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ONTOLOGY-BASED APPROACHES FOR IMPROVING THE INTEROPERABILITY BETWEEN 3D URBAN MODELS

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***SUMMARY**: 3D geodata are more and more available as well as realtime visualization possibilities with free three-dimensional viewers such as Google Earth. This implies a growing demand of 3D city models, which are 3D representations at the scale of the city. Despite their intended wide range of applications, such models cannot be used for many urban tasks as they cannot represent the urban information associated with these tasks. On the contrary, ontologies have proven their capacity and usability in the representation of information and knowledge of various domains. Besides, interoperability is a crucial problem for urban information systems. Transferring information between different systems or models requires the ability to set up correspondences between concepts from one system to concepts in the other one. The use of ontologies can greatly facilitate this mechanism of concept matching. In this paper we will present, on the basis of case studies, how ontologies can overstep the semantic limitation of 3D city models and how ontology-based approaches can be used to interconnect urban models in order to improve their interoperability.*

***KEYWORDS**: Urban models, 3D city models, ontologies, information management, semantics*

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1. INTRODUCTION

According to the Open GIS consortium, interoperability is defined as the "capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units" (OpenGIS, 1996).

For many authors, the use of ontologies improves interoperability among different information systems in general (Gruber, 1992), (Fonseca et al, 2006), (Mena et al, 1996), (Wiederhold, 1994) and in geographical information systems specifically (Fonseca & Egenhofer, 1999), (Kavouras & Kokla, 2002). The subject of ontology is an important field of research in geographical information science (Bishr & Kuhn, 2000), (Bittner & Winter, 1999), (Câmara et al, 2000), (Fonseca et al, 2002), (Frank, 1997), (Frank, 2001), (Kavouras et al, 2005), (Kuhn, 2001), (Mark, 1993), (Raubal & Kuhn, 2004), (Rodríguez et al, 1999), (Smith & Mark, 1998).

According to Fonseca (Fonseca et al, 2006), the litterature proposes many descriptions of ontology based interoperability, ranging from federated databases with schema integration (Sheth & Larson, 1990) and the use of object orientation (Kent, 1993), (Papakonstantinou et al, 1995), to mediators (Wiederhold, 1992) and ontologies (Guarino, 1998), (Wiederhold, 1994). For the same author, the support and use of multiple ontologies is a basic feature of modern information systems if they want to support semantics in the integration of information. Ontologies that capture the semantics of information can be represented in a formal language and be used to store the related metadata enabling a semantic approach to information integration.

An interesting study consists in analysing the differences/commonalities between ontologies and models: Fikes and Farquhar (Fikes & Farquhar, 1999) consider that ontologies can be used as building block components of conceptual schemas. Fonseca (Fonseca et al, 2003) agrees with Cui (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 (Bishr & 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.

Ontologies are generally considered as semantically richer than database conceptual schemas, and thus closer to the user's cognitive model. Conceptual schemas are built to organise what is going to be stored in a database, and then are used to document it. An ontology represents concepts in the real world.

Fonseca (Fonseca et al, 2003) provides a good analysis of the differences between ontologies and conceptual schemas. In the traditional systems modeling approach, the modeler is required to capture a user's view of the real world in a formal conceptual model. In doing so, the modeler follows an established paradigm, such as object-orientation or entity-relational, that is chosen in terms of the available programming environment. Such an approach forces the modeler to mentally map concepts acquired from the real world to instances of abstractions available in his paradigm of choice. This mapping is done informally and in an ad-hoc fashion, thereby introducing inconsistencies and inaccuracies that inevitably lead to conflicts between the user's concepts and the abstractions captured by the conceptual model. The basic reason for these conflicts is the lack of an initial agreement between user and modeler on the concepts of the real world. Such an agreement could be established by means of an ontology, which is a shared conceptualisation of an application domain.

In this paper, we will focus on the way ontologies, used in conjunction with specific conceptual models, can contribute to improve the interoperability between those models. More precisely, we will describe ontology-based approaches for interconnecting urban models with 3D city models.

A 3D city model is a digital mock-up containing the 3D representation of the geometric elements of a city, such as buildings, terrain, streets or vegetation. An increasing number of cities and companies are building 3D city models all around the world. The intended applications are wide (3D cadastre, disaster management, mobile telecommunication, vehicle and pedestrian navigation, tourism, etc.), the main application being urban planning. If the first 3D city models were centered on the geometrical aspects, there is now a trend towards models including semantic and topological aspects. The newly standard for 3D city models, CityGML (OGC 08-007rl, 2008), emphasizes such aspects.

We argue that CityGML is insufficient for representing the semantics of urban information and thus that 3D city models based on CityGML are insufficient for being used in many urban tasks. Urban projects involve many actors ranging from urban planners to inhabitants, and many tools ranging from plans (traditional tools for specialists) to 3D representations (more suited to the general public). So using 3D city models is a good way for communicating urban projects to inhabitants. Let us take the example of transportation issues. The transportation feature of City GML, that consists in infrastructure aspects (such as roads) and in more advanced aspects (such as `TransportationComplex` associated to a function and a usage) cannot represent many transportation or mobility issues such as soft mobility aspects.

These semantic gaps can be filled in by defining and using urban ontologies for representing the different types of urban information. These ontologies can be connected to CityGML (represented itself as an ontology) in order to benefit from the city objects and attributes defined in CityGML, particularly the geometry and appearance of these objects. By defining models based on these urban ontologies, we obtain not only semantically enriched 3D city models (Métral et al, 2009) that can be used for various urban applications but also interconnected models, thus contributing to the interoperability of urban information.

In this paper we (1) briefly describe the semantics of CityGML, (2) describe, on the basis of case studies, which urban information is needed to explicitely and formally define ontologies as well as the resulting models and their applications, (3) explain how and why these experiments could be generalised to improve the interoperability between 3D urban information models.

2. CITYGML

In August 2008 the OGC (Open Geospatial Consortium Inc.) defined an OpenGIS standard for 3D city models named CityGML (City Geography Markup Language). CityGML (OGC 08-007rl, 2008) defines the classes and relations for the most relevant topographic objects in cities and regional models with respect to their geometrical, topological, semantic and appearance properties. CityGML also differentiates five Levels of Detail (LOD) ranging from LOD0 to LOD4. As city objects become more detailed with increasing LOD, their geometry and their thematic is differentiated. A building, for example, is represented in LOD1 as a block with flat roof while having differentiated roof structures (such as overhangs or antennas) and thematically differentiated surfaces (representing walls, roofs, etc.) in LOD2 and in higher LODs. In LOD0, transportation complexes are modeled by center lines, thus establishing a linear network. In LOD1 and in higher LODs, a `TransportationComplex` provides a surface geometry describing the actual shape of the object. In LOD2 and in higher LODs, it is further subdivided thematically into `TrafficArea` (representing the areas used for the traffic of cars, trains, public transport, airplanes, bicycles or pedestrians) and `AuxiliaryTrafficArea` (associated to grass for example). Fig. 1 below shows the transportation model of CityGML as defined in UML, the Unified Modelling Language (UML, 2005).

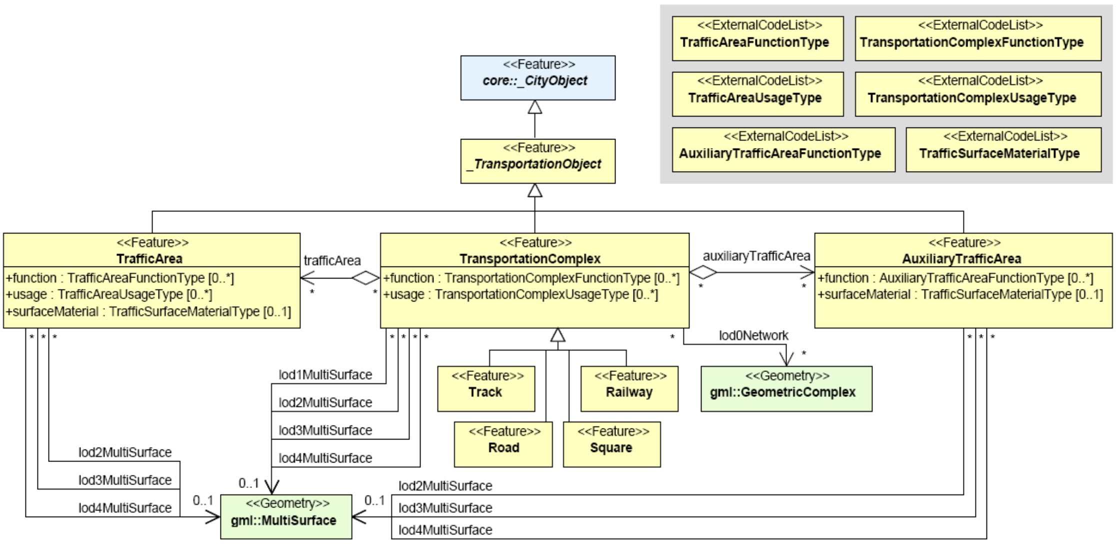

FIG. 1: UML class diagram of the transportation model in CityGML

In CityGML, the city objects (terrain, buildings, water bodies, vegetation, city furniture) or the city thematics (transportation, land use, etc.) are defined by classes related to geometric primitives (such as polygons, lines, points) but also to non-geometric attributes (such as function, usage, height, material, address). In fact, there exists an ontology (very simple) behind CityGML. For example, the UML diagram of the transportation model of CityGML can be translated into the OWL language (OWL, 2004) with the ontology editor Protégé (Drummond et al, 2005). The UML classes and relations of CityGML can be directly translated into OWL classes and properties. The attributes can be either translated into datatype properties or object properties. The cardinality restrictions can be represented by formulas in descriptive logic.

3. AN ONTOLOGY-BASED APPROACH FOR THE COMMUNICATION OF URBAN PROJECTS

Urban projects involve many actors (urban planners, politicians, inhabitants, etc.) and many tools, such as plans, legal texts or 3D representations closer to our vision of the real world. The use of 3D city models for the communication of urban projects is thus tempting. However CityGML is not sufficient to represent such projects since the concepts handled are essentially based on physical objects. More abstract concepts such as `Right_of_way` are missing, as shown on Fig. 2. It would be interesting to associate a geometric form to a `Right_of_way` and to display it in the 3D scene associated to the geometric objects (such as parcels) to which it is associated. Furthermore, the class `TransportationComplex`, although associated to a `function` and a `usage` and with subclasses `TrafficArea` and `AuxiliaryTrafficArea`, is not sufficient for many transportation or mobility aspects such as soft mobility aspects.

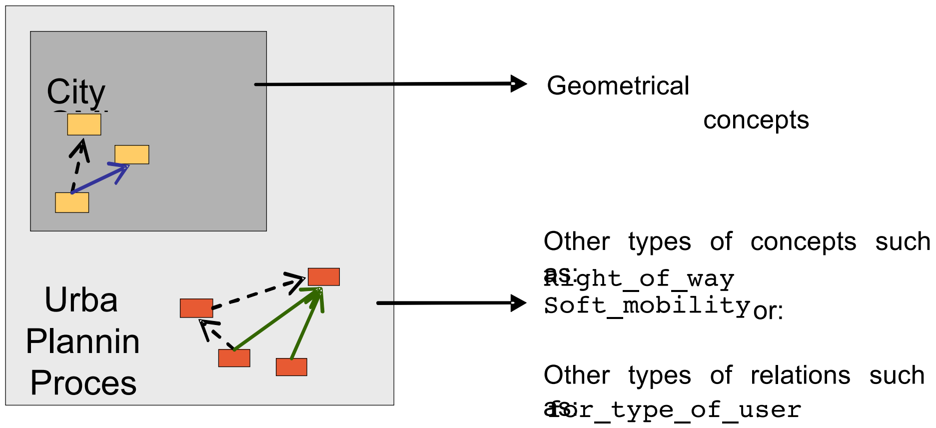

FIG. 2: Examples of the semantics missing in CityGML

Extension capabilities have been defined in CityGML to represent either 3D city objects or attributes (of these objects) not modelled, such as noise, bridges, flood information or detailed building information. In fact CityGML provides two different extension mechanisms: 1) generic objects and attributes, and 2) Application Domain Extensions (ADE). As quoted in (OGC 08-007rl, 2008) the generic objects and attributes approach allows for the extension of CityGML applications during runtime, i.e. any object may be augmented by additional attributes whose names, data types, and values can be provided by a running application without any change of the CityGML XML schema. Similarly, features not represented by the predefined classes of the CityGML model may be modelled and exchanged using generic objects. The second extension mechanism named Application Domain Extensions (ADE) specifies extensions to the UML model. Such additions comprise the introduction of new properties to existing CityGML classes, such as the number of habitants of a building, or the definition of new object types. This approach implies to define an extra XML schema definition file with its own namespace with the advantage that the extension is formally specified. A first ADE for noise pollution simulation has been developed and used for the simulation of environmental noise dispersion.

But, neither the conceptual approach (UML model extension) nor the structural one (XML mechanisms to accept new element types) are sufficient for urban general objectives such as, for example, the promotion of soft mobility which implies typical tasks including:

- computing the travel time for a route (for pedestrians, cyclists, etc.)
- evaluating the appealing character of some paths (promenades, promenades through parks, etc.)
- evaluating the safety of a way (dangerous crossings, accidents, pollution)

For those reasons we decided to define:

- an Ontology of Urban Planning Process named OUPP, including in particular the semantic aspects identified previously in order to be able to represent the information of urban projects
- semantic links between CityGML and OUPP in order to use the geometrical representations of the objects that exist in CityGML

3.1 OUPP

In this paper we describe the part of OUPP related to soft mobility aspects. This part of the OUPP ontology has been defined with the aim of providing an urban actor (an inhabitant for example) with an integrated view of the various aspects related to soft mobility, in order to promote this way of travelling (FAO, 2003). The legal aspects (which are important to urban planners or politicians) are not described in this paper in order to focus on some other aspects such as the duration of travelling for a type of user (as these aspects seem to be an important issue to many potential users). We have also decided to define a general enough ontology to represent soft mobility in different places but sufficiently fitted to Geneva to be directly used and tested as a communication tool in this city. That is why the promenades through parks (public or even private if a right of way has been negociated), have been represented as they are described in legal texts. If soft mobility concerns all the ways of transportation muscularly propelled, the major urban realizations are for pedestrians or cyclists. Fig. 3 below shows (as a graph) part of the ontology that we have defined for representing soft mobility aspects within OUPP.

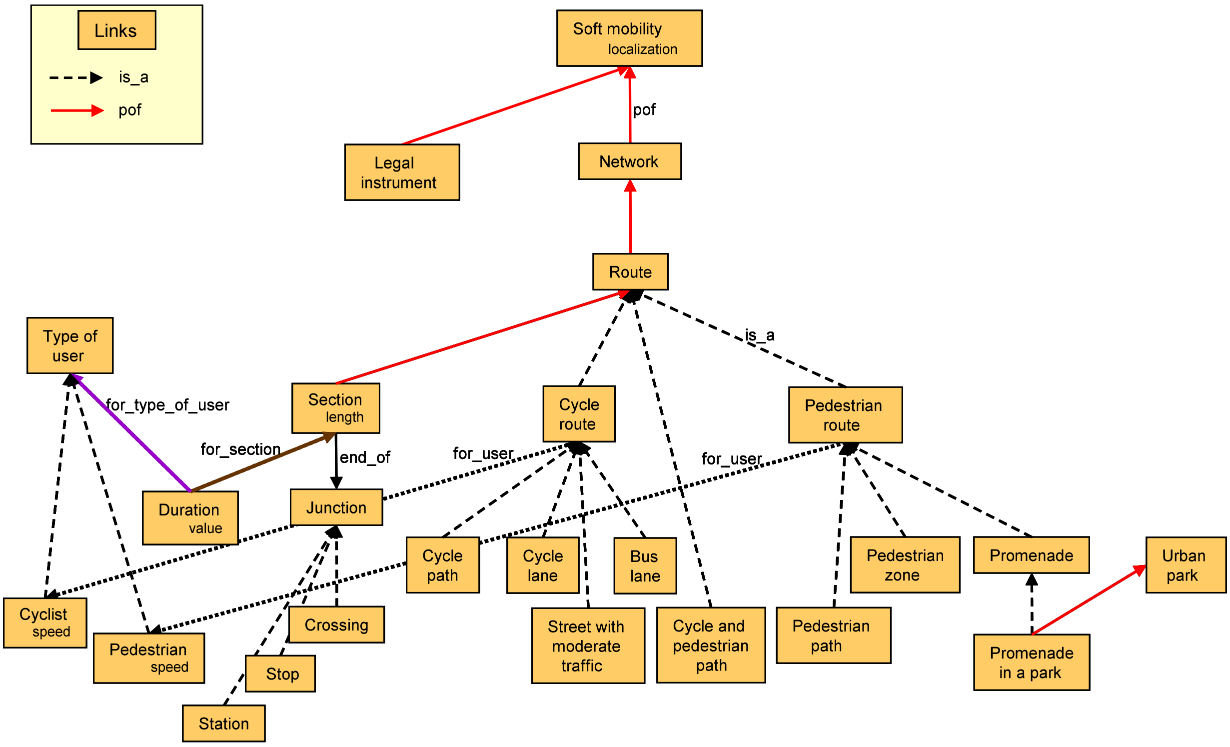

FIG. 3: Part of OUPP related to soft mobility

We then coded this ontology using the OWL language with the editor Protégé (see Fig. 4).

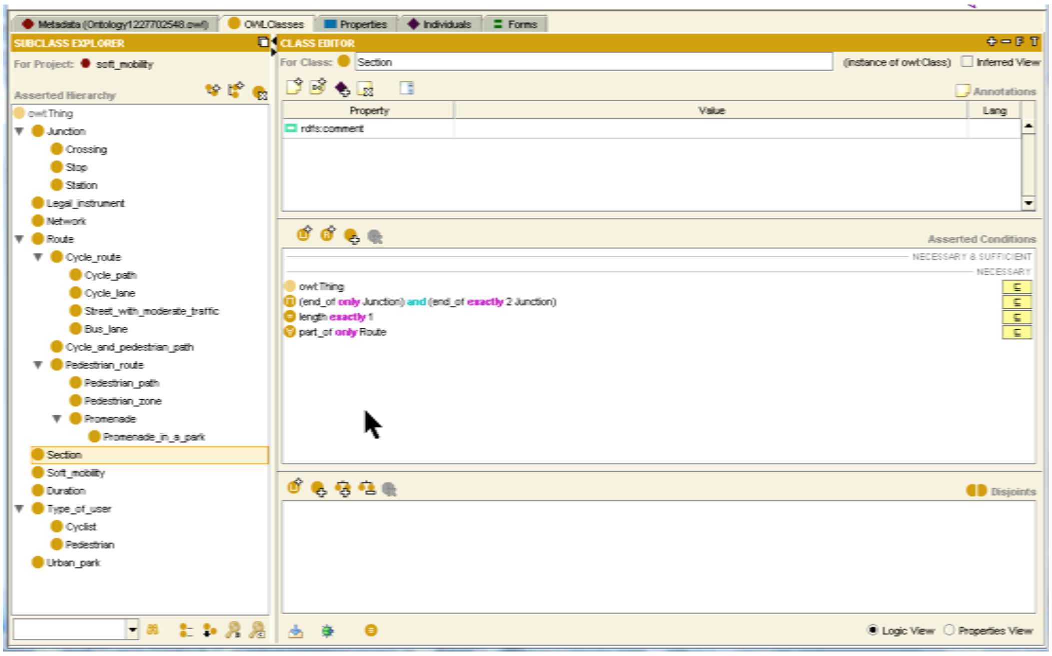

FIG. 4: Part of the ontology of soft mobility defined in OWL with Protégé

We also created a knowledge base of soft mobility in Geneva. We worked on various documents (legal, associative, etc.) available on web sites and on data coming from the Information System of Geneva (Système d'information du Territoire Genevois, SITG, http://etat.geneve.ch/sitg/accueil.html). More precisely, we defined:

- instances, such as `Promenade_des_parcs` which is an instance of `Route`
- semantic annotation links between, on one hand, these data and documents and, on the other hand, concepts and instances of OUPP (see Fig. 5).

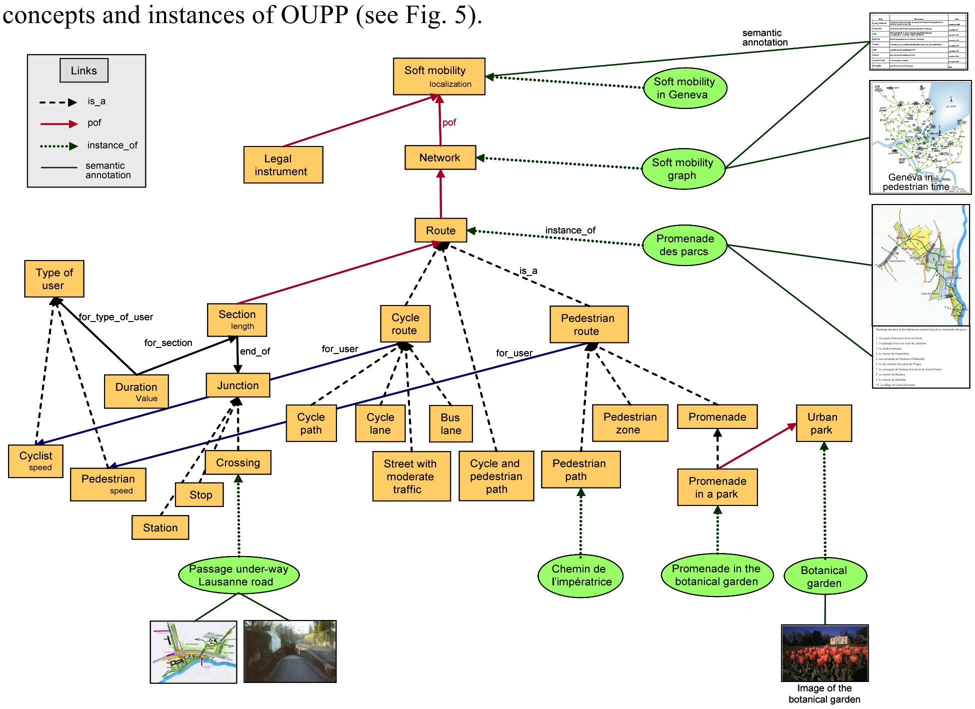

FIG. 5: Knowledge base of soft mobility in Geneva

We thus performed the semantic integration of data and documents of different types, previously disseminated on various sites. We performed this task with RDF, the Resource Description Framework language (RDF, 2004). RDF is a language for representing information (in particular metadata) about resources in the World Wide Web. RDF is intended for situations in which information needs to be processed by applications. In this perspective, RDF provides a common framework for expressing the information (the resources) to exchange: resources are described in terms of properties and property values using RDF statements. Statements are represented as triples, consisting of a subject S, predicate P and object O (S, P, O). A set of linked statements (triples) forms an RDF graph. Furthermore, each resource is uniquely identified by a so called Uniform Resource Identifier (URI) .

Each element (concept, property, instance) of an ontology has an URI. For example, if the URI of the ontology of soft mobility is http://SoftOnto.owl, the URI of the concept `Soft_mobility` is http://SoftOnto.owl#Soft_mobility while the URI of the instance `Soft_mobility_graph` is http://SoftOnto.owl#Soft_mobility_graph. It is thus possible to define in RDF the semantic annotations of Fig. 5 above.

With the knowledge base of soft mobility we can compute the duration of a particular route (`Promenade_des_parcs` for example) for a type of user (`Pedestrian`). As `Promenade_des_parcs` is an instance of a `Route,` it is part of a `Network` which is in this case the `Soft_mobility_graph` of Geneva. With the SITG, we have the `Sections` that form the `Promenade_des_parcs` with their length. A `Duration` can then be associated to each `Section` for a `Type_of_user`, in our case a `Pedestrian.`The `Duration` value is computed in the following way: speed of a `Pedestrian` **x** length of the `Section`. The values of the different sections of `Promenade_des_parcs` can then be added to obtain the duration value for a pedestrian travelling through this promenade.

3.2 Interconnection between CityGML and OUPP

If we look at CityGML we see that the concept of `TrafficArea`:

- provides elements which are important in terms of traffic usage like car driving lanes, pedestrian zones or cycle lanes
- has a function including crosswalk, green spaces, footpath, cyclepath, combined footpath/cyclepath
- enables a usage including pedestrian, bicycle, horse.

`TrafficArea` (in CityGML) and `Section` (in OUPP) can be connected by a subsumption relation: `Section` $\subseteq$ `TrafficArea`, as shown on Fig. 6.

Through the use of the geometry and appearance that are associated to objects in CityGML we can now present to the user and within a 3D scene the urban information that has been previously integrated. This visualization can be adapted to the profile and the centres of interest of the user (Métral et al, 2007).

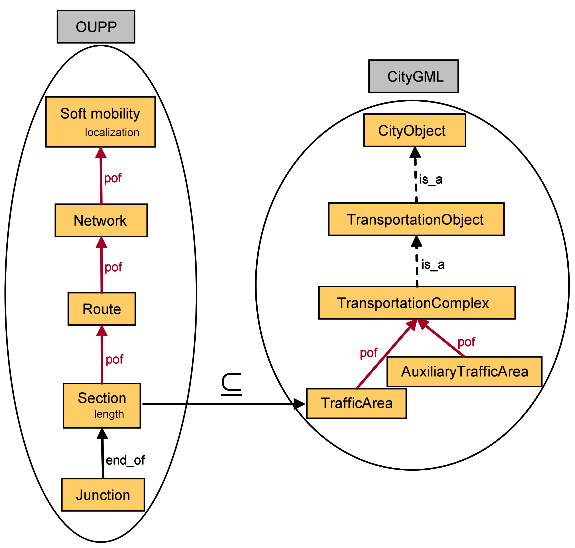

FIG. 6: Interconnection between OUPP and CityGML

3.3 Interconnection between OUPP and OTN

As a possible candidate of our investigation, we also identified an Ontology of Transportation Networks (OTN), defined within the framework of the REWERSE project (Lorenz et al, 2005). OTN describes various transportation aspects but none related to soft mobility. As it is, OTN seems to provide a complementary approach to our ontology of soft mobility and can be used to extend this ontology to other transportation issues such as public transportation for example.

Fig. 7 below shows an excerpt of the OTN ontology represented in OWL with Protégé.

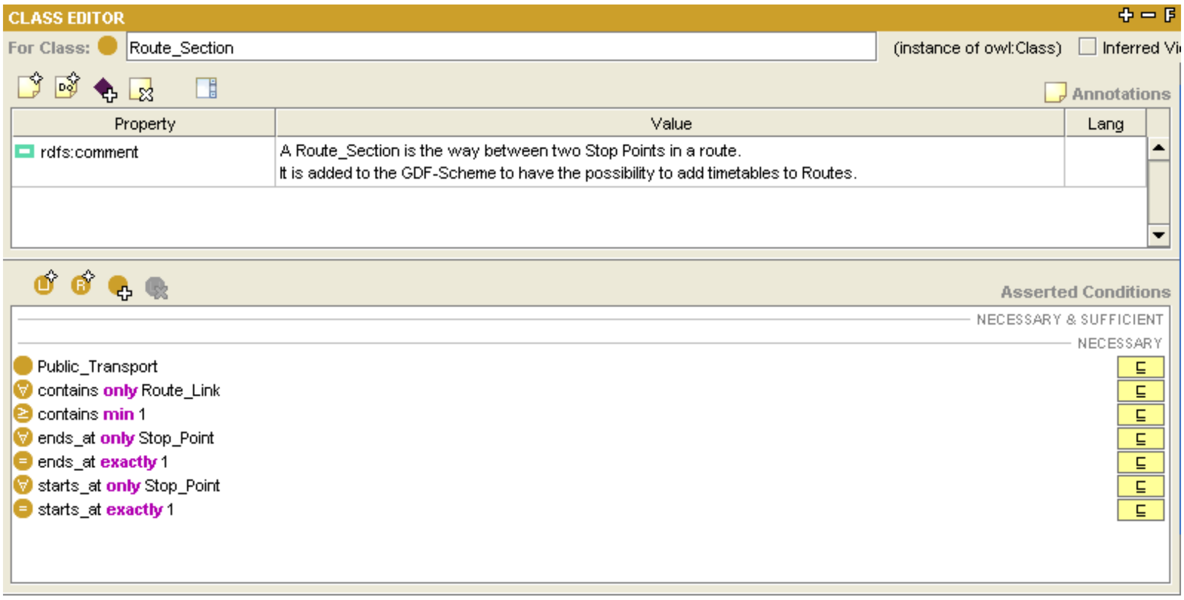

FIG. 7: Excerpt of the OTN ontology defined in OWL with Protégé

OTN differentiates a `Start_Point` and a `Stop_Point` for a `Route_Section`, in order to be able to represent a travelling direction. Even if we did not perform such differentiation for soft mobility, we have similar conceptual structures on both sides: `Routes` containing `Route_Sections` starting and ending at `Stop_Points` in OTN, `Routes` composed of `Sections` ended by `Junctions` in OUPP, as shown on Fig. 8. The main difference is that OUPP is related to soft mobility issues while OTN represents public transport.

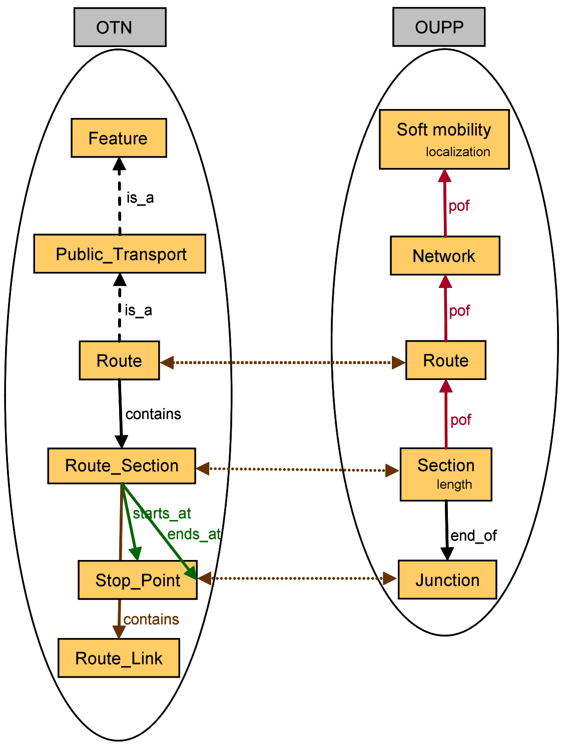

FIG. 8: Possible interconnection between OUPP and OTN

In order to represent different types of urban transport, it is possible to generalize OUPP by defining `Junctions`, `Sections`, `Routes` and `Networks` as general concepts and to define sub-concepts related to soft mobility such as `Soft_Route`, `Soft_Section` or `Soft_Junction` (see Fig. 9). Of course those sub-concepts are related to the other concepts of the ontology of soft mobility defined previously. Restrictions have also to be defined. For example, a `Soft_Route` is a `Route` but composed only of `Soft_Sections`:

```
Soft_Route ≡ Route and pof only Soft_Section
```

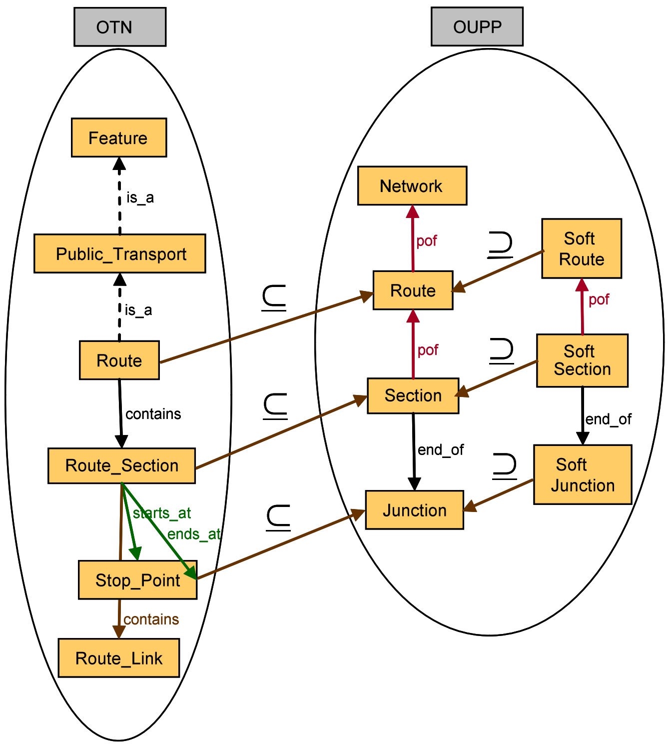

FIG. 9: Interconnection between OUPP and OTN

As OUPP and OTN are interconnected it is now possible to define routes partly by foot and partly with public transportation systems.

3.4 Interconnection between OUPP, OTN and CityGML

With OUPP, OTN and CityGML interconnected (see Fig. 10), it is possible to visualize the information and knowledge contained in the ontologies within 3D city models based on the standard CityGML. This is possible because `TrafficArea` is associated to `MultiSurface` geometries.

Fig. 10 shows also that the degree of genericity increases from OTN to OUPP and from OUPP to CityGML. For example `Route` in OTN is subsumed by `Route` in OUPP which itself is subsumed by `TransportationComplex` in CityGML:

```
OTN.Route ⊆ OUPP.Route ⊆ CityGML.TransportationComplex
```

It is thus possible to consider CityGML as a generic model providing the core concepts shared by the different specialized representations of 3D urban information. Besides, based on the geometric features of CityGML, it becomes possible to provide 3D geometrical representations of those specific concepts. In our case, we obtain a vision of mobility aspects through 3D.

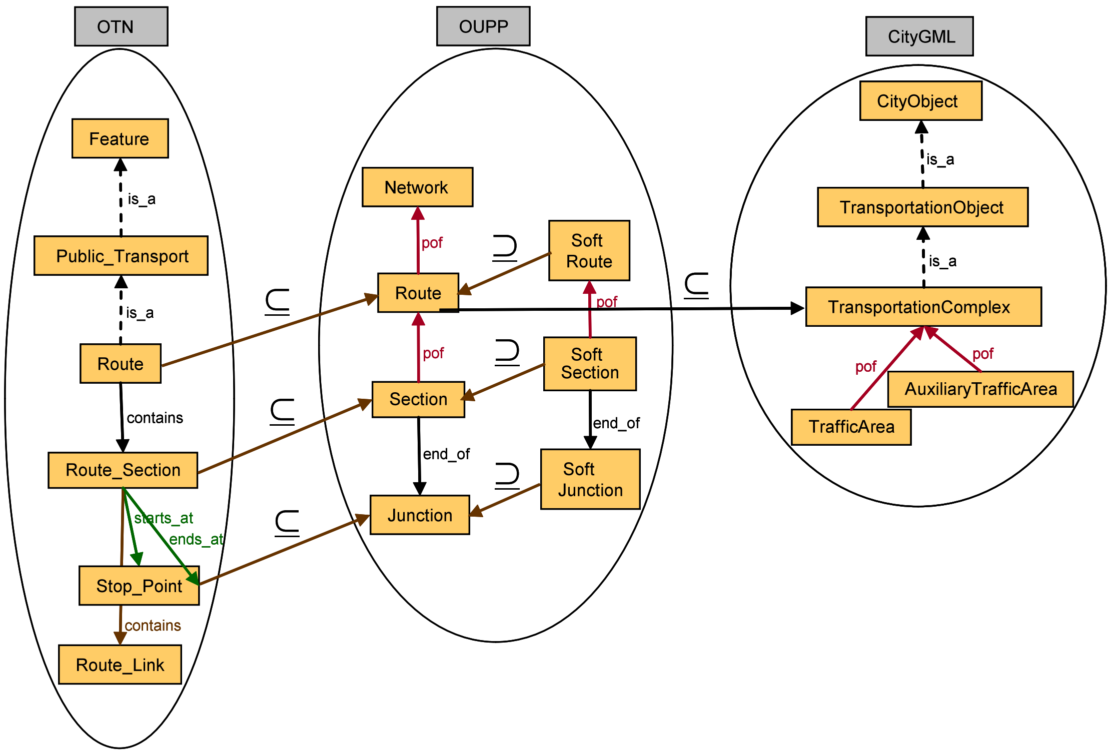

FIG. 10: Interconnection between OUPP, OTN and CityGML

4. AN ONTOLOGY-BASED APPROACH FOR VARIOUS PURPOSES

The ontology-based approach described in the paper can be used for other purposes than urban mobility issues. Such examples are given below.

4.1 Air quality

In urban areas, traffic-related pollution is one of the more environmental crucial problems (EAA, 2006), and reducing pollutant emissions to the atmosphere is imperative. In dense urban areas one major pollution problem is related to street canyons. Indeed, those relatively narrow streets between buildings can induce serious pollution problems because pollutants emitted in a street canyon (such as vehicle exhaust gases) tend to disperse less than those emitted in an open area.Various types of air quality models have been defined to simulate flow and dispersion of pollutants in urban street canyons such as (Huang et al, 2000) or (Kim & Baik, 2004).

Interconnecting air quality models with 3D city models can contribute to enhance decision-making in urban planning by providing an evaluation of air flows for a planned urban project or by finding the best position for a sidewalk or a cycle path (the best in terms of level of pollution).

The ontology-based approach described in this paper can be used for performing the interconnection of air quality models with CityGML even if, such an interconnection needs defining interconnection concepts that may have different types of semantic links with the source ontologies (air quality and CityGML) (Métral et al, 2008).

4.2 Archaeology

Archaeological remains are important components of our current cities. It is therefore sensible to consider them in an urban modelling context. However, their integration in such a virtual system is far from being straightforward. Indeed, archaeological and more generally cultural heritage domains present some specific issues one of these being the uncertainty; knowledge is almost always unsupported (notably concerning shape, function or chronology) and information is linked to structures with a very often incompletely known geometry. Moreover, those archaeological structures are nowadays hidden or replaced by others, more recent. Sometimes they have disappeared. Besides, archaeological data are known for their semantics complexity. For example, a building is likely to have host several levels of function (main, minor, symbolic...) and sometimes different functions connected to a same level. This non-permanence of knowledge gives rise to interpretation changes. For this reason, such information should be handled in a flexible and evolving way by combining different levels of archaeological ontologies and connecting them to urban ontologies or models.

This approach, notably based on the CIDOC Conceptual Reference Model (CIDOC, 2008), has been adopted for the structure II Sub C of the Maya city of Calakmul (Yucatan, Mexico). In the history of Calakmul, this building, the oldest one of the city, certainly played the following roles: symbol of the holy mountain evoked in the myth of Maya creation, the mountain from where came the "original" twins, the building pointed out the sacred origin of "royal" lineage. It was the place where the *ahaw* (the "king") came in contact with the heavenly forces, the place inside of which, thanks to men supports, the sun could be regenerated and reappears as each morning the rays proved it which crossed the crest (Rodrigo Campero, 2000).

To perform the integration of this information and to be able, when needed, to update it easily, it is necessary to consider three successive ontological models at least: a generic archaeological ontology, an ontology dedicated to the Maya world and, finally, an ontology specifically dedicated to the city of Calakmul. In the following, we present an excerpt of what could be such a succession of ontologies: the first ontologies describing archaeological "universal concepts", the second one gathering classes of terms and concepts developed by archaeologists, historians and anthropologists to describe the preclassical Maya civilization and finally the third one dealing with specific objects and situations linking the Calakmul site (see Fig. 11). For this purpose also, a link with CityGML allows to deal with structural and geometrical issues. In that case, building descriptions of CityGML seem to be well suited to the representation of the geometry and the structural nature of some archaeological items.

An extension of CityGML could be envisaged for some domain applications, but archaeological domain is so far away from the original CityGML considerations that such extensions seem impossible. Therefore, the use of ontologies seems to be the only sensible solution to integrate archaeological knowledge and information in a broader urban model.

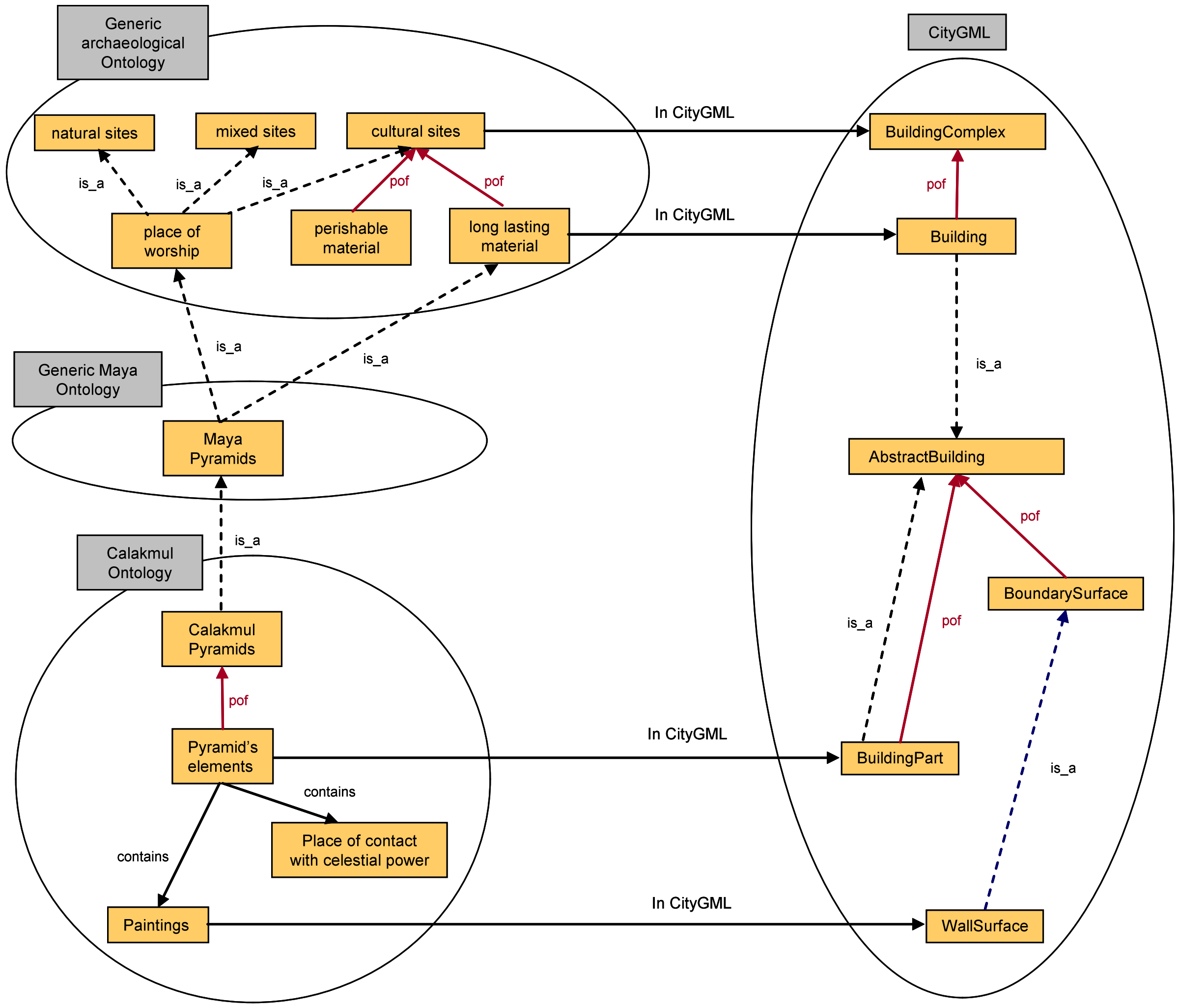

FIG. 11: The different ontologies with their interconnections

5. TOWARDS GENERIC MODELS BASED ON URBAN ONTOLOGIES

Based on our experience, it becomes clear that developing a unique universal urban model is impossible; urban reality perception is diverse and multiple. On the other hand, developing isolated models for each application is unconceivable. The solution we have adopted for interconnecting urban information can be generalised for interconnecting models by means of ontologies in order to gradually build a strongly interconnected set of models representing different perceptions of an urban environment. Such an interconnected set of models could be built around the CityGML model, as proposed on Fig. 12.

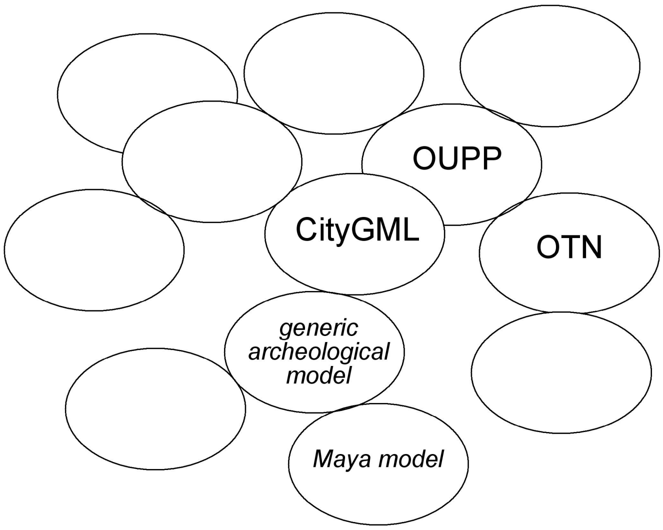

FIG. 12: A set of models around CityGML

However, to ensure a strong interconnection between those models, rules must be adopted. Models should conform to existing standards when available and applicable, for example ISO or OGC geometric features. Beyond comprehensive feature data catalogues, it is crucial to have detailed semantic descriptions of modelled objects to avoid semantic heterogeneity issues. Each database model ontology must be provided together with, if possible, links to existing application and domain ontologies. The more central (or connected) in the set is a model, the more strongly described it must be. In our example, if elements of the Maya model change, this change does not have any impact on the other connected models. However, a change of some CityGML object definitions could have a huge impact on model interconnections.

Building such a set of interconnected models allows for processing specific queries: for example, combining soft mobility and public transportation for routing purposes or exploring buildings that had worship function in Maya's culture (see Fig. 13).

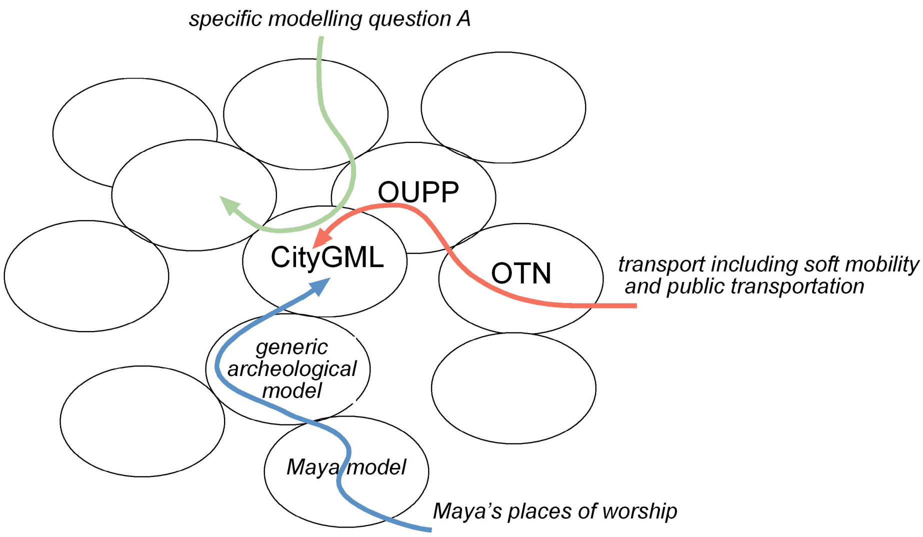

FIG. 13: Towards an interconnectet set of models around CityGML

CityGML seems to be a good candidate as a central model dealing with urban fabric and geometry. However, it shows some conceptual drawbacks which should be overcome. As mentioned above, models must be strictly described to allow a high level of interaction. Ideally, they should be associated with a meta-model enabling a clear and strict model definition. It is not to date the case of CityGML. A solution would be to strengthen the ontological bases of CityGML as proposed by Billen (Billen et al, 2008). In this position paper, the authors show that some CityGML's objects could be retrieved from the associated hierarchical meta-model.

6. ISSUES AND PERSPECTIVES

In this paper, after a short presentation of the semantics of CityGML, we have described some case studies integrating urban information, more particularly the kind of urban information necessary to explicitely and formally define ontologies as well as the resulting models and their applications. We have also tried to explain how and why these experiments could be generalised to improve the interoperability of 3D urban information.

Work is currently on-going in this domain, the authors of the paper being working together to build up a representation of the different kinds of urban information that is common and ontology-based. This work implies to rely on a formal and explicit representation of the knowledge embedded in the models.

Another important feature of the models developed is to enable the interoperability of the urban information on the basis of those common representations (Grangel et al, 2007).

All this work can be considered as a first step towards the development of generic models, representing different points of view. It also provides a first stage towards the development of patterns of models that can be tailored to specific needs, thus enabling their use and their adaptation to various specific applications.

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