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THE HANDLING 3D SPATIAL MODEL USING FUNDAMENTAL SPATIAL RELATIONSHIPS FOR 3D GIS

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ABSTRACT

Spatial model and topological relationship are important for GIS to represent the real world objects. This representation requires appropriate spatial models to deal with object's semantics, geometry and spatial relationships. A special case of spatial models is the topological model, which maintains topological relationships, i.e. provides logical spatial connection between objects. Without such topological formalism, many GIS operations and spatial analysis are difficult to perform. Existing GIS topological models based node, arc/line, and face in 2D and 2.5D are straightforward. The 3D case is much more complex. A number of 3D topological models and frameworks have been developed and tested by several research groups, but still no consensus on 3D model is achieved. This paper describes an ongoing work on the 4-intersection model, which is referred as the Primitive Relationship (PR) model. The PR model deals with spatial primitives nodes, lines, faces and solids. The model addresses an essential group of spatial relationship applicable for real

objects and provides an approach for implementation in DBMS with visualization in a front-end.

Keywords: 3D topology, primitive relationship, and 3D GIS

1.0 INTRODUCTION

In general, topology provides a strong mechanism for handling relationships between spatial datasets. It is the basis for many spatial questions such as: find objects in given area, overlay of two and more partitions (maps), select neighboring objects, find the shortest path, etc. The implementation of 2D topological models (e.g. wing-edge, wheel) is well known but it is only applicable for 2D spatial datasets. However the world we are living is 3D and more and more applications require true 3D analysis. Increasing number of vendors (GIS, CAD and DBMS) is looking into the third dimension and they are providing tools for 3D (Zlatanova et al., 2002). A lot of research is devoted to 3D topological models and frameworks as well (Zlatanova et al., 2004). Some examples of topological frameworks are the 4- and the 9-intersection models (Egenhofer & Herring 1991, 1992) and the Dimensional Model (DM) by Billen et al. (2002). Different spatial models and frameworks have their own advantages and disadvantages with respect to the application and the analysis to be performed. The challenges in 3D modeling are much higher compared to 2D and therefore it is considered difficult to achieve consensus on a 3D topological model. Oosterom et al., 2002 suggest organization of different 3D topological models in geo-DBMS using a metadata with descriptive parameters (type primitives, rules, explicit relationships, etc.).

The complete set of spatial relationship can be used in different manner i.e. dimension and calculus-based method (Clementini, et al., (1993)), object's properties-based method (Egenhofer & Herring (1991 & 1992)), extended object's properties-based method in 3D (Zlatanova, 2000). All these relationship approaches were defined using the properties of object itself, i.e. interior, border and exterior, with the association of the emptiness and non-emptiness intersections. A common consequence from these approaches could lead to many types of complex relationships from any intersection of an object pair, which might not be of interest for the user. There may exist certain applications where these complex models could be extended to even greater complex relationship, but many of them might not applicable due to certain, specific model constraints and rules (e.g. allowed intersection of objects, permitted holes). Considering the complete relationship model would involve simple and complex relationships as a whole, it can be minimized to least number of potential topological relationships.

In this paper, we concentrated on the topological primitives of the 4-intersection model as a framework providing a simpler set of spatial relationships and we present our approach for DBMS implementation. The framework for representing spatial relationships is named *Primitive Relationship* (PR) model. The model implements only those topological primitives of real object that are able to detect in the real world, i.e. boundary and interior. In contracts to the 4-intersection model, PR does not operate with all the 4 intersection but with a selected subset of them depending on the types of objects to be considered. The framework considers four simple object primitives, i.e. node, line, face and solid.

The paper is organized in the following order: first, short description of the 4- and 9-intersection models is given and the properties of each primitive are described. Then, the topological relationships between objects are discussed in detail. The set of possible relationships to be detected by PR model follows. The paper describes the experiments on the PR model using Oracle database and AutoDesk Map 3D.

2.0 THE *4-intersection* and *9-intersection* MODELs

The widely accepted framework for detecting topological relationships is based on specific abstractions of parts of objects named *topological primitives*, i.e. *interior*, *boundary* and *exterior*. The formalism has its origins in set theory and gives strong mathematical background for representing relationships between objects (since every object has its boundary, interior and exterior)

According to the 4-intersection model, binary topological relations between two objects, *A* and *B*, can be defined in terms of the four intersections of *A*'s boundary (∂A) and interior (A^o) with the boundary (∂B) and interior (B^o) of *B* (Egenhofer and Franzosa 1991). If two spatial objects A and B are defined in a same topological space, they form four intersections of topological properties. A (2x2)-matrix as indicated below:

$$R(A,B) = \begin{pmatrix} A^o \cap B^o & A^o \cap \partial B \\ \partial A \cap B^o & \partial A \cap \partial B \end{pmatrix}$$

The 4-intersection model can be extended by considering the exterior of the objects. Thus, the comparison between two cells involves interior (^{o}), boundary (∂), and exterior ($^-$). If two spatial objects A and B are defined in a same topological space, they have six topological primitives denoted by A^o, ∂A, A^- for object A, and B^o, ∂B, B^- for object B. The intersection between these primitives results into (3x3)-matrix as follow:

$$R(A,B) = \begin{pmatrix} A^o \cap B^o & A^o \cap \partial B & A^o \cap B^- \\ \partial A \cap B^o & \partial A \cap \partial B & \partial A \cap B^- \\ A^- \cap B^o & A^- \cap \partial B & A^- \cap B^- \end{pmatrix}$$

This matrix is known as the 9-intersection model. The 9-intersection model is recommended as a framework for implementing topological relationships by Open Geospatial Consortium (http://www.opengeospatial.org/) and is already widely accepted by many vendors, e.g. ArcGIS, Intergraph, Oracle Spatial, PostGIS, Informix. Eight of the relationships have standard names, i.e. *Equals, Disjoint, Intersects, Touches, Crosses, Within, Contains and Overlaps*. It should be noticed that the framework is universal and can be used for any spatial model. Despite the acceptance as a standard, there is a lot of criticism (Zlatanova, 2000). Among all, it is often mentioned that not all the theoretical relationships (512) are possible in the reality. For example two objects have always intersecting exteriors, which reduces immediately the number of relationships to 256. Furthermore the exterior of an object is usually impossible for 'representation' in all spatial models and most of the algorithms is based on checking intersections between interior and/or boundary.

In this paper we investigate possible relationships with respect to the 4-intersection model, i.e. the ones based on detecting boundary and interior of objects.

3.0 SOME PROPERTIES OF THE SPATIAL PRIMITIVES

Prior discussing the relationships between the objects, we present the spatial model to be considered. The model is a topological model consisting of *node*, *line*, *face* and *solid*. The properties and the constraints of the primitives are described in the text below.

3.1 Node

Node represents by (x, y, z) coordinates in three-dimensional space (**R**^{3}). It appears as 0D object in 3D Euclidean space. The interior of a node is the empty set, denoted by P^o. For any cases, interior of a node will not be related to any kind of primitives due to the intersection results an empty set. The boundary of a node, denoted by ∂P, is the node by itself. Two different nodes should appear in different locations if they are not being part of any object. For instance, two spot lamp posts will not appears in the same location. A node can be on a line, on a face and in a solid (if it is part of these objects). There relationships are explicitly maintained in the model. Figure 1 denoted a node's properties.

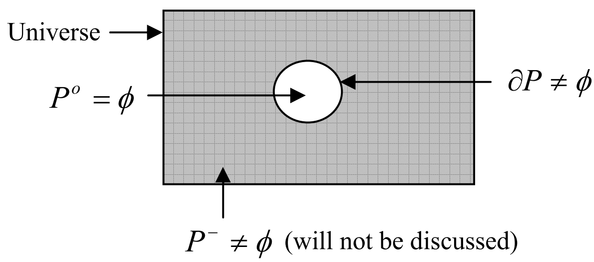


Figure 1: Properties of a node

3.2 Line

Line can be defined as a series of nodes connecting together with an appropriate sequence. It appears as 1D object in 3D Euclidean space. A line connects at least two nodes to form a line. The start and end nodes are defined as the border of a line, denoted by ∂l. The interior of a line is defined as the line segment itself, denoted by l^o. In PR model, line is could be an arc, or the combinations from many arcs that forms a linear line. This kind of linear line would be used to create planar face in PR model. However, the attention will be given to components of a line, i.e. interior and border, because these components will be use to define the module(s) from PR model. A line can be a part of other high dimensional primitives, i.e. line on line, line on face, line in solid (if it is part of these object) are explicitly maintained. The Figure 2 denoted line's properties.

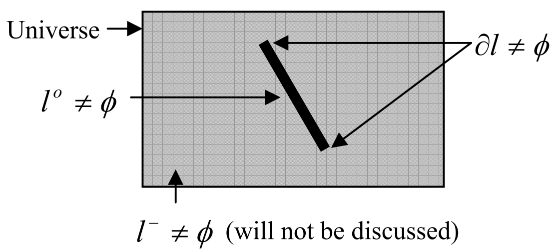


Figure 2: Properties of a line

3.3 Face

Face can be defined as a series of linear lines connecting together with an appropriate sequence. It appears as 2D object in 3D Euclidean space. A face connects at least three nodes that form a planar surface. The face is flat. The start and end nodes is the same node that defined as the border of a face, denoted by ∂Po. In the PR model, either a simple face or face with holes, the properties of face will not affect the topological relationship between other objects in this model. The different between these two kinds of face is the face with hole consists of two or more borders, whereas the simple face only remains one border. The interior of a face is defined as the area of face, denoted by Po^o. Figure 3 denoted the faces' properties.

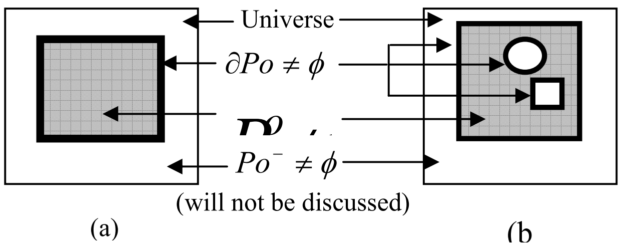


Figure 3: Properties of (a). Simple face, and (b). Face with holes

3.4 Solid

A solid is defined as an indexed set of surfaces (faces) joining together that forms a volumetric object. It appears as 3D object in 3D Euclidean space. The nodes, lines, and faces that form a solid are defined as the border of solid, denoted by ∂So. A solid is allowed to have holes and tunnels. They are borders of the solid. The interior of solid is defined as the closure of all borders, denoted by So^o. Figure 4 denoted the properties of solid.

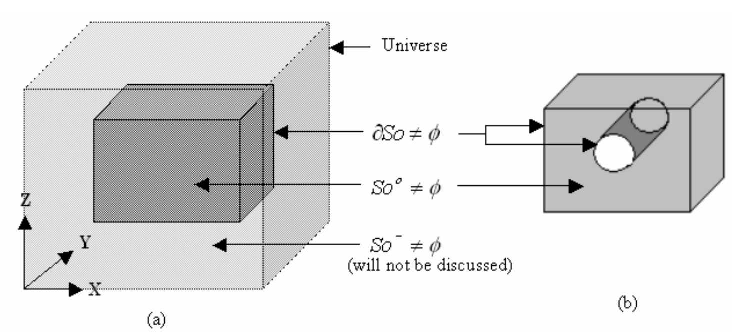


Figure 4: Properties of (a). simple solid, & (b). solid with holes

4.0 PRIMITIVE RELATIONAL (PR) MODEL

Since the framework gives the relationships between two spatial primitives, the full set of topological relationships is node-node, node-line, node-face, node-solid, line-line, line-face, line-solid, face-face, face-solid, and finally, solid-solid. Figure 5 denotes the complete set of topological relationship between object primitives.

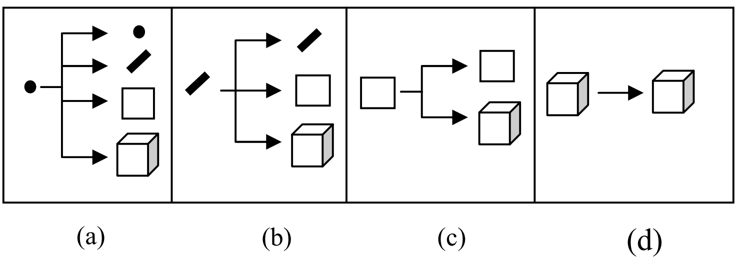


Figure 5: Complete set of topological relationship between primitives: (a). node-, (b). line-, (c). face-, & (d). solid-

The PR model uses only boundary and interior, i.e. it is based on the 4-intersection model, but only subset of the matrix is used for detection of relationships. Furthermore only *non-empty* intersections between the topological primitives are considered. The elimination of the empty set intersection from 4i model is done with the idea to increase performance. The intention is to conclude on a relationship with a minimal number check of intersections between topological primitives. The model consists of a set of topological intersections that are used to detect relationships between object pairs (see Figure 5). The differences between 4i model and PR model are:

1). No empty intersections between topological primitives will be considered.

2). Only 2 topological primitives are considered, i.e. interior and border.

3). PR set of relationships may consist of max two combinations of topological intersections.

4). The set of intersections in the PR model are related to (dependent on) the objects pairs

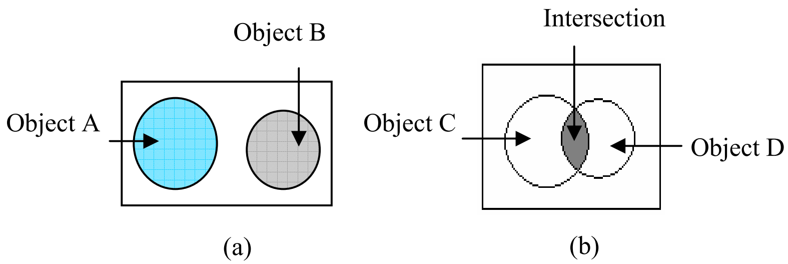
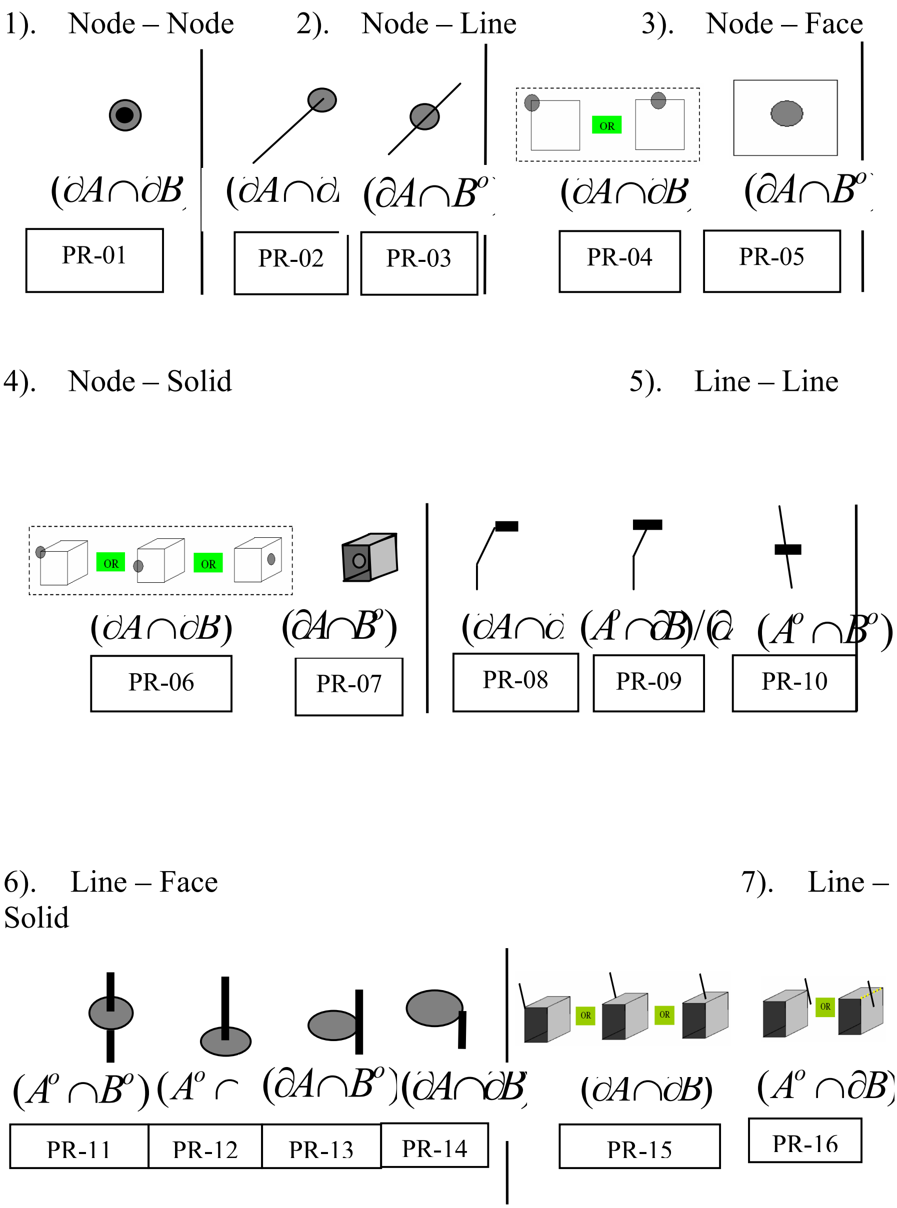


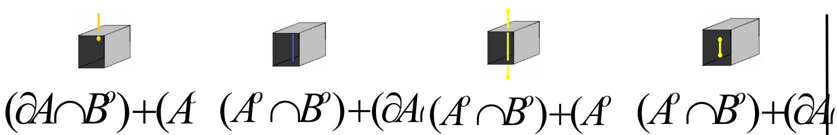
Figure 6: (a) Disjoint, and (b) joint relationship

4.1 Possible relations of the Primitive Relational (PR) Model

As mentioned above, to form the intersections in the PR model, it is necessary specify the object pairs. For this paper, the four primitives objects defined in section 3 will be used, i.e. node, line, face, and solid. A complete PR model is illustrates in the following section:



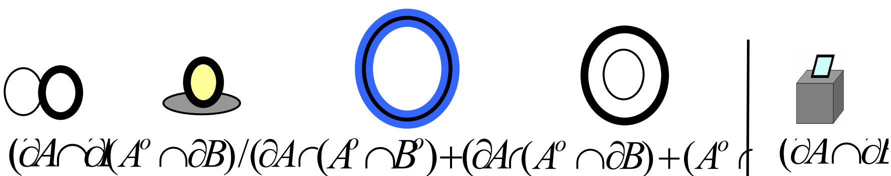
1). Node – Node
2). Node – Line
3). Node – Face
OR
PR-01
PR-02
PR-03
PR-04
PR-05
4). Node – Solid
5). Line – Line
OR
(∂A∩∂B)
(∂A∩B°)
(A°∩B°)
PR-06
PR-07
PR-08
PR-09
PR-10
6). Line – Face
7). Line – Solid
OR
(A°∩B°)
(∂A∩B°)
(∂A∩∂B)
PR-11
PR-12
PR-13
PR-14
PR-15
PR-16



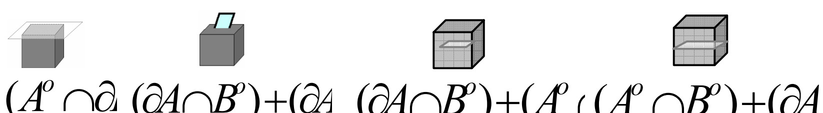
PR-17 PR- PR-19 PR-20

8). Face – Face

9). Face – Solid

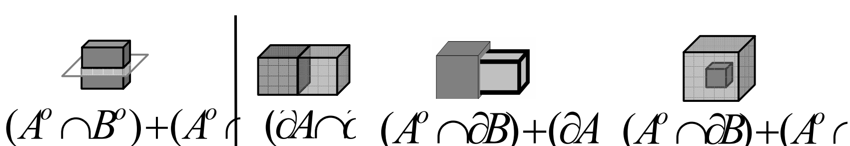


PR-21 PR-22 PR-23 PR-24 PR-25



PR-26 PR- PR-28 PR-29

10). Solid – Solid



PR-30 PR-31 PR-32 PR-33

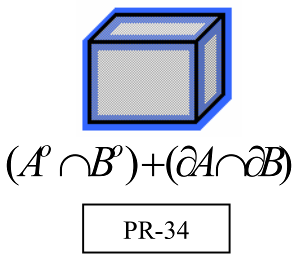


Figure 7: All possible topological relationship for PR model

5.0 THE EXPERIMENT

In order to verify the usability of PR model, we tested the model using Oracle database. All objects semantics and relationship's properties, i.e. node-N1 "is part of" line-L1, or line-L2 "is inside" solid-So1, are stored in Oracle database. Each of the primitives, i.e. node, line, face, and solid, is named according to the Figure 8. In PR model, each of the primitive objects is named in three parts. The first part represents the kind of primitive, i.e. node is represented by an alphabet "N", whereas line, face, solid are represented by an alphabet "L", "F", and "S", respectively. The second part involves the object ID, i.e. a node with ID "A" named as "NA", where "N" represents the kind of object primitive, whereas "A" represents the ID of the node. The object ID will be used to represent the type of feature object explicitly, e.g. A represents a room, B represents a road. However, the object ID is not restricted to a single alphabet. Any numbers or even the combination of number and alphabet could represent it. The third part involves numbering system of the object, i.e. line "B" consists of 5 nodes. They are, NA1, NA2, NA3, NA4, and NA5.

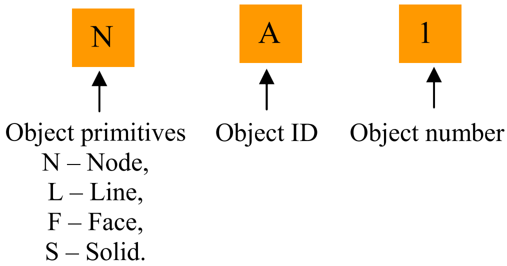


Figure 8: Format for object IDs convention

The example of a box with 6 faces, 12 edges and 8 nodes that follows the format of ID convention is given in Figure 11.

ID	*X*	*Y*	*Z*
NA1	10	10	10
NA2	10	20	20
-	-	-	-
-	-	-	-
NA8	80	80	80

a

ID	List of Nodes
LA1	NA1, NA2
LA2	NA3, NA4
-	-
-	-
LA12	NA11, NA12

b

ID	List of Lines
FA1	LA1, LA2
FA2	LA3, LA2
-	-
-	-
LA6	LA11, LA12

c

ID	List of Faces
SA1	FA1, FA2, FA3, FA4, FA5, FA6

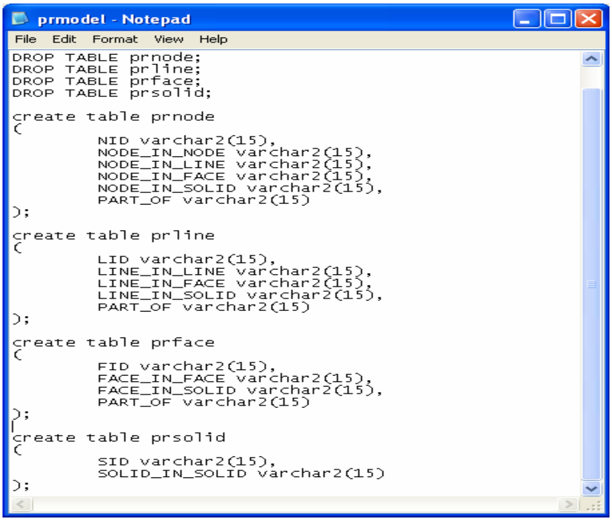
d

Figure 9: Complete datasets of a box, A. (a) node, (b) line, (c) face, and (d) solid tables

5.1 Implementation within Oracle database

After objects IDs are given, Oracle module will be implemented for storing all objects properties in database format. As mentioned in the previous section, object ID will be the "ID" column in Oracle environment. Four Oracle tables will be created, i.e. node, line, face, and solid. Each of these tables will store all related topological information. For example PR-32 (refer to Figure 9), solid "S" and "T" are involved. Both objects are cube. Therefore, both solid "S" and "T" have eight nodes, twelve lines, six faces and one solid object, respectively.

In this paper, Oracle control file will be implemented for creating the database table. Figure 10 denotes the SQL file of PR-32.




```
DROP TABLE prnode;
DROP TABLE prline;
DROP TABLE prface;
DROP TABLE prsolid;

create table prnode
(
        NID varchar2(15),
        NODE_IN_NODE varchar2(15),
        NODE_IN_LINE varchar2(15),
        NODE_IN_FACE varchar2(15),
        NODE_IN_SOLID varchar2(15),
        PART_OF varchar2(15)
);

create table prline
(
        LID varchar2(15),
        LINE_IN_LINE varchar2(15),
        LINE_IN_FACE varchar2(15),
        LINE_IN_SOLID varchar2(15),
        PART_OF varchar2(15)
);

create table prface
(
        FID varchar2(15),
        FACE_IN_FACE varchar2(15),
        FACE_IN_SOLID varchar2(15),
        PART_OF varchar2(15)
);

create table prsolid
(
        SID varchar2(15),
        SOLID_IN_SOLID varchar2(15)
);
```

Figure 10: Oracle SQL table file

After Oracle table are created, topological information will be inserted into each related table. From the node table, “NID” column represents the ID of object, whereas “NODE_IN_NODE” column denotes the possible relationship that attaches to another node, so as to “NODE_TO_LINE”, “NODE_TO_FACE”, and “NODE_TO_SOLID”. However, in some cases, a node may be an object feature, the “PART_OF” column will be filled as “NULL”, otherwise, it will be filled as the object ID. Figure 11 denotes the comparison between “NULL” and “NOT NULL” in “PART_OF” column.

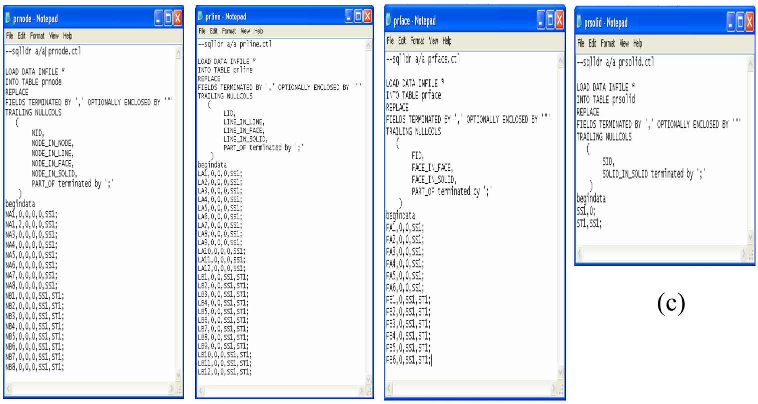
- Node NA1 represents a traffic sign.
- Node NB1 and NC1 are part of a line LA1 (LA1 represents a road)

In Oracle node table:

ID	PART_OF
NA1	NULL
NB1	LA1
NC1	LA1

Figure 11: Node table

After all tables are created, data will be inserted into these table. In this context, Oracle bulk load will be implemented. Figure 16 shows the entire bulk load file for node, line, face, and solid.



(a) (b) (c) (c)

Figure 12: Bulk load for (a) node, (b) line, (c) face and (d) solid tables

5.2 The rules of PR model and query

In order to handle object's relationship from PR model, rules for each of the thirty-two models must be followed. In this context, PR-32 is discussed. Refer to Figure 12 and Table 1, two cubes are involves, i.e. solid "S" and "T". Solid ST1 is inside solid SS1. Therefore, rules for PR-32 are:

- ALL nodes (PART_OF = ST1) from "NODE_IN_SOLID" column = SS1 **OR**
- ALL lines (PART_OF = ST1) from "LINE_IN_SOLID" column = SS1 **OR**
- ALL faces (PART_OF = ST1) from "FACE_IN_SOLID" column = SS1 **OR**

- ALL solid (PART_OF = ST1) from “SOLID_IN_SOLID” column = SS1

After the rule of PR-32 is set, database query will be introduced. From the SQL terminal, query will be done as follow (see Figure 13):

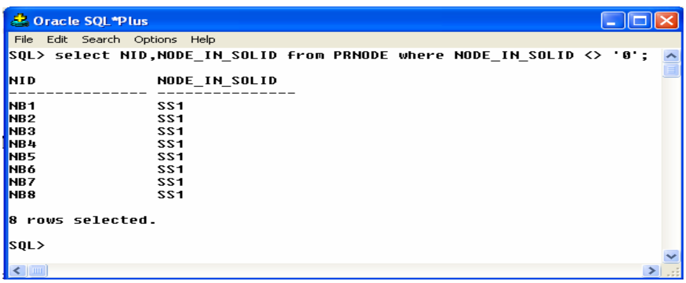


Figure 13: Oracle database query from node table

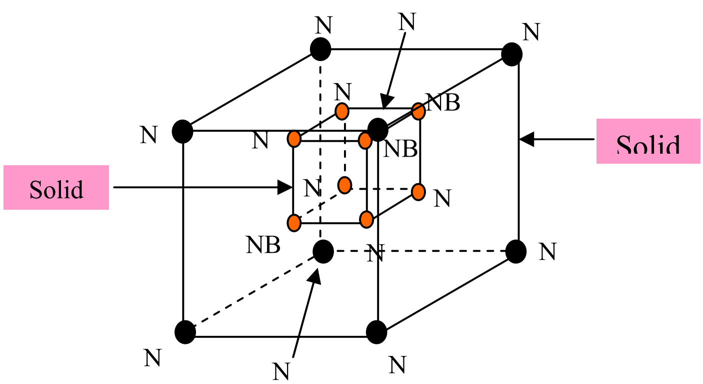


Figure 14: Two solid objects for PR-32 model

The explanation of the example from Figure 14 is given in Figure 15.

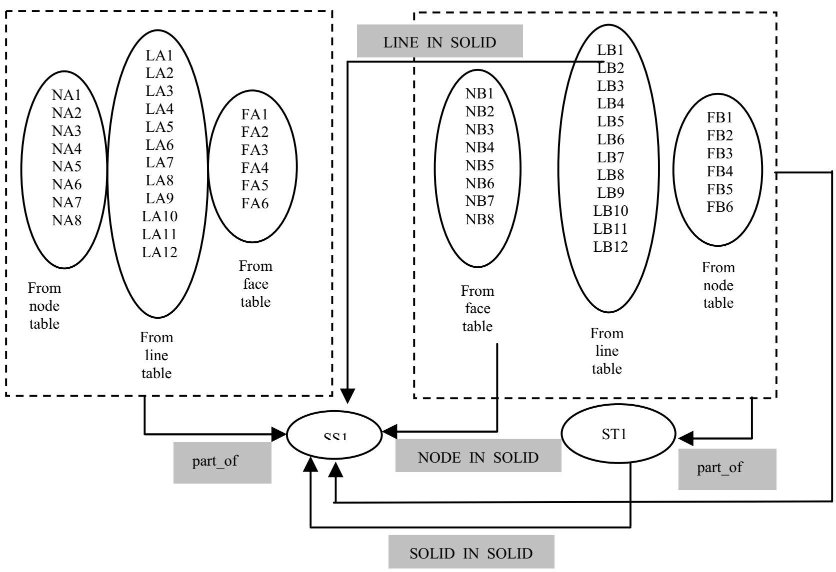
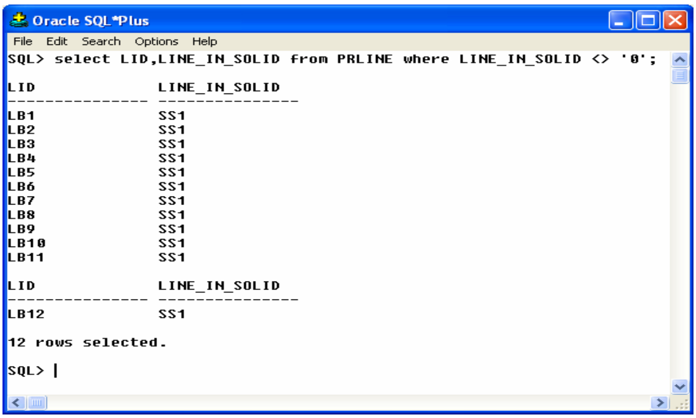
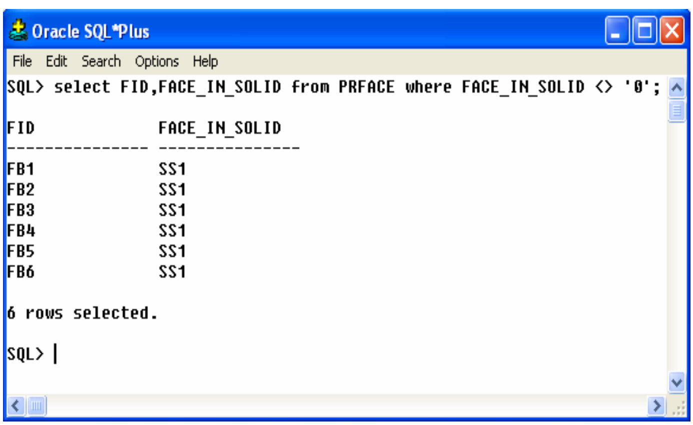


Figure 15: Implementation of Oracle table of PR-32

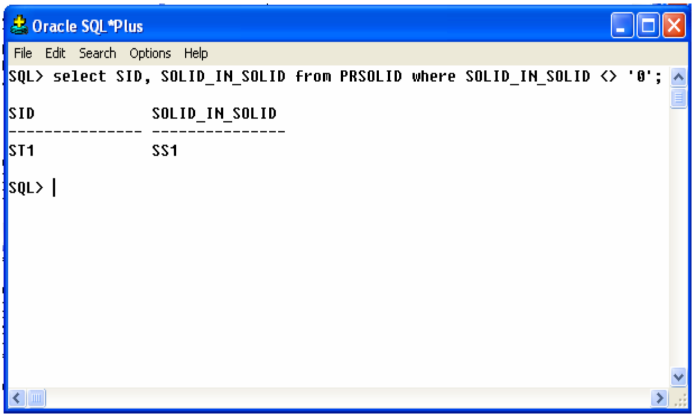
Same cases are implemented for other rules for PR-32, which make query from line, face, or solid table (see Figure 16).



(a)



(b)



(c)

Figure 16: Oracle database query from (a) line, (b) face, and (c) solid table

6.0 CONCLUDING REMARKS

The paper presents the Primitives Relational (PR) model, which is set of 33 simplified intersections between topological primitives boundary and interior. The 33 intersections are subdivided in 10 groups with respect to the object pairs. The benefits of deriving this model are expected to be twofold: (1) Relationships between objects can be progressively tested from simple to more complex. (2) The process of checking relationships can be simplified, which is beneficial for the performance of the spatial analysis. The PR model was tested using Oracle database. The rules for PR model, which based on the properties of interior and boundary components, produce all possible relationships (see Figure 10). These rules are implemented for database query using Oracle module.

Despite the encouraging results, several important issues need further investigation. A formalism has to be to develop for building and estimating the 33 intersections of PR model. The intention is to restrict PR model to having only a set of possible intersections between 2 objects. In this respect several questions has to be answered:

1). Which intersections between topological primitives, i.e. interior-interior, interior-border, border-interior, and border-border, are most critical in developing each of the PR modules?

2). Which rules and restriction could be used to enhance to possible intersection between 2 objects in reality.

3). How the PR model can be applied for detecting complex relationship?

A comparative study will be carried out to investigate benefits of the model with respect to the several other models, e.g. 4-intersection model, Simplified Set of relationships (Clementini et al., 1993) Dimensional model. The implementation of the model will be further improved, elaborated and tested with real world data.

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