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A two-level topological model for 3D features in CityGML

Lin Li [a,b], Feng Luo [a], Haihong Zhu [a,*], Shen Ying [a], Zhigang Zhao [c]

[a] School of Resource and Environment Science, Wuhan University, 129 Luoyu Rd., Wuhan, 430079, China
[b] Geospatial Information Science Collaborative Innovation Center of Wuhan University, 129 Luoyu Rd., Wuhan, China
[c] Shenzhen Research Center of Digital City Engineering, 518034 Shenzhen, China

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ABSTRACT

CityGML, as the standard for the representation and exchange of 3D city models, contains rich information in terms of geometry, semantics, topology and appearance. With respect to topology, CityGML adopts the XLink approach to represent topological relationships between different geometric aggregates or thematic features; however, it is limited to shared objects. This paper proposes a two-level model for representing 3D topological relationships in CityGML: high-level (semantic-level) topology between semantic features and low-level (geometric-level) topology between geometric primitives. Five topological relationships are adopted in this model: *touch*, *in*, *equal*, *overlap* and *disjoint*. The semantic-level topology is derived from the geometric-level topology on the basis of the shared geometric primitives. To maintain the 3D topology, topological consistency rules are presented. An Application Domain Extension, called TopoADE, is proposed for the implementation of the topological model. The TopoADE consists of three modules: Topology, Feature and Geometry. Finally, 3D city models with LoD1 to LoD4 are used to test this model. Experimentation on those data sets indicates a validation of the proposed topological model in CityGML.

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1. Introduction

Increased development of 3D GIS and the need for 3D city models used in planning and analysis promote many applications, such as energy applications (Carrión, Lorenz, & Kolbe, 2010; Eicker, Nouvel, Duminil, & Coors, 2014; Strzalka, Bogdahn, Coors, & Eicker, 2011), facility management (Mignard & Nicolle, 2014), indoor navigation (Becker, Nagel, & Kolbe, 2009; Isikdag, Zlatanova, & Underwood, 2013) and 3D cadastre (Góździ, Pachelski, Van Oosterom, & Coors, 2011; Rönsdorff, Wilson, & Stoter, 2011). 3D city models in the past focused on visual graphics and geometric information, neglecting the representation of semantics and topology. As a consequence, these models could not satisfy the constantly increasing need for thematic query, spatial analysis and data mining. As an international standard of the Open Geospatial Consortium (OGC) for the representation and the exchange of 3D city models, CityGML shows its merit in geometrical, semantic and visual representation of 3D city models (Gröger & Plümer, 2012).

Topological relationships have played a primary role in spatial operations, queries and analysis. Topological relationships indicate the invariant characteristics under topological transformation of the referenced objects (Egenhofer, 1989; Egenhofer & Herring, 1990), such as adjacent and connected relationships between spatial objects. In many 3D applications, topological relationships are widely discussed in data validation, spatial analysis and visualization (Ellul & Haklay, 2006), which has introduced a great necessity and importance for representing topological relationships in 3D city models.

With respect to modeling topology, diverse topological data models have been proposed, such as 3DFDS (Molenaar, 1990), SSM (Zlatanova, 2000a), OO3D (Shi, Yang, & Li, 2003) and STS model (Ellul, 2008). As a commonly used 3D model for the virtual city, CityGML adopts a different model based on simple topology-incidence. When two geometries share a common part, this part is represented only once in one geometry and referenced by another. With this mechanism, redundancy is avoided and an explicit topological relationship between geometries is maintained. To implement this model, CityGML uses the concept XLinks provided by GML. Each geometry object is assigned a unique identifier, and the shared object is referenced by the GML geometry. The XLink topology is simple and flexible, but one of its obvious disadvantages is that it does not provide any effective means in construction of 3D topology either on the level of geometric primitives or on the level of semantic features. The XLink topology is limited to the features or the geometries which have a shared part (generally surfaces and solids). Through XLink topology, the relation *overlap* could be represented only if the shared part is represented as an independent geometry. In other words, the geometry of the shared part is explicitly represented in the document of CityGML. As seen in Fig. 1, the overlap part of face f_1 and face f_2 is face f_3. If f_3 is stored independently in the document of CityGML, then the relation *overlap* can be represented through the shared and existed

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[*] Corresponding author.
E-mail address: hhzhu@whu.edu.cn (H. Zhu).

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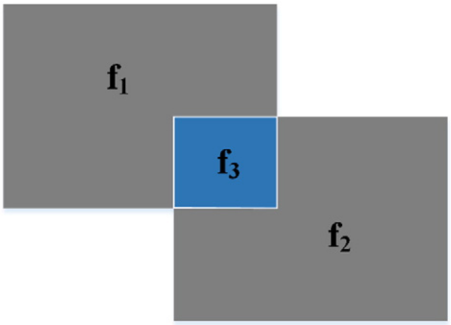

Fig. 1. The case of relation *overlap* in CityGML.

geometry of f_3 in XLink. Otherwise, the shared parts could not be represented in XLink. Another disadvantage is that navigation between topologically connected objects can only be performed in one direction (from an aggregate to its components).

This paper aims to develop a model for representing 3D topological relationships between semantic features from topological construction of geometric primitives in CityGML. Two levels of topology are used to describe topology of 3D entities in CityGML since CityGML provides data organization in two levels: geometry and semantic. To maintain the topological consistency in 3D space, topologically consistent rules of geometric primitives are discussed. This model illustrates a valid topological relationship between semantic features (e.g., between walls and windows), which is built from topological relationships (*touch*, *in* and *disjoint*) between geometries (geometric primitives and aggregates). To incorporate this topological model in CityGML, an Application Domain Extension (ADE) of topology is proposed. The topological ADE, TopoADE, contains topological relationships and topological primitives in CityGML. The obvious merit of this model is that topological relationships can be built from 3D data in the format of CityGML and are explicitly represented through TopoADE, which is useful in topological query and spatial analysis.

The remainder of this paper is organized as follows. Section 2 gives a brief introduction about conceptually topological models and topological research in 3D city models. To maintain topology in 3D city models, topologically consistent rules of geometric primitives are discussed, followed by presentation of a topological relationship model for semantic features and geometric primitives in Section 3. Section 4 introduces the TopoADE incorporating the topological model in CityGML by means of an Application Domain Extension. In Section 5, 3D data sets from LoD1 to LoD4 are experimented upon to verify the topological model and TopoADE. Finally, some conclusions are drawn for this study in Section 6.

2. Related work

2.1. Models for representing spatial relations

Designing models for representing spatial relations is an important issue in the field of geo-spatial information. Fundamental and influential models include the four-intersection (Egenhofer & Franzosa, 1991) and nine-intersection (Egenhofer & Herring, 1991) models. These models proposed using the intersection of interior, boundary and exterior according to the theory of point set topology to describe the spatial relation between spatial objects. The distinction between the four-intersection and nine-intersection model is noted by Egenhofer, Sharma, and Mark (1993). The common drawback of the two models is that the intersections between interiors, boundaries or exteriors of spatial objects are either empty or non-empty in a coarse granularity. To overcome this limitation, Clementini, Di Felice, and van Oosterom (1993) proposed the dimensionally extended model, which could distinguish the detailed intersection of objects in 3D space. Wei and Jun (1997) proposed the formal description of a topological spatial relationship in 3D space based on point set topology.

In addition to the dimensionally extended models mentioned above, a lot of research has discussed the improved topological relation model that relied on four-intersection or nine-intersection model, such as the Voronoi-based spatial algebra for spatial relations (Chen, Li, Li, & Gold, 2001; Li, Zhao, & Chen, 2002), computational model for natural-language spatial relations with metric details (Dube, Barrett, & Egenhofer, 2015; Egenhofer & Shariff, 1998; Randell, Cui, & Cohn, 1992; Shariff, Egenhofer, & Mark, 1998), topological relations between regions with holes (Egenhofer, Clementini, & Di Felice, 1994), topological relations between composite regions (Clementini, Di Felice, & Califano, 1995), and topological relations between two spatial objects whether they are convex or not (Liu & Shi, 2007). Zlatanova (2000b) presented the exhaustive possible topological relationships between multi-dimensional simple objects from 0D space to 3D space; Shi and Guo (2002) presented a study of formal representations of topological relationships between uncertain spatial objects; Tang, Kainz, and Wang (2010) discussed the topological relationships between fuzzy spatial objects; Brahim, Okba, and Robert (2015) proposed a mathematical framework of modeling the topological relationships between ribbons and regions.

In general, according to the nine-intersection model, eight topological relationships are possible between spatial objects: *disjoint*, *contains*, *inside*, *equal*, *meet*, *covers*, *coveredBy* and *overlap*. Clementini, Sharma, and Egenhofer (1994) indicated at the query language level that five topological relationships {*touch*, *in*, *cross*, *overlap* and *disjoint*} are in principle enough in applications. In addition, some other topological relationships are introduced in related research, such as *disconnected* and *composes* (De la Losa & Cervelle, 1999) and *surrounds* (Dube & Egenhofer, 2014). Thus in different models the definitions and classifications of topological relationships may be distinct.

2.2. Topology in 3D city models

In CityGML, the research of topology is mainly divided into two directions. One involves geometrical-topological modeling, for example, the validation of topological consistency for 3D city models; the other one involves spatial analysis in 3D city models combining the topological data structure and semantics in practical applications, such as indoor navigation and emergency response.

Regarding the geometrical-topology, Ledoux and Meijers (2011) presented a new extrusion procedure to construct topologically consistent 3D city models and modeled the topological relationships between polygons and polyhedra with the concept of a node column, which could solve the problem of building topological relationships in LoD1 models. Gröger and Plümer (2011a) proposed axiomatic definitions for spatial consistency of 3D city models. Both the consistency of components in 3D city models and the consistency of 3D city models are discussed with validation tests. This study focused on the spatial aspects of consistency, neglecting the semantical consistency of 3D city models. The obvious problem is that it could not be decided whether the window is part of the wall or part of the roof.

With respect to the semantic-topology, Borrmann and Rank (2009) presented a spatial query language for building information models. Semantics of topological operators in 3D space were defined using the nine-intersection model. Gröger and Plümer (2011b) extended the existing axiomatic characterization of 3D surfaces to guarantee the semantic-topological consistency of semantic handle objects (e.g., bridges and tunnels) in 3D city models. Xie, Zhu, Du, Xu, and Zhang (2013) proposed a semantic-constrained profiling approach to complex 3D city models. The consistency of geometrical, topological and semantic relationships is ensured in the approach; however, topological relationships between semantic features are not defined nor represented in those articles.

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