TOWARDS SEMANTICALLY ENRICHED 3D CITY MODELS : AN ONTOLOGY-BASED APPROACH

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ABSTRACT:

Various urban models have been developed and are used in the urban domain, to perform for example air quality calculation, building energy consumption analysis or traffic simulation. The use of urban models, particularly 3D city models representing the structure of a city in three dimensions, is increasing in urban planning. The consequence of an integrated approach is the joint use of different models, most of the time in an interconnected way able to model the urban issues together with their inter-relations. 3D city models play a central role in this approach since the knowledge related to different urban issues and models can be integrated within or interconnected with 3D models. This approach leads to semantically enriched 3D city models that are well suited to decision support. Those models can also be used for a 3D visualisation of this knowledge. It is generally agreed that ontology-based approaches can provide a generic and robust way to interconnect and integrate different models. In a certain number of cases, it is necessary to take into consideration the possibility of computations involved in the correspondences between concepts. In this paper, we will focus on the description and the role of ontology-based approaches, considered as a powerful tool to improve the interoperability of the different types of urban models.

1. INTRODUCTION

Various urban models have been developed and are used in the urban domain, to perform for example air quality calculation, building energy consumption analysis or traffic simulation. 3D city models representing the structure of a city in three dimensions are special urban models derived from 3D GIS (3 Dimensional Geographic Information Systems). The use of urban models, particularly 3D city models, is increasing in urban planning. Besides, the current trend in city models is the use of "rich" models, offering more than a mere representation of usual concepts. Recent city models, such as CityGML are not purely geometric: in addition to geometric information about city objects (each object being associated with a geometry made of basic geometric objects like polygons, points, lines, etc.) those models provide a general classification of objects (building, water body, road, street, etc.) as well as non-geometric attributes like function, address, etc.

The objective of this paper is to present an ontology-based model contributing to define semantically enriched 3D city models. The first part of the paper will give an overview of urban information models and present the specificity of this kind of information. In the second part, we will present the notion of ontology and the application of ontologies to the management of the diversity and the complexity of urban information and knowledge.

As ontologies provide the basic concepts for powerful approaches facilitating the interoperability of urban models we will present in the last section some developments related to the urban field, that can be considered as the first steps towards semantically enriched 3D city models.

2. URBAN INFORMATION MODELS

According to the point of view and the purpose, the same reality can be expressed through different models: for example a physical or a numerical mock-up, an information model associated with geo-data or a mathematical model of processes represented through differential equations, as shown in Figure 1 below (from a personal discussion with Professor François Golay from EPFL, Lausanne, Switzerland).

The term *urban model* is usually related to simplifications and abstractions of real cities, in contrast to its earlier usage referring to ideal cities (Foot, 1981). Today, accurate models can be used to perform, for example, urban simulations (Waddell and Ulfarsson, 2004), building energy consumption analysis (Jones et al, 2000), water quality calculation (Kianirad et al, 2006) or air quality estimation (Moussiopoulos et al, 2006; Borrego et al, 2006).

According to Foot (1981), urban models:

– are used to evaluate the effects of changes in relation to certain land-use activities (such as residential or industrial development), transport network, etc.;

– mainly relate to spatial aspects of the urban system although they attempt to estimate the spatial consequences of changes in non-spatial variables.

Air quality models, for example, are associated with complex processes taking into account many parameters related to pollutant sources, prevailing wind, or the configuration of the streets and buildings.

Different 3D city models have been or are developed all around the world, with an intended wide range of applications such as planning and design, infrastructures and facility services, marketing or promotion (Shiode, 2001). According to the same authors, 3D city models differ by elements such as their degree of reality, i.e. the amount of geometric details that are represented, their data acquisition methods and their functionality, i.e. the degree of utility and analytical features that they allow.

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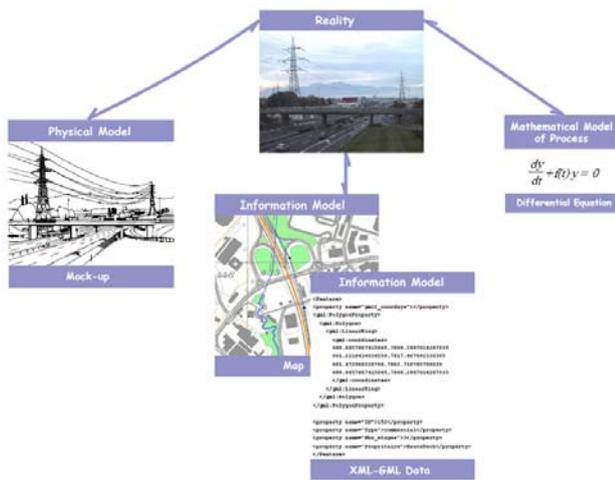
Figure 1. Different models of different types for the same reality

CityGML (OGC 08-007, 2008) is a unified model for the representation of 3D city models based on the standard GML3 of the Open Geospatial Consortium ; it is an open information model for the representation and exchange of virtual 3D city models on an international level. Urban objects (relief, buildings, vegetation, waterbodies, transportation facilities, city furniture) are represented in CityGML by features with geometric, topological and thematic properties. CityGML does not only represent the graphical appearance of city models but also contains semantic representations for thematic properties, taxonomies and aggregations of digital terrain models, sites (including buildings, bridges, tunnels), vegetation, water bodies, transportation facilities and city infrastructure. The underlying model differentiates five consecutive levels of detail (LoD), where objects become more detailed with increasing LoD for both geometry and thematic differentiation (Kolbe et al, 2005). Applied to buildings, for example, they do not exist at LoD0 as this LoD defines a coarse regional model. They exist as extruded blocks at LoD1, with their roof at LoD2, with more detailed roofs and façades at LoD3 and with their interior at LoD4. The LoD are different from what can be obtained by texturing the model in terms of visual aspect only.

Although urban models are considered as decision-making tools, they most of the time relate to one domain at the same time, such as transportation, air quality or building energy consumption, or to the physical aspects of the city as in 3D city models. Urban models could benefit from data and information coming from various domains taken into account at the same time, through a kind of "multiple inheritance", thus making this information directly available within 3D city models while providing results which could, in turn, be used and visualised through city models. As urban issues are interrelated in the real world, the interconnection of urban models can be considered as reflecting the reality more precisely. This approach would also allow urban actors to explore and to plan the city in a more global way.

In the next sections of this paper, and on the basis of case studies related to the urban domain, we will show how domain ontologies can provide a robust and reusable method to interconnect urban models and so to contribute to the semantic enrichment of urban models. Further, the use of ontology-based representations enable the development of consistency checking and reasoning features.

3. ONTOLOGIES

In the field of Artificial Intelligence several definitions of the term "ontology" have been given. According to Gruber an ontology is an "explicit specification of a conceptualization" (Gruber, 1993). A slightly different definition is "a formal, explicit specification of a shared conceptualisation" (Studer et al, 1998). A conceptualization is an abstract, simplified view of some domain that we wish to represent for some purpose, i.e. the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them. "Formal" means that some representation language have been used and so that the ontology is machine-readable. "Explicit" means that both the type of concepts used and the constraints on their use have been defined (Benjamins et al. 1998). "Shared" refers to a common understanding of some domain that can be communicated across people and computers (Studer et al, 1998).

Studies have been performed in the geographic domain which is closely related to the urban domain. Thus, following Anselin (1989) and Egenhofer (1993), the author asks a good question, about the specificity of the geographic and urban world: "What is special about spatial?". To adequately represent the geographic world, we must have computer representations capable of not only capturing descriptive attributes about its concepts, but also capable of describing the geometrical and positional components of these concepts. These representations also need to capture the spatial and temporal relationships between instances of these concepts. For example, in order to represent a public transportation system, the application ontology must contain concepts such as *street*, *neighborhood, bus stop,* and *timetable.* The computer representation of the transportation system has to recognize relationships such as "this bus line crosses these neighborhoods", "there is a bus stop near the corner of these streets" and "the bus stops at this location at 1:00 pm". Unlike the case of conventional information systems, most of these spatial and temporal relationships are not explicitly represented in a GIS, and can often be deduced using geographic functions.

Fikes and Farquhar (1999) consider that ontologies can be used as building block components of conceptual schemas. Fonseca (2003) agrees with Cui et al (2002) in that there is a main difference between an ontology and a conceptual schema: they are built with different purposes. While an ontology describes a specific domain, a conceptual schema is created to describe the contents of a database. Bishr and Kuhn (2000) consider that an ontology is external to information systems and is a specification of possible worlds, while a conceptual schema is internal to information systems and is chosen as the specification of one possible world.

Interconnection of urban models is made possible through an ontology-based approach. The general methodology can be summarized in the following way:

– representing as ontologies (i.e. to formally represent the underlying knowledge of) the resources to integrate or to interconnect;
– interconnecting these ontologies, what is generally not a trivial task since it is necessary to fill in the semantic gap between the source ontologies.

The following section presents the approach, on the basis of real case studies. A first part explains the way of creating the ontologies while the second part focuses on the articulation between the resulting ontologies.

4. TOWARDS SEMANTICALLY ENRICHED 3D CITY MODELS

Research and practice in the field of ontologies showed that the construction of an ontology is a complex task requiring not only a great knowledge of the field to be described but also a control of the structuring of the concepts using formal languages. During the last years several approaches and tools have been developed to do these concept extractions automatically or semi-automatically. For instance Stojanovic (2002) and Astrova (2004) propose techniques to extract ontologies from relational database schemas, while Velardi et al (2001) use text analysis technique to help in the construction of ontologies. At the same time, several languages have been developed to formalize ontologies, those being based primarily on predicate logic, on frames or on descriptive logic. The most recent works concern the language OWL which is a recommendation of the consortium W3C within the framework of the "semantic Web". New tools and new methods for analysis of ontologies are under development (Corcho et al, 2003).

4.1 Creation of the ontologies

In this section, we will briefly describe some domain ontologies related to urban models, with their main features and specificities.

Ontology of CityGML

CityGML defines the most relevant features in cities and regional models with respect to their geometrical, topological, semantical, and appearance properties. Thus we have: the terrain (named as *Relief Feature*), the coverage by land use objects (named as *Land Use*), transportation (both graph structures and 3D surface data), vegetation (solitary objects, areas and volumes, with vegetation classification), water objects (volumes and surfaces), sites (in particular buildings; bridge, tunnel, excavation or embankment in the future), *City Furniture* (for fixed object such as traffic lights, traffic signs, benches or bus stops).

CityGML has been defined as classes and relations in UML, the Unified Modeling Language (UML). Figure 2 shows a part of the UML diagram of CityGML.

A *TransportationComplex* is a particular kind of *TransportationObject* (which is itself a particular kind of *CityObject*) and is subdivided thematically into *TrafficArea*

(representing the areas used for the traffic of cars, trains, public transport, airplanes, bicycles or pedestrians) and *AuxiliaryTrafficArea* (associated with grass for example). In fact, a *TransportationComplex* is composed of *TrafficAreas* and *AuxiliaryTrafficAreas*. Defining the ontology of CityGML is thus relatively easy:

– UML classes will be translated into concepts;
– associations/roles will be translated into semantic relations; association cardinalities will be expressed as restrictions relatively to relations;
– aggregation/composition will be expressed as "part of" links;
– generalisation will be expressed as "is a" links (with the meaning of subconcept);
– UML attributes will be translated either into concept attributes or into relations between concepts.

Figure 3 below shows this UML diagram (without the part corresponding to the geometry) in an ontological form.

Here are some examples to illustrate the way according which attributes have been translated:

– function as a relation between TransportationComplex and TransportationComplexFunctionType itself defined as a concept;
– *surfaceMaterial* also as a relation between the concepts T*rafficArea* and *TrafficSurfaceMaterialType* but with the following restriction: a *TrafficArea* has at most one *TrafficSurfaceMaterialType*.

Ontology of Urban Planning Process (OUPP)

The ontology of urban planning process (OUPP) is still under development at the University of Geneva. In this paper we describe the part of OUPP related to soft mobility aspects. Soft mobility refers to all ways of travelling by muscular motion. To define this ontology we have used the method proposed by Uschold and King (1995) extended by Uschold and Gruninger (1996). This method is composed of four phases: (1) identify the purpose of the ontology, (2) build it, (3) evaluate it, (4) document it.

Phase 1. Identification of the purpose and the scope of the ontology

In this phase we have to answer questions such as: For which purpose is the ontology built? What are its intended uses?
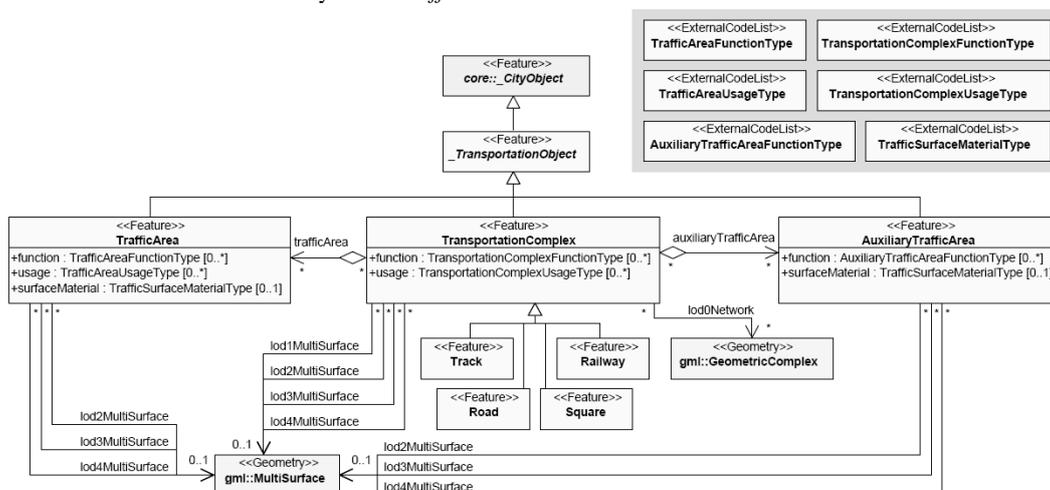

Figure 2. Part of the UML diagram of the Transportation feature of CityGML
Legend: Prefixes are used to indicate XML namespaces associated with model elements
Element names without a prefix are defined within the CityGML Transportation module

In our case the purpose is to promote soft mobility. The legal aspects (which are important to urban planners or politicians) will not be described in this paper in order to focus on some aspects such as the duration of travelling for a kind of user (as these aspects seem questioning to many potential users) or the appealing character of some paths (promenades, for example, and particularly promenades through parks). So the relevant terms to be put in the ontology include: *Duration* (of a travel), *Type_of_user* (Cyclist, Pedestrian, etc.).
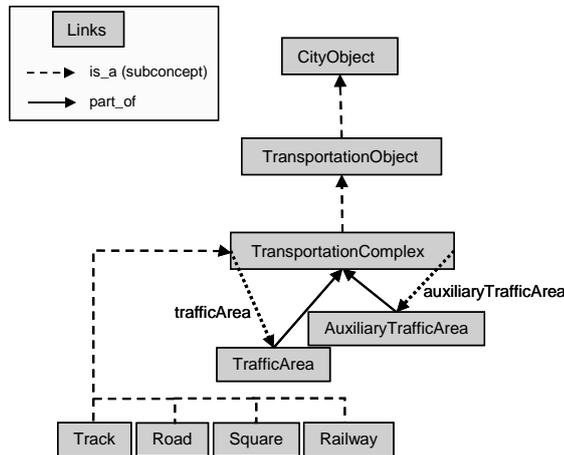

Figure 3. Part of the ontology of the Transportation feature of CityGML

Phase 2. Construction of the ontology

This phase is broken down into three parts: ontology capture, ontology coding and integration of existing ontologies (if any) into the current one.

Phase 2a. Ontology capture

This means identifying key concepts and relationships that will represent the knowledge of the domain of interest, then define them precisely and unambiguously. The knowledge can originate from experts of the domain, text mining, meta-data of databases, etc. In this case study, various documents and data related to soft mobility were mainly used. The knowledge thus extracted has to be structured. Textual definitions have to be defined by referring to other terms and including notions such as class, relation, etc. To perform this task, Uschold and Gruninger (1996) recommend the middle-out strategy, namely identifying first the core of basic terms, then specifying and generalizing them as required. In this case study, what has been identified first includes: *Type_of_user* which is a class; *Duration* which is a class and is defined by a *Value* for a particular *Type_of_user* and a particular *Section*.

Then, the top and the bottom concepts of these core concepts have been defined: the bottom concepts of *Type_of_user* are *Cyclist* and *Pedestrian*; a *Section* is ended by a *Junction* at each extremity and is part of a *Route*. Then the different kinds of *Routes* (*Cycle_route*, *Pedestrian_route*, etc.) and the different kinds of *Junctions* (*Crossing*, *Stop*, etc.) have been defined.

Phase 2b. Ontology coding

As quoted by Gomez-Perez et al (2004) this phase means (a) committing to basic terms that will be used to specify the classes, relations, entities and (b) writing the code in a formal representation language. The Figure 4 below shows

as a graph the ontology defined for representing soft mobility aspects within OUPP.
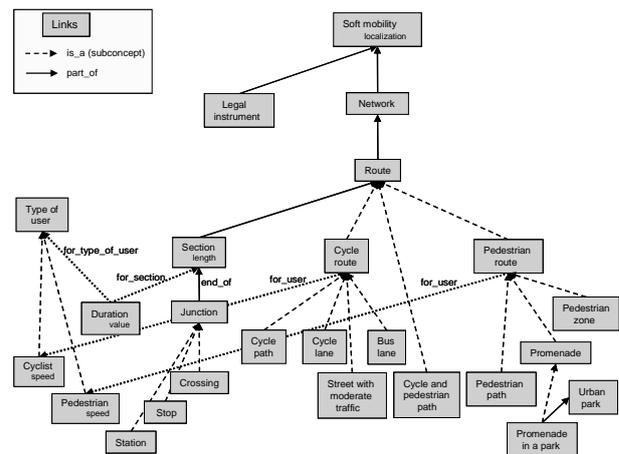
Figure 4. Part of OUPP related to soft mobility aspects

Phase 2c. Integration of existing ontologies

This optional phase deals with the identification of ontologies that already exist in the domain and their evaluation in order to be able to say to which extent they can (or cannot) be reused. This phase can be achieved in parallel with the previous phases. In our case study, an Ontology for Transportation Systems (OTN) was identified (Lorenz et al, 2005). In fact, OTN describes various transportation aspects but nothing related to soft mobility. So re-using OTN is not pertinent for creating an ontology of soft mobility but it can be useful for extending this ontology to other transportation issues such as public transport for example as this issue is represented within OTN.

Phase 3. Evaluation of the ontology

This evaluation has to be made in a pragmatic way to determine the adequacy between the ontology and the concerned application. The criteria include the following: consistency, completeness, concision (no redundancy, good degree of granularity), etc. As this case study aims at defining an ontology-based model for promoting soft mobility for the inhabitants, the evaluation phase should include usability tests with end-users.

Phase 4. Documentation of the ontology

This documentation can differ according to the type and purpose of the ontology. It means producing definitions (formal, non formal) to specify the meaning of the terms of the ontology, giving examples, etc. It can also include naming conventions such as the use of upper or lowercase letters to name the terms.
In this case study, the names of the classes begin with uppercase letters while the names of the properties begin with lowercase letters. Work on a knowledge base composed of the source documents associated with the ontology is on-going. All these ontologies have been coded into OWL using the Protégé editor.

Ontology of Air Quality Model

Air quality models are important tools to study, understand and predict air pollution levels. One of the main air quality problems at the scale of the city is related to the street canyons retaining pollutants. That is while our case study focuses on street canyon models. Many street canyon models have been defined. While most of them are two-dimensional models such as (Baik & Kim, 1999; Huang et al, 2000), there exists some three-dimensional models such as (Kim & Baik, 2004; Santiago et al, 2007).

Although different, these models show some common characteristics.

Their input parameters are:
- the pollutant source characteristics (source location, emitted product, etc.);
- the meteorological conditions, mainly the prevailing wind conditions (speed, direction related to the street canyon, etc.) but also, to some extent, the thermal conditions (solar heating);
- the street canyon geometry, in particular its aspect ratios such as height-to-width ratio, height-to-height ratio or its orientation with respect to the ambient wind.

Their output parameters are:
- a flow mainly characterized by its vortices (associated to an intensity, a rotation direction, a location, etc.);
- a pollutant dispersion distribution.

An ontology has been defined according to the same method as for OUPP. Figure 5 below shows it in a graph form.

4.2 Interconnection of the ontologies

In simple cases, concepts of the two ontologies can be directly connected together while more complex cases require an articulation or a link between the two ontologies (Mitra et al, 2000; Métral et al, 2008).

In this paper, we will limit the presentation to the interconnection of simple cases.
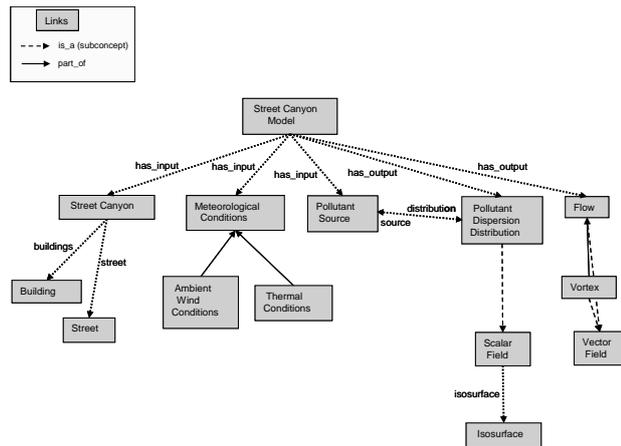
Figure 5. Part of the Ontology of a Street Canyon Model

The direct interconnection of ontologies can be done either through an equivalence link or through an inclusion link. Figure 6 below shows such an example of a direct interconnection.

The concept *Route* of OUPP is similar to the concept *Route* of OTN. The only difference relies on the context: *soft mobility* for OUPP and *public transport* for OTN. The concepts *Section* (OUPP) and *Route_Section* (OTN) are also similar: the difference here is that a *Route_Section* is oriented while a *Section* is not. A *Junction* (OUPP) is also similar to a *Stop_Point* (OTN) while being more general. Similarly, a *Section* (OUPP) is similar to a *TrafficArea* (CityGML) which is more general as it is related to all kinds of transport. As features of CityGML are related to a geometry, these interconnections make possible the representation within 3D city models of the instances associated with the concepts of OUPP or OTN.
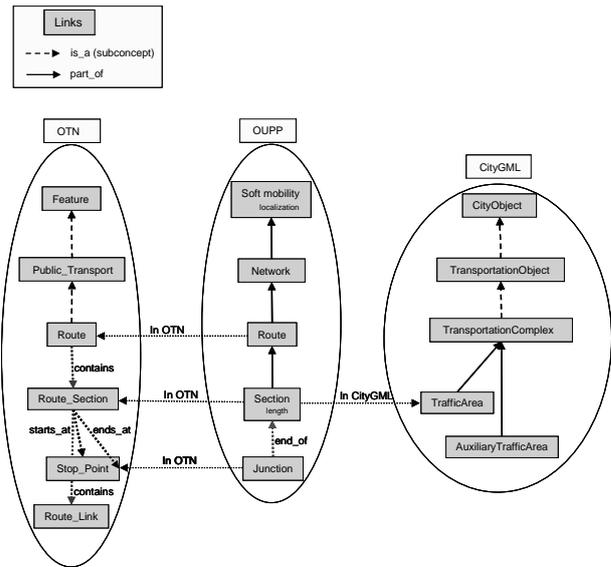
Figure 6. Direct interconnection of ontologies

5. CONCLUSION AND PERSPECTIVES

Integrating or interconnecting urban data or information is crucial, even when focusing on a single issue. A disaster management, a flood for example, requires information not only about the levels of water but also about the height of terrain and of city objects (buildings, tunnels, bridges, etc.) in order to determine which objects are affected and to which extent. These data and information can originate from different services of the same city or from different neighbouring cities but have to be interpreted, inter-related or integrated in order to manage the disaster in a global way.

After a short comparison of model-based and ontology-based approaches, an ontology-based approach has been described to interconnect urban models and information in a perspective of semantic enrichment of those models. With such interconnections it is now possible:
- to promote soft mobility by users: indeed, with the interconnection of CityGML, OUPP and OTN, it is possible to visualize in 3D soft mobility routes or routes accessible partly by foot and partly with public transportation systems;
- to compute the duration of a particular route for a type of user (Métral et al, 2009);
- to visualize, within 3D city models based on CityGML, the pollution induced by vehicle traffic in street canyons;
- to identify the best positioning of a sidewalk or a cycle path, for example;
- to visualize, within 3D city models based on CityGML, the decrease of pollution induced by the travelling of n vehicles replaced by soft mobility travelling.

The approach presented in this paper can be used for analysing multiple interconnections of urban models, for example transportation or building energy consumption models. It also enables the development of consistency checking and reasoning features that are particularly helpful when dealing with large models.

It is the first step towards what can be called semantically enriched 3D city models, with an improved semantics and thus an improved adequacy to urban planning purpose. This research work is the subject of a new COST Research Action, about semantic enrichment of 3D city models (TU0801, 2008).

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