3D Spatial Data Models

The schemes for solid modelling include CSG(Construction Solid Geometry) and B-rep(Boundary Representation). In CSG, constructionof 3D solids is relatively simple, but relationships between solids could hardly be stored, and spatial analysis is also hardly supported in CSG. In contrast, in B-rep, construction of 3D solids could be rather complicated, but representations of topological relationships and spatial analysis are supported very well.

Compared with schemas of solid modelling, 3D spatial data models aremuch more detailed.Up to now, there are many 3D spatial data models including 3D FDS(3D Formal Data Structure), TEN(Tetrahedron), SSM(Simplified Spatial Model), UDM(Urban Data Model), OO3D(Object-oriented 3D Model)(Zlatanova et al. 2004; Zlatanova et al. 2002). These data models focus on different geometrical and topological primitives. TEN which is based on a simplicial complex is a typical CSG approach. 3D FDS is a formal description based on the 3D vector map, and the combination of geometries and thematic elements is proposed firstly in 3D FDS.However, strict definitions of topological relationships between 3D spatial objects desired in 3D cadastre are lacking in 3D FDS. SSM is a simplified model of 3D FDS, and the geometric primitive Arc is omitted(although an Arc can be represented by two consecutive nodes), and faces have to be convex. Such a simplified data model has an advantage in the visual inquiry speed in web-oriented applications, but the restriction that every face must be convex is not suitable for immediate representation of cadastral data(although a concave polygon could be decomposed into several convex polygons). UDM is a special version of SSM, and faces are limited to triangles. In OO3D, every volume is composed of triangles in essence(i.e. every volume is composed of faces, and every face is composed oftriangles), so it seems not to besuitable for immediate representation of cadastral data as well. So, a cadatre-oriented 3D spatial model is desired.

However, every spatial data model mentioned above follows the basic principle that a 3D solid is constructed hierarchicallyby primitives(i.e. points, arcs, faces and bodies), and the combined method(i.e. explanations of primitives with constraints of topological relationships) is employed to describe the data model.

2.2 Definitionsof 3D Solids

In 3D spatial data models, definitions and validities of 3D primitives and lower-dimensional primitives are important, as shown below.

2.2.1 Definitions of 2D Polygons

(1) Simple Polygons, Relatively Simple Polygons in CGAL(CGAL 2012)

In CGAL(Computational Geometry Algorithm Library), a polygon is simple if edges don't intersect, except consecutive edges which intersect in their common vertex, i.e. a polygon whose curves are pairwise disjoint in their interior. In other words, a polygonin which each vertex's degree equals two is defined as a simple polygon. Such a polygon has a well-defined interior and exterior, and it is topologically equivalent to a disk.

In CGAL, a relatively simple polygon allows vertices with a degree bigger than two, but all of their edges must be disjoint in their interior. Furthermore, a relatively simple polygon must be an orientable polygon. Namely, a traversal of curves would not lead to a crossing over a previously traversed curve.

(2) Polygons in ISO 19107, GML 3 (GML3 2007), and CityGML(CityGML 2012)

In ISO 19107 'Spatial Schema' (ISO 2003), a polygon is defined as follows: a GM_Polygon is a surface patch that is defined by a set of boundary curves(mostly similar toGML_CurveSegments) and an underlying surface to which these curves adhere. The defaultis that the curves are coplanar and the polygon uses planar interpolation in its interior. It is clear that there is just one outer boundary and there can be zero or more inner boundaries. Also the ISO standard is very explicit about the orientation of the outer and inner boundaries: counter-clockwise for the outer boundary and clockwise for the inner boundaries(when looking down).

The ISO definition of a polygon is at the abstract level, and it is implemented by the OpenGIS Simple Feature Specification(SFS) for SQL. In GML, a polygon is a planar surface defined by one exterior boundary and zero or more interior boundaries. Each Interior boundary defines a hole in the polygon, and the exterior of a polygon with one or more holes is not connected.

In CityGML, the definition of polygons in GML3(i.e. gml:Polygon) is just used.

(3) Polygon in Oracle(Kazar et al. 2008)
A polygon in Oracle strictly adheres to the definition in GML3(nothing new added).

(4) A Sort of User-defined Valid Polygon(van Oosterom et al. 2004)
A Particular definition of a valid polygon with holes is as follows: a polygon is defined by straight-line segments, all organized in rings, representing at least one outer ring(oriented counter-clockwise) and zero or more inner boundaries(oriented clockwise). It should be noticed that rings are not allowed to cross, but it is allowed that rings touch, or even partially overlap themselves or each other in some cases where the toleranceplays an important role.

2.2.2 Definitions of 3D Solids

(1) Polyhedron in CGAL(CGAL, 2012)
It is known that, if the neighborhood of any point in the topological space X is homeomorphic to a disc or a half disc, the topological space X is called 2-manifold. And the Winged-edge data structure and the Half-edge data structure are only suitable for representation of orientable 2-manifold while the Quad-edge data structure is suitable for representation of both orientable 2-manifold and non-orientable 2-manifold. In CGAL, the surface of the polyhedronis 2-manifold, and it is organized by Half-edge data structure(also regarded as DCEL, Doubly-Connected Edge List).

(2) 3D Solids in ISO 19107, GML3, and CityGML
According to ISO 19107 ‘Spatial Schema’, spatial characteristics are described by one or more spatial attributes whose values are given by a geometric object(GM_Object) or a topological object(TP_Object). The corresponding 3D objects are GM_Solid and TP_Solid.

GM_Solid is a subclass of GM_Primitive, and it is the basis for 3-dimensional geometry. The extent of GM_Solid is defined by the boundary surfaces, i.e. the boundary defines a sequence set of GM_Surface that limits the extent of this GM_Solid. These surfaces shall be organized into one set of surfaces for each boundary component of the GM_Solid. Each of these shells shall be a cycle(closed composite surface without boundary). The ‘top’ of each GM_Surface as defined by its orientation shall face away from the interior of the solid.

In GML3, gml:Solid implements GM_Solid in ISO 19107. The extent of a solid is defined by the boundary surfaces as specified in ISO 19107, i.e. gml:exterior specifies the outer boundary, gml:interior specifies the inner boundary of the solid. Meanwhile, there are other 3D objects taken into consideration in the OGC specification, e.g. cone, sphere. And some 3D objects are not regarded as volumetric solids, but they still appear in 3D space, e.g. free-form curves and free-form surfaces.

In CityGML, gml:Solid is just used(nothing new added).

(3) 3D Solids in Oracle(Kazar et al. 2008; Arens et al. 2005)
Oracle's data model for storing 3D geometries follows OGC/ISO GML3 specifications.

Oracle supports two variants of solids, i.e. simple solids and composite solids. In Oracle, a composite solid is a combination of N simple solids, so analysis will be concentrated on validation of simple solids. In Oracle, a simple solid is defined as a 'Single Volume' bounded on the exterior by one exterior surface and on the interior by zero or more interior composite surfaces. So, through-holes are allowed in simple solids in Oracle.

Particularly, a simple solid must obey the following rules:
1)Closedness test: the boundary has to be closed;
2)Connectedness test: the volume has to be connected;
3)No-inner-ring in polygons: each polygon of the composite surfaces has only an outer ring but no inner rings.(This is a restriction comparable to the GML definition, but without losing any expression power).

(4) Valid 3D Parcels(Karki et al. 2010; Thompson et al. 2011)
(Karki et al. 2010) discussed the validity of 3D parcels, including the internal validity of 3D parcels, spatial relationships between 3D parcels and surface or based parcel, as well as relationships to other 3D parcels, etc.

Later, instead of formulating valid 3D parcels in natural language, (Thompson et al. 2011) further formalize them by using mathematical formalisms including core axioms, parsimony axioms and redundant axioms.

2.2.3 <u>Topological Relationships between 3D Solids</u>
Topology is defined as incidence or connectivity between various geometric primitives, i.e. topology deals with characteristics of geometric figures that remain invariant when space is deformed elastically and continuously.

(1) Topological Relationships in ISO 19197 'Spatial Schema'(ISO 2003)
In ISO 19107 'Spatial Schema', aggregate package, complex package(including composites) are used to represent topological relationships between geometries. And it is greatly referenced in GML3 and CityGML, so detailed explanations will be in GML3 and CityGML shown below.

(2) Topological Relationships in GML3(GML3 2007)
Geometric aggregates are arbitrary aggregations of geometry elements. They are not assumed to have any additional internal structure. Geometric complexes are closed collections of geometric primitives, i.e. they will contain their boundaries. A geometric composite represents a geometric complex with an underlying core geometry that is isomorphic to a primitive, i.e., it can be viewed as a primitive and as a complex. In 3D, a gml:CompositeSolid is represented by a set of orientable surfaces. It is a geometry type with all the geometric properties of a (primitive) solid. Essentially, a composite solid is a collection of solids that join in pairs on common boundary surfaces and which, when considered as a whole, form a single solid.

(3) Topological Relationships in CityGML(CityGML 2012)
Spatial properties of CityGML features are represented by objects of GML3's geometry model. This model is based on the standard ISO 191907'Spatial Schema'. CityGML actually uses only a subset of the GML3 geometry package, defining a profile of GML3.

Combined geometries can be aggregates, complexes or composites of primitives. For an aggregate, the spatial relationship between components is not restricted. They may be disjoint, overlapping, touching, or disconnected. GML3 provides a special aggregate for each dimension, a Multi-point, a Multi-curve, a Multi-surface, and a Multi-solid. In contrast to aggregates, a complex is topologically structured: its parts must be disjoint, must not overlap and are allowed to touch, at most, at their boundaries or share parts of their boundaries. A composite is a special complex provided by GML3. It can only contain elements of the same dimension. Its elements must be disjoint as well, but they must be topologically connected along their boundaries. In 3D, composite solids must be topologically connected by common boundary surfaces.

3. DESIGN OFTHE CADASTRE-ORIENTED 3D SPATIALDATAMODEL

3.1 Design of the Conceptual Model

Retrospection of the history of designing the conceptual model for the cadastre-oriented 3D spatial data model is given. At first, the 3D conceptual model integrating land properties and house properties was proposed, i.e. "a joint register mechanism" (Lin and Guo 2006).Later, a more accurate definition of the property object as the target of cadastral management is given: a property object is an object integrating boththe physical object and corresponding property right information, and it is closed by right boundary curves or right boundary surfaces, and it has a definite geographical location and shape. It could be a 2D property object or a 3D property object(Zhang et al. 2010).In addition, there exist two types of 3D property objects, i.e. right spaceobjects and physical spaceobjects. Right spaceobjectsare more focused on in the title registration(e.g. title registration of transferring of the right to use land for construction in China, more details see"Property Law of People's Republic of China").Later, (Guo et al. 2010; Guo et al. 2011)give more detailed explanations about this data model from the perspective of technologypresented in figure 1, i.e. the compatibility between PSLG (Planar Straight-line Graph) and PLC(Piecewise Linear Complex) in B-rep is greatly referenced in this data model. Representation of both 2D property objects and 3D property objects is supported in this data model which is one of the effective approaches for 3D title registration (i.e. full 3D cadastre mode, the hybrid mode, the tagged mode)(Stoter et al. 2002).Meanwhile, (Ying et al. 2011) give detailed explanations about how to obtain body information in this data model(i.e. construction of the smallest bodies based on discrete faces). Analysis of topological relationships supported by this data model is given as well. Especially topological primitives in this data model and topological primitives in Google Sketchup are compared. Later, this data model has beenapplied in cases of Shenzhen, China(Guo, Ying, et al. 2011). However, systematic analysis of the corresponding logical model of this data model has not been given yet which is greatly desired for deeper understanding of this data model.

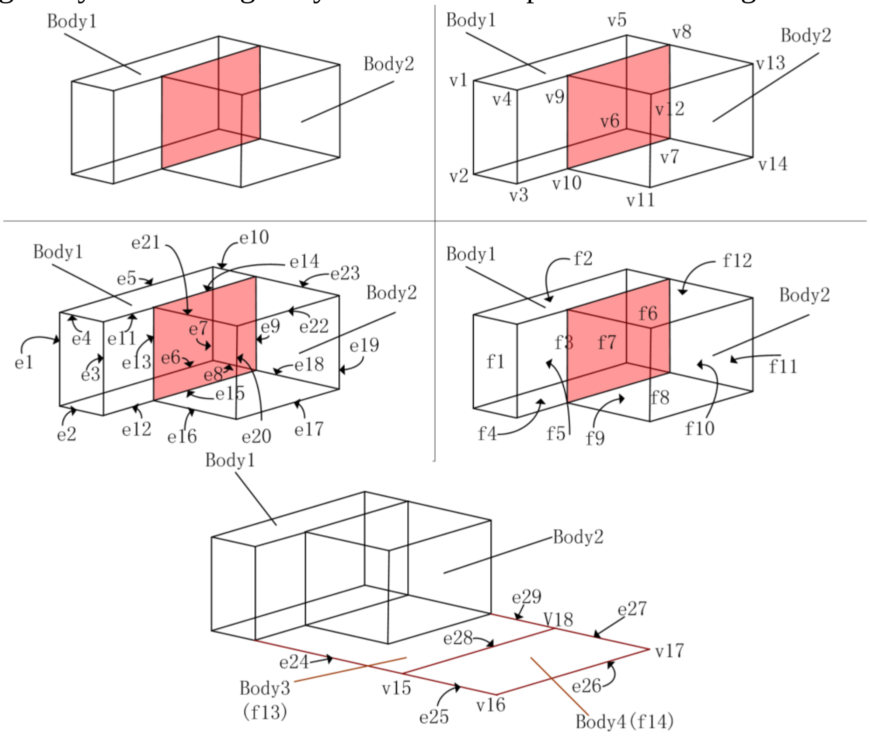


Figure 1. The Cadastre-oriented 3D Spatial Data Model (Guo Renzhong, Ying Shen,2010)

When the conceptual model is designed, the E-R diagram is often used to explain relationships between entities. Different from PSLG which is more flexible than a polygon and PLC which is more flexible than a polyhedron, entities involved in cadastre(e.g. 2D parcels, 3D parcels, boundary surface, boundary curve, boundary points) must obey the following specific rules:

(1) Constraints for the single parcel
In 2D parcel, isolated edges, dangling/hanging edges, and isolated points are not allowed. In contrast, they are permitted in PSLG.

In 3D parcels, isolated edges, dangling/hanging edges, and isolated points are not allowed as well.In contrast, however, in PLC, they are allowed, because eachfacet in PLC could be represented by PSLG(Si and Gartner2005).

(2) Constraints between the parcels

For topological relationships between 2D parcels, a lot of discussionswere given. Therefore they are omitted here.

Fortopological relationships between 3D parcels, 3D parcels must be disjoint, i.e. mutually exclusive, in the interior. Spatial relationships including disjoint, which meet through lower-dimensional primitives are allowed.

fortopological relationships between the 2D parcel and the3D parcel.Often some restrictions exist(Karki et al. 2010). Nowadays, 3D parcels(including 3D parcels above the ground, 3D parcels on the surface, 3D parcels underground) are often obtained by extrusion(i.e. push/pull)from surface 2D parcelsalong the vertical direction. In other words, 2D parcels are often regarded as the projectionof 3D parcels on the ground surface.

The detailed design of the 3D spatial data model is presented in figure 2. In the detailed design, there exist three layers, i.e. the geometric layer, the topological layer, the entity layer(rectangle closed by dashed blue lines) respectively. In the geometric layer, geometric primitives(i.e. Point, Arc, Polygon, Volume, TIN, TEN) are included, and these geometric primitives are the basic primitives for constructing 3D solids. In the topological layer, topological primitives(i.e. Node, Edge, Face, Body) are included, and these topological primitives composed of geometric primitives are immediate primitives for the construction of 3D solids. In the entity layer, cadastral entities(i.e. Boundary surfaces, Boundary curves, Boundary points) are included, and these entities formingproperty objects could alsobe regarded as topological primitives combined with semantic information.In the data model, detailed design of 2D property objects is a subset(rectangle formed by dashed green lines in figure 2), and detailed design of 3D property objects is also presented(rectangle formed by dashed red linesin figure 2).

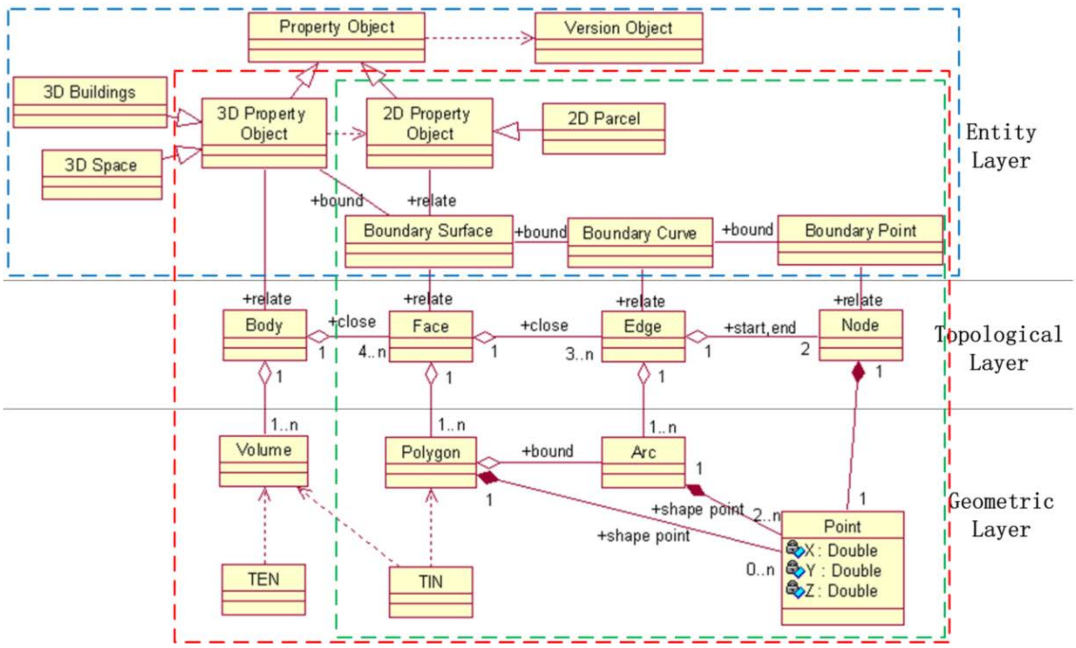


Figure 2.Detailed Design of the 3D Spatial Data Model

3.2 Design of the Logical Model

In order to describe the detailed data model, a combined approach(i.e. explanations of primitives with constraints of topological relationships) is used here. Firstly, primitives and entities presented in figure 2 include:

(1) Point

Every Point is a point in 3D space, and it is recorded in the form of (X,Y,Z). A Node is a point feature in 3D space consisting of a Point.

(2) Arc

An Arc is a directed line segment in 3D space, and it is bounded by two points, i.e., the beginning point and the ending point, and the direction of the Arc is from the beginning point to the ending point. These two points should not belong to the same point. And an Edge is a curve existing in 3D space which is composed of one or more Arcs.

(3) Polygon

APolygon is a closed region bounded by at least threeArcs, and these Arcslocated in the same plane must be arranged one by one to form a ring. The Polygon is a relatively simple polygon, and it could be convex, concave, or may have holes(in some cases inner rings are allowed to touch the outer ring) as shown in figure 3(a). A Face is a surface in 3D space comprising one or morePolygons. In 2D property objects, Faces have no directions. In 3D property objects, Faces which are used to enclosea Body have directions.

(4) Body

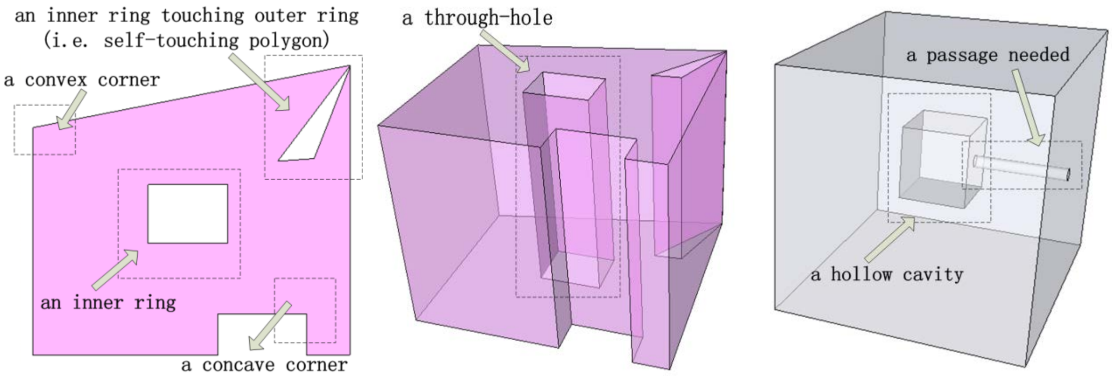
ABody is a closed volume bounded by at least fourFaces, and directions of Facesare differentiated. The Facedirectedtowards the interior of the body is regarded as the back Face, and the Facedirected towardsthe exterior of the body is regarded as the front Face. The direction of the Face is determined by the normal which can be calculated from the orientation of Edges bounding the Face. However, Edges bounding the Face may have different orientations, so a common rule should be employed. In practice, the right-hand rule is employed, i.e., the thumb points to the normal of the Face, and the orientation of the other four fingers is the orientation of Edges. When Edges bounding the Face have been determined, the orientation of Edges will be compared with the orientation of each Edge itself. If they match, the Edge will be tagged “+”, otherwise “-”. A Body can be convex, concave, or may have through-holes(the samedefinition as the simple solid in Oracle)shown in figure 3(b).

It is clear that in our definition of Body through-holes are allowed. As a consequence, hollow cavities should also be taken into account. As shown in figure 3(c), the biggest body(i.e. the biggest cube) bounded by two shells(i.e. the outer shell and the surface of the hollow cavity) is not supported in Oracle. However,when a part of 3D space is removed from the biggest body, there is hope that smaller bodies will be built inside thehollow cavity. In fact, these smaller bodies will not exist inside the hollow cavity alone forever, so a passage needs to be built connecting the hollow cavity and the outer 3D space. In other words, at this time the biggest body returns to be a 2-mainfold again which is supported in Oracle.

The theory of topology could be applied to describe the situation mentioned above: the 3D property object must be connected, however, not necessarily in a simple way (i.e. through-holes are allowed). In topology, connectedness and simple connectedness are defined as follows(Amstrong 1983):

(1) Connectedness
In topological space X, if X could not be decomposed into the union of two non-empty, mutually exclusive open sets, then X is called connected.

(2) Simple Connectedness
In topological space X, if any circuit of any point in X could shrink into the point continuously, then X is called simply connected.



(a) The Polygon Supported (b)The Body Supported (c)The Body Assumed
Figure 3. The Geometries Supported and the Body Assumed

Besides theprimitives mentioned above, topological relationships between Points, Arcs,Polygons and Bodies must obey, but are not limited to,the following rules:

(1) The relationships between Point and Arc
The same point can be incident to different arcs, i.e., it could be shared by different arcs.

(2) The properties of Arc
The arc is directed, i.e., from the starting point to the end point; an arc can be shared by several polygons, i.e., the adjacent polygons can be incident to the common arc.

(3) The relationships between Arc and Arc
The arcs are broken at the intersecting point if they intersect, and new arcs are formed by original arcs and the intersecting points, i.e. finally there is no intersecting relationship between arcs.

(4) The relationships between Arc and Polygon
The arcs are arranged one by one to form a polygon, and no isolated arcs, hanging/dangling arcs and duplicated arcs are allowed.

(5) The relationships between Polygon and Polygon

Intersection betweenPolygons is not allowed while disjunction and connection are allowed(connection at a common node or edge).

(6) The relationships between Face and Body
The body is composed of a series of adjacent faces which form a closed volume. No isolated faces, hanging/dangling faces and duplicated faces are allowed.

(7) The relationships between Body and Body
Intersection between bodies is not allowed while disjunction and connection are allowed(connection at a common node, edge, orface).

The ideas of "non-intersection" and "shareness" reflected in design of the logical model shown above provide the basis for the construction of the smallest bodies(Ying et al. 2011).They are very important, because how to obtain the 3D solids seems to belacking in GML3 and CityGML(although the conceptof 3D solid has been proposed already). It should be noticed that, the data model elaborated above is a kind oflinear topological structure which is suitable in most situations where the surfaces of the body are planar. Meanwhile,a curved surfacecan be represented by a collection of polygons(e.g. triangles), and a curvecan be represented by a collection of straight-line segments(i.e. arcs) which does not lead to any expression power.

3.3 Detailed Design of the Logical Modelbased on the Relational Database

3.3.1 The Encoding Rule for Topological Primitives

In the system designed, a node is composed of one point, an edge is composed of one arc, and a face is composed of one polygon. So, only topological primitives are coded, and they obey the following encoding rule: The ID(i.e. the unique identifier) of the body starts from 9000000 while the remaining space after 3D partition is labeled as 0. The ID of the face starts from 8000000,the ID of the edge from 5000000,and the ID of the Node from 1000000.

3.3.2 Detailed Design of Tables

Based on the relational database(e.g. Oracle), the tables are designed as follows.There are five tables in total, includingtwo tablesdescribing geometric data:the table describing geometric data of Nodes (Table1 GEOM_NODE), and the table describing geometric data of Bodies(Table2 GEOM_BODY). Additionally, there are three tables describing topological information: the table describing topological information between Bodies and Faces (Table3 TOPO_FACE_BODY), the table describing topological information between Faces and Edges (Table4 TOPO_FACE_EDGE), and the table describing topological information between Edges and Nodes (Table5 TOPO_EDGE_NODE).

Table 1. GEOM_NODE

Node_ID	*X_Coord*	*Y_Coord*	*Z_Coord*
1013866	115319.6	18094.5	-15.1

Table 2 GEOM_BODY(optional)

Body_ID	*Volume*	*XMin*	*YMin*	*ZMin*	*XMax*	*YMax*	*ZMax*
9000312	0	115256.9	18094.5	-15.1	115319.6	18253.5	3

Table 3 TOPO_FACE_BODY

Face_ID	*OutLoop_Edge*	*Face_FrontBody*	*Face_BackBody*
8005027	5018122	0	9000312

Table 4 TOPO_FACE_EDGE

Face_ID	*Face_Edge*	*Next_Edge*
8005021	5018118	5018119

Table 5 TOPO_EDGE_NODE

Edge_ID	*Begin_Node*	*End_Node*
5018118	1013866	1013867

Particularly, for the topological relationship between body and face, traditionally the body is regarded as the primary key because it is often described that a body is surrounded by faces, but in fact the face is employed as the primary key(i.e.Table3 TOPO_FACE_BODY). In detail,this means that if the body is regarded as the primary key, the face information contained in every record has variable length. This makes no use of the relational database. In contrast, if the face is regarded as the primary key, the body information contained in every record has a fixed length(i.e. front body, back body) although the number of records is increased.

It should be noticed thatboth Table4 TOPO_FACE_EDGE and Table3 TOPO_FACE_BODY are needed to distinguish inner rings from the outer ring. There is only one outer ring which is determined by Face_ID and OutLoop_Edge(i.e. the starting edge of the only outer ring) in Table3, and other edges in the outer ring are stored in Table4. After traversing overall the edges in the outer ring, remaining edges in Table4 TOPO_FACE_EDGE filtered by the FACE_ID are used to build inner rings of the face, and there could be zero or more inner rings. In Table3 TOPO_FACE_BODY, OutLoop_Edge could be an arbitrary edge in the only outer ring.

Table2 GEOM_BODY is derived after construction of the body, and it is a brief description of body information. The MBB(Minimum Bounding Box) recorded in Table2 is mainly used for spatial index(e.g. R-tree), so Table2 is optional.

Using the tables describing geometric data and topological information listed above, not only the body could be constructed completely in logic, but also thedesign of the tables is reasonablewhich could be measured by normal forms. A normal form(NF) is a set of conditions on a schema that guarantees certain properties(relating to redundancy and update anomalies). Nowadays, taking FD (functional dependence) into account, there exist many NFs in the design of relationship databases, e.g. 1NF, 2NF, 3NF, BCNF(Boyce-Codd Normal Form), 4NF, 5NF, DKNF(Domain-Key Normal Form)and 6NF. And a relation is in good form if the relation preferably is either 3NF or BCNF.

The relation proposed above satisfies BCNF, i.e. satisfies the following normal forms:
1)1NF, i.e. no repeating groups.
2)2NF, i.e. no non-key attributes are dependent on part of a key, i.e. no partial dependencies.
3)3NF, i.e. every attribute transitively dependent on a key is a key attribute, i.e. no transitive dependencies.
4)BCNF, i.e. every determinant is a candidate key.

More specifically, the storage modes of body information could be divided into two categories, i.e. the implicit mode and the explicit mode.

(1) The Implicit Mode for Storing Body Information
In this mode, body information is not stored explicitly, and it is built on the fly when needed which often costs a lot of time. However, it is suitable for editing the body information(e.g. splitting of parcels, merging of parcels, etc.). And the implicit mode is often used in the C/S(Client/Server) architecture. Taking construction of a body(Body_ID=k) as example, the corresponding SQL is presented in figure 4.

Step 1: Search for all faces bounding the body

$Select * \ from \ table3 \ where \ Face\_FrontBody = k \ or \ Face\_BackBody = k \ as \ A$

$Foreach \ A \ in \ Step1$

Step 2: Search for the beginning edge of the only outer ring bounding the face

$Select * \ from \ table4 \ where \ Face\_ID = A.Face\_ID \ and \ Face\_Edge = A.OutLoop\_Edge \ as \ B$

Step 3: Search for all the edges of the only outer ring bounding the face

$Do(Select * \ from \ table4 \ where \ Face\_ID = A.Face\_ID \ and \ Face\_Edge = B.Next\_Edge \ as \ C)$

$Util(C.Next\_Edge == A.OutLoop\_Edge)$

$Foreach \ B \ in \ Step2, Foreach \ C \ in \ Step3$

Step 4: Search for the beginning node and the ending node bounding the edge

$Select * \ from \ table5 \ where \ Edge\_ID \ in \ (B.Face\_Edge, C.Face\_Edge) \ as \ D$

$Foreach \ D \ in \ Step4$

Step 5: Search for the geometrical data of the node

$Select * \ from \ table1 \ where \ Node\_ID \ in \ (D.Begin\_Node, D.End\_Node) \ as \ E$

$Foreach \ A \ in \ Step1$

Step 6: Search for the beginning edge of a certain inner ring bounding the face

$Select \ top \ 1 * \ from \ table4 \ where \ Face\_ID = A.Face\_ID \ and \ Face\_Edge \ not \ in \ (B.Face\_Edge, C.Face\_Edge) \ as \ F$

Step 7: Search for all the edges of a certain inner ring bounding the face

$Do(Select * \ from \ table4 \ where \ Face\_ID = A.Face\_ID \ and \ Face\_Edge = F.Next\_Edge \ as \ G)$

$Until(G.Next\_Edge == F.Face\_Edge)$

$Foreach \ A \ in \ Step1$

Step 8: Search for the beginning edge of the next inner ring bounding the face

$Select \ top \ 1 * \ from \ table4 \ where \ Face\_ID = A.Face\_ID \ and \ Face\_Edge \ not \ in \ (B.Face\_Edge, C.Face\_Edge, F.Face\_Edge, G.Face\_Edge)$

Step 9: Search for all the edges of the next inner ring bounding the face

....

Figure 4. The Hierarchical Construction of a Body Through SQL(In the Implicit Mode)

(2) The Explicit Mode for Storing Body Information

The method to construct body information in this mode is the same as that in the implicit mode, but body information is stored explicitly as one record which provides convenience for the access of body information.And the Explicit mode is often used in the B/S(Browser/Server) architecture where fast visualization is needed. However, construction of the body has tobe preprocessed. Taking storage of a body(Body_ID=k)as example, detailed body information stored explicitly in the CLOB(Character Large Object) field as one record is shown in figure 5.

$$\begin{aligned}
&Body(Body_ID,\\
&Node(id,x,y,z), Node(id,x,y,z), Node(id,x,y,z), Node(id,x,y,z), \ldots,\\
&Edge(id,bn,en), Edge(id,bn,en), Edge(id,bn,en), Edge(id,bn,en), \ldots,\\
&Face(id,be,\ldots,ee;\ldots;be,\ldots,ee), Face(id,be,\ldots,ee;be,\ldots,ee), \ldots)
\end{aligned}$$

Figure 5. Body Information Stored in the CLOB(in the Explicit Mode)

4. CASE STUDY

Based on the logical model elaborated above, analysis is given taking the right space object of a certain underground 3D parcel(the underground parking lot of the energy building in Futian District, Shenzhen, China) as example (seefigure 6).

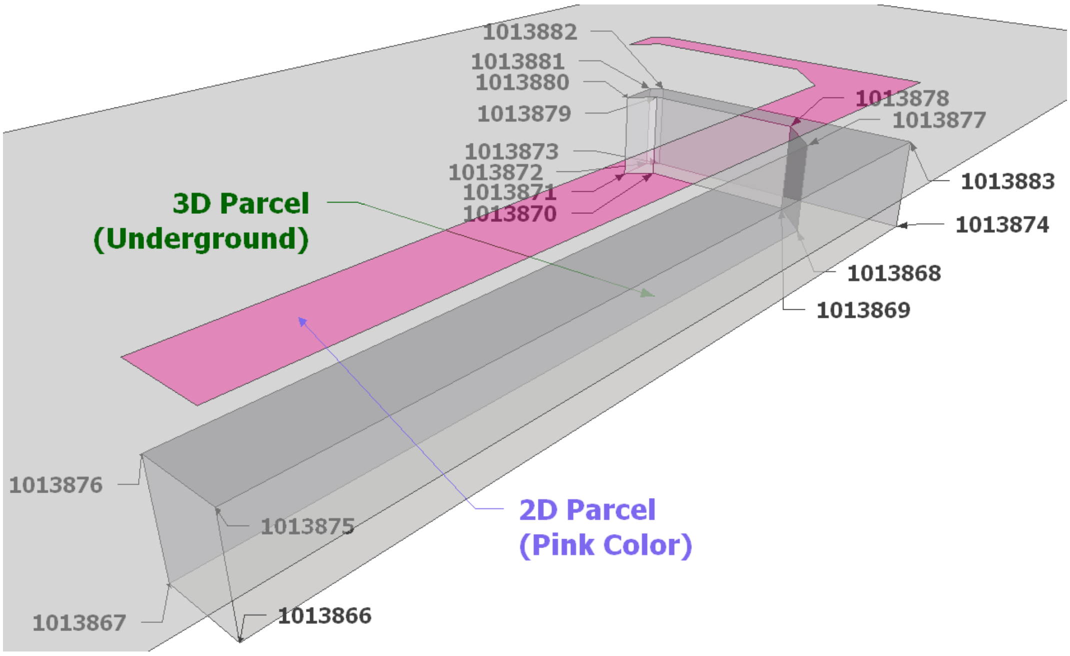


Figure 6. Right Space Object of a Certain 3D Parcel(Underground Parking Lot in Futian District, Shenzhen, China)

In order to describe the spatial shape of this 3D parcel, geometric data and topological information is listed in the Appendix:TableA(GEOM_NODE) where vertex is regarded as the primary key(18 records), TableB(GEOM_BODY) where body is regarded as the primary key(1 record), TableC(TOPO_FACE_BODY) where face is regarded as the primary key(11 records), TableD(TOPO_FACE_EDGE) where combination of face and edge is regarded as the primary key(54 records), and TableE(TOPO_EDGE_NODE) where edge is regarded as the primary key(27 records). And SQL for storing the body information in the implicit mode is presentedin figure F in the Appendix while body information recorded in CLOB in the explicit mode is presented in figure G in the Appendix. Due to limited pages in this paper, tables of 2D parcels are not listed, and the 3D parcel and the 2D parcel are linked by ID.

More cases are shown in Table6 taking right space objects of typical buildings in Shenzhen as example. In Table6, the node number, the edge number, the face number, the body number, and time cost in accessing body information in C/S and B/S in each caseare listed.

Table 6. Analysis of Right Space Objects of Several Typical Buildings in Shenzhen, China

Name	*Node Number*	*Edge Number*	*Face Number*	*Body Number*	*Timer in C/S* / ms	*Time in B/S* / ms
FengShenTing(bazaar)	516	799	350	36	>4000	<100
Excellence Century Center	84	138	64	6	>4000	<100
Convention&Exhibition Center	108	186	82	5	>4000	<100
Underground Parking Lot	18	27	11	1	>1000	<100
Luohu Railway Station	48	72	30	3	>4000	<100

Metro from Laojie to Guomao	582	891	328	14	>4000	<100
Power Supply Bureau	16	28	16	3	>3000	<100
WanXiangCheng(i.e. The MixC)	50	75	31	3	>3000	<100
ZTE Building	81	130	58	6	>4000	<100
Hongkong-Shenzhen Western Corridor	515	807	289	7	>4000	<100

5. CONCLUSION

Nowadays, related issues about 3D cadastre are widely discussed all over the world, covering technological, organizational and legal aspects. But up to now no country has really built a full 3D cadastre. In a long period from now on,there will be a focus on how to design a useful 3D spatial data model in 3D cadastre. It is hoped that what has been discussed in this paper could provide some references for the design of cadastre-oriented 3D spatial data model.

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APPENDIX

Table A. GEOM_NODE

Node_ID	*X_Coord*	*Y_Coord*	*Z_Coord*
1013866	115319.6	18094.5	-15.1
1013867	115305.5	18094.5	-15.1
1013868	115305.5	18237.8	-15.1
1013869	115296.5	18246.8	-15.1
1013870	115262.3	18246.8	-15.1
1013871	115257.6	18241.9	-15.1
1013872	115256.9	18251.4	-15.1
1013873	115259.2	18253.5	-15.1
1013874	115319.6	18253.5	-15.1
1013875	115319.6	18094.5	3
1013876	115305.5	18094.5	3
1013877	115305.5	18237.8	3
1013878	115296.5	18246.8	3
1013879	115262.3	18246.8	3
1013880	115257.6	18241.9	3
1013881	115256.9	18251.4	3
1013882	115259.2	18253.5	3
1013883	115319.6	18253.5	3

Table B. GEOM_BODY(optinal)

Body_ID	*Volume*	*XMin*	*YMin*	*ZMin*	*XMax*	*YMax*	*ZMax*
9000312	0	115256.9	18094.5	-15.1	115319.6	18253.5	3

Table C. TOPO_FACE_BODY

Face_ID	*OutLoop_Edge*	*Face_FrontBody*	*Face_BackBody*
8005027	5018122	0	9000312
8005028	5018123	0	9000312
8005029	5018124	0	9000312
8005030	5018125	0	9000312
8005031	5018126	0	9000312
8005021	5018118	0	9000312
8005022	5018127	0	9000312
8005023	5018118	0	9000312
8005024	5018119	0	9000312
8005025	5018120	0	9000312
8005026	5018121	0	9000312

Table D. TOPO_FACE_EDGE

Face_ID	*Face_Edge*	*Next_Edge*
8005021	5018118	5018119
8005021	5018119	5018120
8005021	5018120	5018121
8005021	5018121	5018122

8005021	5018122	5018123
8005021	5018123	5018124
8005021	5018124	5018125
8005021	5018125	5018126
8005021	5018126	5018118
8005022	5018127	5018135
8005022	5018135	5018134
8005022	5018134	5018133
8005022	5018133	5018132
8005022	5018132	5018131
8005022	5018131	5018130
8005022	5018130	5018129
8005022	5018129	5018128
8005022	5018128	5018127
8005023	5018118	5018137
8005023	5018137	5018127
8005023	5018127	5018136
8005023	5018136	5018118
8005024	5018119	5018136
8005024	5018136	5018128
8005024	5018128	5018138
8005024	5018138	5018119
8005025	5018120	5018138
8005025	5018138	5018129
8005025	5018129	5018139
8005025	5018139	5018120
8005026	5018121	5018139
8005026	5018139	5018130
8005026	5018130	5018140
8005026	5018140	5018121
8005027	5018122	5018140
8005027	5018140	5018131
8005027	5018131	5018141
8005027	5018141	5018122
8005028	5018123	5018141
8005028	5018141	5018132
8005028	5018132	5018142
8005028	5018142	5018123
8005029	5018124	5018142
8005029	5018142	5018133
8005029	5018133	5018143
8005029	5018143	5018124
8005030	5018125	5018143
8005030	5018143	5018134
8005030	5018134	5018144
8005030	5018144	5018125
8005031	5018126	5018144

8005031	5018144	5018135
8005031	5018135	5018137
8005031	5018137	5018126

Table E. TOPO_EDGE_NODE

Edge_ID	*Begin_Node*	*End_Node*
5018118	1013866	1013867
5018119	1013867	1013868
5018120	1013868	1013869
5018121	1013869	1013870
5018122	1013870	1013871
5018123	1013871	1013872
5018124	1013872	1013873
5018125	1013873	1013874
5018126	1013874	1013866
5018127	1013875	1013876
5018128	1013876	1013877
5018129	1013877	1013878
5018130	1013878	1013879
5018131	1013879	1013880
5018132	1013880	1013881
5018133	1013881	1013882
5018134	1013882	1013883
5018135	1013883	1013875
5018136	1013867	1013876
5018137	1013875	1013866
5018138	1013868	1013877
5018139	1013869	1013878
5018140	1013870	1013879
5018141	1013871	1013880
5018142	1013872	1013881
5018143	1013873	1013882
5018144	1013874	1013883

Step 1:

```
select "SZ3D"."TOPO_FACE_BODY"."FACE_ID",
    "SZ3D"." TOPO_FACE_BODY "."OUT_LOOP_EDGE",
    "SZ3D"." TOPO_FACE_BODY "."FACE_FRONT_BODY",
    "SZ3D"." TOPO_FACE_BODY "."FACE_BACK_BODY"
  from "SZ3D"." TOPO_FACE_BODY "  where FACE_FRONT_BODY=9000312 OR FACE_BACK_BODY=9000312
```

Resluts: 11 records

Step 2, Step 3:

```
select "SZ3D"."TOPO_FACE_EDGE"."FACE_ID",
  "SZ3D"."TOPO_FACE_EDGE"."FACE_EDGE ",
  "SZ3D"."TOPO_FACE_EDGE"."NEXT_EDGE "
     from "SZ3D"."TOPO_FACE_EDGE"  WHERE FACE_ID in
     (8005027,8005028,8005029,8005030,8005031,
     8005021,8005022,8005023,8005024,8005025,8005026)
```

Results: 54 records

Step 4:

```
select "SZ3D"."TOPO_EDGE_NODE"."EDGE_ID",
  "SZ3D"."TOPO_EDGE_NODE"."BEGIN_NODE",
  "SZ3D"."TOPO_EDGE_NODE"."END_NODE"
     from "SZ3D"."TOPO_EDGE_NODE" where EDGE_ID in (
     5018118, 5018119, 5018120, 5018121, 5018122, 5018123, 5018124, 5018125, 5018126,
     5018127, 5018128, 5018129, 5018130, 5018131, 5018132, 5018133, 5018134, 5018135,
     5018136, 5018137, 5018138, 5018139, 5018140, 5018141, 5018142, 5018143, 5018144)
```

Results: 27 records

Step 5:

```
select "SZ3D"."GEOM_NODE"."NODE_ID",
     "SZ3D"."GEOM_NODE"."X_COORD",
     "SZ3D"."GEOM_NODE"."Y_COORD",
     "SZ3D"."GEOM_NODE"."Z_COORD"
  from "SZ3D"."GEOM_NODE" where NODE_ID in (
  1013866, 1013867, 1013868, 1013869, 1013870, 1013871, 1013872, 1013873, 1013874,
     1013875, 1013876, 1013877, 1013878, 1013879, 1013880, 1013881, 1013882, 1013883)
```

Results: 18 records

Figure F. SQL of Construction for a Certain 3D Parcel(the Underground Parking Lot of the Energy Building)

```
Body(9000312,

Node(1013866,115319.6,18094.5,-15.1),Node(1013867,115305.5,18094.5,-15.1),
Node(1013868,115305.5,18237.8,-15.1),Node(1013869,115296.5,18246.8,-15.1),
Node(1013870,115262.3,18246.8,-15.1),Node(1013871,115257.6,18241.9,-15.1),
Node(1013872,115256.9,18251.4,-15.1),Node(1013873,115259.2,18253.5,-15.1),
Node(1013874,115319.6,18253.5,-15.1),Node(1013875,115319.6,18094.5,3),
Node(1013876,115305.5,18094.5,3),Node(1013877,115305.5,18237.8,3),
Node(1013878,115296.5,18246.8,3),Node(1013879,115262.3,18246.8,3),
Node(1013880,115257.6,18241.9,3),Node(1013881,115256.9,18251.4,3),
Node(1013882,115259.2,18253.5,3),Node(1013883,115319.6,18253.5,3),

Edge(5018118,1013866,1013867),Edge(5018119,1013867,1013868),Edge(5018120,1013868,1013869),
Edge(5018121,1013869,1013870),Edge(5018122,1013870,1013871),Edge(5018123,1013871,1013872),
Edge(5018124,1013872,1013873),Edge(5018125,1013873,1013874),Edge(5018126,1013874,1013866),
Edge(5018127,1013875,1013876),Edge(5018128,1013876,1013877),Edge(5018129,1013877,1013878),
Edge(5018130,1013878,1013879),Edge(5018131,1013879,1013880),Edge(5018132,1013880,1013881),
Edge(5018133,1013881,1013882),Edge(5018134,1013882,1013882),Edge(5018135,1013883,1013875),
Edge(5018136,1013867,1013876),Edge(5018137,1013875,1013866),Edge(5018138,1013868,1013877),
Edge(5018139,1013869,1013878),Edge(5018140,1013870,1013879),Edge(5018141,1013871,1013880),
Edge(5018142,1013872,1013881),Edge(5018143,1013873,1013882),Edge(5018144,1013874,1013883),

Face(8005027,5018122,5018140,5018131,5018141),Face(8005028,5018123,5018141,5018132,5018142),
Face(8005029,5018124,5018142,5018133,5018143),Face(8005030,5018125,5018143,5018134,5018144),
Face(8005031,5018126,5018144,5018135,5018137),Face(8005026,5018121,5018139,5018130,5018140)
Face(8005023,5018118,5018137,5018127,5018136),Face(8005024,5018119,5018136,5018128,5018138),
Face(8005025,5018120,5018138,5018129,5018139),
Face(8005021,5018118,5018119,5018120,5018121,5018122,5018123,5018124,5018125,5018126),
Face(8005022,5018127,5018135,5018134,5018133,5018132,5018131,5018130,5018129,5018128) )
```

Figure G. Information Stored in CLOB for a Certain 3D Parcel(the Underground Parking Lot of the Energy Building)

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