Spatial relations and properties for semantically enhanced 3D city models

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1. Introduction

In the domain of GIS, the topic of explicit semantics in terms of ontologies has gained in importance in recent years. It refers to the enrichment of data models to obtain data which is more usable and easier to integrate – especially in an automatic way. For example, Kolbe et al. (2005) propose to enrich existing purely geometric and texture based 3D models with more information to identify objects, classify them, and describe their properties and their relations (mostly aggregation and topology). Smart et al. (2011) extract information from different sources and annotate this information in the 3D models. Kieler (2008) uses geometric correspondences to infer correspondences on a semantic level in order to provide automatic techniques for ontology integration.

This paper extends upon the two following hypothesises.

The first hypothesis is that, in the context of city models, explicit semantics in terms of spatial relations and spatial properties play a crucial role for many applications and use cases. This is true for common users, for professionals, and for researchers. For example, pedestrian navigation and orientation can be much enhanced with the analysis of projective relations in a 3D model to support the generation of expressions that are meaningful to users that include relations like "opposite of" (Bartie et al. 2011). Civil engineering applications heavily use topological relations, urban rules are expressed with intervisibility and distance criteria (Caneparo et al. 2007)(Brasebin et al. 2011). Research on data integrity use relations as integrity constraints (Tarquini and Clementini 2008). Researchers studying urban dynamics focus on relations between cities or between objects within cities like hierarchies and networks (Bretagnolle and Pumain 2010). Furthermore, spatial relations and properties cannot only be the main focus of the application but they also provide useful inputs to semantic enrichment processes. For example, identifying shape and accesses patterns of buildings helps assessing the building functions (Chaudhry et al. 2009).

The second hypothesis is that 3D models offer new opportunities (but also new challenges) to manage spatial relations and properties in city models beyond mere visualisation of these properties and relations, as is illustrated in (Becker et al. 2010).

This work presented in this draft has been performed in the context of the COST TU0801 and more specifically WG2. The aim of this action is precisely to study the semantic enrichment of 3D city models. The action addresses issues such as determining the more relevant enrichment directions; finding efficient enrichment techniques (particularly techniques based on ontologies); and assessing the usability of enriched 3D city models.

There are several long term objectives in this work. We aim at proposing an extension of CityGML to increase its semantic expressiveness with respect to spatial relations. The extension should, include a shared typology of spatial relations and properties that are important in city models and to list existing tools and literature. Based on this, we also aim at facilitating discussions and exchanges between the various communities dealing with spatial relations and properties in cities. Indeed, as identified in (Clementini and Laurini 2008), spatial relations have been studied in several scientific domains like computer science, linguistic, philosophy and psychology and within the very domain of computer science, there are several contributions to the domain.

The more limited objective of this paper is to draft the typology and the extension of CityGML. It is organised as follows. The first part reviews existing spatial properties and relations relevant to management of semantics in city models (2D or 3D). The second part analyses existing proposals for these items first to represent them formally and draft a proposed extension of CityGML.

2. Existing spatial properties and relations relevant to the management of semantics in city models

This section reviews existing relations and properties that are mentioned or used by authors in diverse works somehow related to semantics.

An interesting process in our context is the generalisation of urban models in 2D and 3D. A generalisation process aims either at modifying objects to support the drawing process or at changing a level of details of a representation. Authors identify important information that must be preserved during the data transformation process even if this information is not explicit in the original and final data. This information corresponds, in our view, to the definition of valuable semantics. In the domain of generalisation, a general property attached to a representation is the required level of detail, e.g. the scale of a map (Mackaness 2007). Objects also have some inherent scale property. Last, the same object may have several representations at different levels of details. This exists in CityGML, where there are several properties connecting an object to its geometry corresponding to five different levels of detail important in city models (e.g. lod0Geometry, lod1Geometry, etc.). In a cartographic generalisation process a very important property attached to a representation is that of minimal dimension and minimal distance so that a detail is legible and two features can be distinguished. A typology of constraints on a process is proposed by Burghardt et al. (2007): topology, position/orientation, shape, pattern, distribution/statistic. Some constraints explicitly refer to relations (topology, orientation) or properties (shape) and others don't but are expressed, in the computing model, as relations and properties. To summarize, the main relations in generalisation are: **topology, relative orientation, distance, alignment, density, belonging to a group, being decomposed into** (e.g. a city is decomposed into a street network and building blocks, a building block is decomposed into buildings). The main properties are: **orientation, isolation, shape, size, granularity**. As generalisation requires a large set of operators (to characterise and transform), generalisation of 3D data will progress with the availability of 3D operators like intersection (Kada 2007). There are several approaches for 3D-generalization; many of them extend existing 2D approaches to 3D.

In the domain of sketch maps, landmarks for pedestrian navigation and qualitative geography, the authors identify relevant properties and relations for someone to locate himself otherwise than with coordinates in space (Kopczynski 2004)(Wang et al. 2011). These works concentrate on identifying relations and properties that can be perceived and that are discriminating, typically a property will be a **comparative property relative to a context** "the highest building in the neighbourhood". They also focus on how people express these relations, which include **vagueness.** Finally, some **relations are relative to a user point of view** like "behind" (Bartie et al. 2011).

In 3D, additional relations are relevant: besides directional relations (north, west, ...) also **vertical relations** (above, below) are used (Borrmann & Rank, 2009).

In interoperability, people study what kind of model is needed to describe a city model. (Kolbe et al. 2005) focus on a taxonomy of features to enrich terrain model with more information needed by applications. A specific property in their model is that of **level of detail of objects and composition relations**. (Billen et al. 2008) propose a meta-model to describe cities. Their proposal firstly models the urban space through empty space and filled-in/occupied space and **interfaces** between both. As compared to CityGML, this model definitely puts a highlight on topological relations and more precisely the ability to go from one place to another. Secondly, their model includes new kinds of features like juridical features (people, organisms, etc.) and abstract features (cadaster) which in turn will lead to including new kind of relation in a model like "own", "is applicable on the jurisdiction area", "sits in".

City abstract features have been studied in the context of urbanism to represent urban rules and important building properties like "**sunshine**", "**intervisibility**" and **minimum distance**. Brasebin et al. (2011) propose and implement a model to represent urban rules and to automatically detect project inconsistencies with respect to these rules. Evaluating a 3D relation may be based on 2D operators but may also necessitate 3D operators like 3D intersection. Caneparo et al. (2007) propose an ontology to represent buildings as arrangements of functional units. They propose a typology of buildings including offices, logistic centre, industrial building, warehouse, research center. Buildings properties are used as variables to adapt an ontology item to a specific case : **width**, **depth** and **rise**. Other properties are different **size properties** like the ratio between floor gross surface and open surface, **construction cost, land value, solar availability, minimal distance** (between buildings, from edge). Structures of buildings are described as sets of elementary components and relations between these components. Besides **part_of** and **related_to** relation they use an ontology of relations from the architectural domain including **topological, directional** and **proximity** relations.

Other works enrich the data with explicit semantic properties based on geometries. **Shapes, symmetries, repetition** are important to classify buildings and networks.
Methods for detecting regularities and/symmetries are important as buildings do exhibit such a structure. Mitra et al. (2006) find regularities in 3D models starting from

characteristic points, defined by the curvatures of the model's surface. Hypotheses of point pairs corresponding to symmetries are found using the RANSAC principle. Haunert (2011) finds symmetries in 2D building ground plans using string matching. In Kieler (2007) also, an important property is **regularity** or **symmetry**. Pauly et al. (2008) find repetitive structures based on local similarity sets gained with the approach of Mitra et al. (2006), and extend them to uniform grids. Recognition of repetitive structures in road networks has been investigated by Heinzle and Anders (2007). Another possibility is to use formal grammars as a structural representation of facades, as has been used for the interpretation of building facades (Ripperda and Brenner 2009) and for building reconstruction (Huang et al. 2011).

In (Chaudhry et al. 2009) composition relations are analysed based on **access to the street network** and functions are assessed based on these too as well as on **shape of sets** of buildings. In Klien and Lutz (2005) the case study is flood management and important properties and relations are relative to the shape of the ground: being **planar**, being n meters **above the level** of the river. In a similar domain, (Gaffuri 2007) who concentrates on preserving a 3D topology relation: the hydrography network outflows in the valleys of the relief.

3. Formal representation of these relations and properties

According to (Clementini and Laurini 2008), spatial relationships can be categorized in three different levels of representation: the geometric level, the computation level, and the user level. The geometric level is an abstract representation of objects in mathematical terms, where the spatial relationships between objects are defined by specific geometric properties. At the computation level, spatial objects are represented as spatial data types and spatial relationships between objects, must be calculated by spatial operators. User-level objects and spatial relationships are linked to a specific application context. We can assume that these concepts can be defined in a spatial ontology: there are various approaches in the literature, for example, in the context of urban information systems (Berdier and Roussey 2006) or more in general in conceptual modeling (Parent et al. 2006). Spatial relationships at this level are highly dependent on various factors, such as the domain peculiarity, the imprecision and vagueness implied in the terms adopted by users, and variability of terms in different countries and natural languages.

The definition of spatial ontologies describing the classes of a specific application domain (for example browsing the Internet for travel information) and the possible spatial relationships between the objects of these classes is a research issue. A user-level object (e.g., a river) can have multiple representations in geometry, because a river can be represented as a single line or a complex line, or as a two-dimensional region. Therefore, a semantic relationship between two spatial streams (e.g., a river flows into another river) can be modeled with various geometric relationships based on the adopted representations.

Conceptual modeling is independent of various geometric representations (Clementini 2010). In particular, it is independent of the dimension of the embedding space: e.g., modeling how cars interact with roads is independent from the fact that we could use a 2-D spatial representation of cars and roads or a 3-D spatial representation. In fact, the conceptual (semantic) model is not restricted to a single data representation: therefore, multiple geometric representations can correspond to a single semantic model.

We should keep separate the geometric level, which can be put into correspondence with the semantic level via a mapping. At the geometric level, the topological relations can describe the interaction between geometric features. The geometric level can actually be thought of as to be based on multi-representations. The road entities can be mapped to a 2-D geometric representation where they are represented by polylines and the topological relations by existing models, or they can be mapped to a given 3-D geometric representation where they are represented by surfaces and volumes and the topological relations are taken from a 3D set of relations.

The remaining of this section presents our reflexion to extend CityGML for an improved management of relations in Citymodels.

The aim of this extension is to add spatial relations to CityGML. Since GML (the geographic foundation of CityGML) does not include spatial relations, the proposed extension must cover the geometric level and the user level defined by Clementini and Laurini (2008). In this case the user level corresponds to the city objects ofCityGML.

In order to organize these relations we will follow a kind of linguistic approach, inspired by the proposals in (Clementini 2010). The idea is to consider geometric level relations, such as 'touches', 'collinear', 'closer', ... and to define their city level counterparts. In general, there is no direct and unique correspondence between these levels. For instance "A touches B" has a well-defined meaning as a topological relationship between geometric objects, while it may have several meanings in the application domains, such as for city objects. It may mean "the volume occupied by A touches the volume occupied by B" or "A and B share a common part, such as a wall", or "A and B touch a connecting object, such as a passageway". Therefore, in the proposed ontology of relations, every geometric level relation R corresponds to a generic city relation cityR that may have several subrelations corresponding to different meanings.

Since usual description logics provide only binary relations, we have to represent spatial relations (that can be ternary, quaternary, or more) as objects that belong to subclasses of a general CitySpatialRelation class. Figure 1 shows partial views of the geometric (left) and city (right) spatial relation hierarchies.

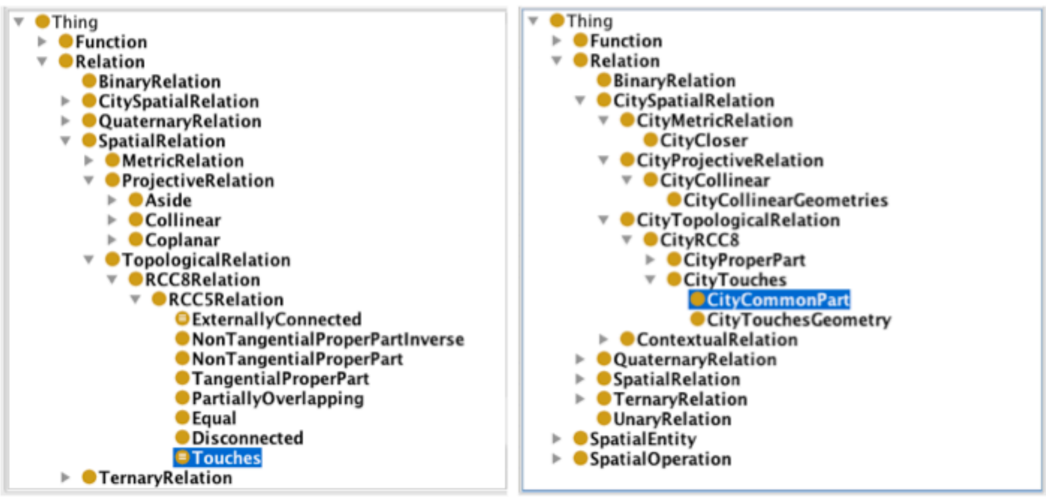

Figure1. Partial views of the SpatialRelation and CitySpatialRelation subclasses in the spatial relation ontology.

Each class will be complemented with SWRL rules that formally define (and derive) the relation from geometry and city level relations

Ideally the axioms on spatial relations should be directly transposed to axioms on city relations. This would ensure that the meaning of the city relations is effectively aligned with the meaning of the corresponding spatial relations.

This approach is applicable to objects that are considered in isolation, without taking the rest of the model into account. In a 3D city model some relations are global, or context dependent. For instance the inter-visibility relation between two points depends on all the objects that belong to the 3D city model. Similarly, the notion of isolated object or group depends on the context. Thus the city level of the ontology contains contextual relations that are not directly related to a geometric relation. Nevertheless, the definition and computation of these relations are generally based on primitive geometric relations.

Once completed, this ontology can be directly connected to an OWL version of CityGML. The resulting ontology can be directly used to :

- check the consistency of the proposed extension w.r.t. CityGML
- provide a structure for storing CityGML+Relations data in RDF
- reason on these data, either directly with description logic reasoners or with specialized reasoned (e.g. RCC8 reasoners)
- derive a concrete extension made of UML classes and attributes (or XML schemas) to include in the current CityGML UML (or XML) schemas

4. Conclusion

The availability of 3D models is rapidly growing. Advanced application will be possible, if advanced explicit properties and relations will be contained in the model. Automatically extracting these properties and relations and use them in an application dependent way has a large potential of research and poses some research challenges. This paper has drafted a list of important relations and properties in city models and an extension of CityGML to handle them. We list relevant relations and properties at the same time in the work of thematiciens (so far architecture and urbanism) and of specialists of geodata management (DB integrity management, generalisation) to propose an ontology that will relate relevant relations with operations on data to determine them.

Besides pursuing the implementation of this extension, further work will also address the completeness of the model, from the point of view of thematiciens and from the point of view of specialists in computational geometry.

We can notice that many city semantics are related to streams in the broadest sense of this word (stream of people, car, sun light, view, water, wind, noise, pollution). Other important aspects are aesthetics, symmetries and repetitions revealing man made features. Hence, we see some interesting research perspectives in adding a high level layer in a ontology of spatial relations and properties considering appearance and affordance.

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