Ontology-based Models for Improving the Interoperability of 3D Urban Information

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Abstract. 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. 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 models can be interconnected thus increasing the interoperability of urban information.

Keywords. 3D city models, knowledge, ontologies, interoperability, information

1. Introduction

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. CityGML, the newly standard for 3D city models, 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. For example 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. Archaeology is another case where the package of CityGML features does not offer the appropriate tools to incorporate the whole knowledge generated by data.

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 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 necessary to explicitly 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 of 3D urban information.

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 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 [1]. 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). The figure 1 below shows the transportation model of CityGML, as defined in UML (Unified Modeling Language) [2].

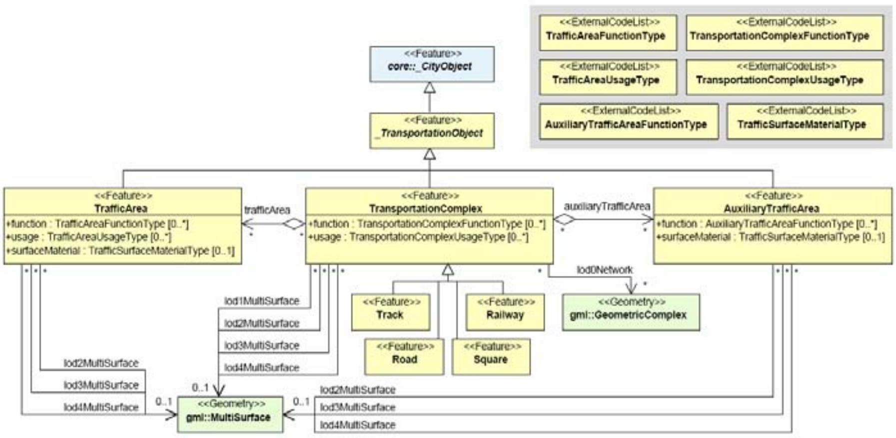

Fig. 1 : UML class diagram of the transportation model in CityGML

In CityGML, the city objects (relief, 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 [3] with the ontology editor Protégé [4]. 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 Model 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 management of communication in 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 Figure 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.

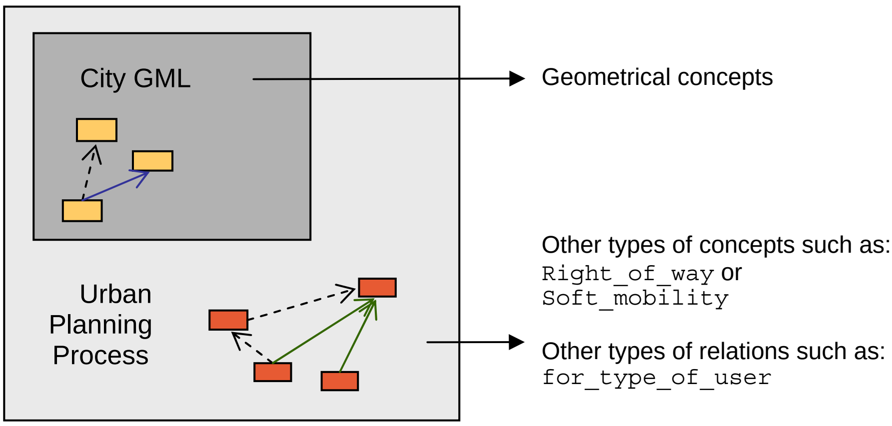

Fig. 2 : Examples of the semantics missing in CityGML

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 [5]. 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 negotiated), 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. The figure 3 below shows (as a graph) the ontology that we have defined for representing soft mobility aspects within OUPP.

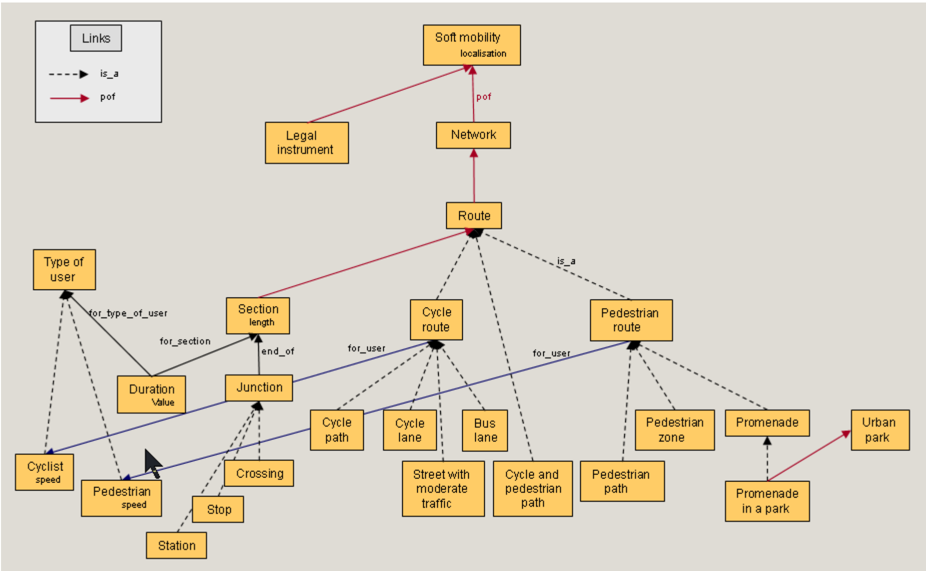

Fig. 3 : Part of the ontology of soft mobility

We then coded the ontology using the OWL language with the editor Protégé (see the Figure 4). 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) [6]. 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 the Figure 5.

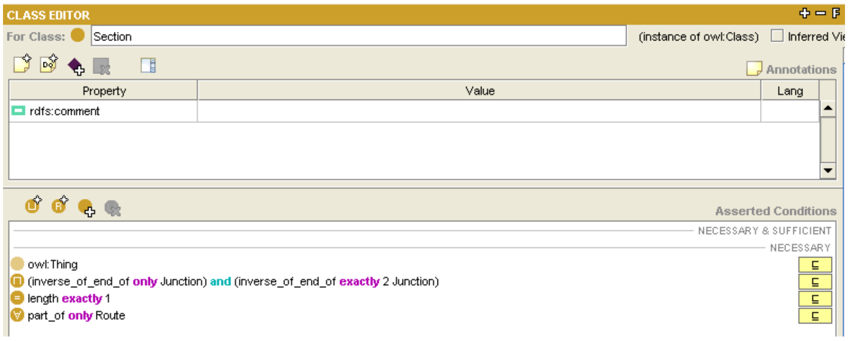

Fig. 4 : Part of the ontology of soft mobility defined in OWL with Protégé

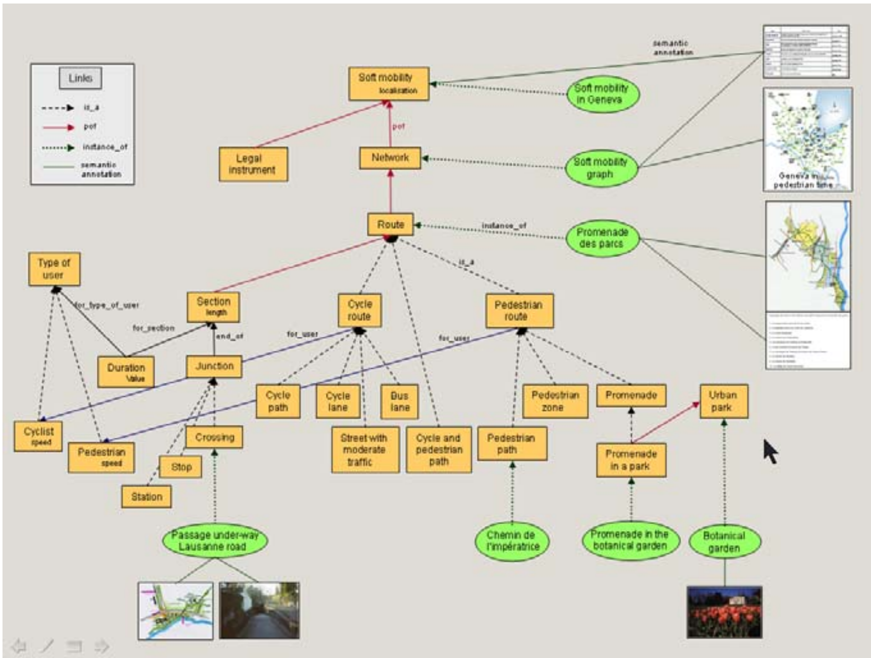

Fig. 5 : Knowledge base of soft mobility in Geneva

As illustrated in the figure 6 below, we performed the **semantic integration** of data and documents of different types, previously disseminated on various sites.

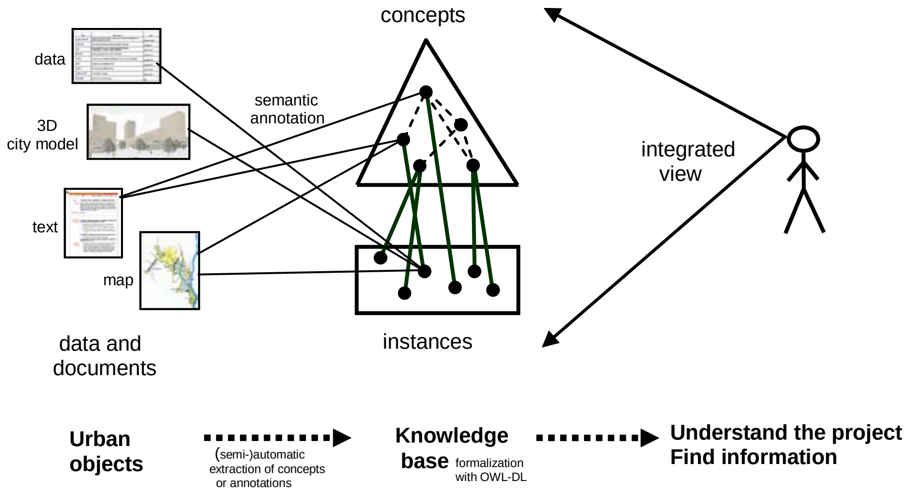

Fig. 6 : Semantic integration of the urban information

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 from the speed of a `Pedestrian` **x** the 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 `TrafficAreas`:

– 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` and `Section` can be connected by a subsumption relation: `Section` $\subseteq$ `TrafficArea`, as shown on Figure 7.

Through the use of the geometry and appearance that are associated to objects in CityGML we can now present the urban information (that has been previously integrated) to the user within a 3D scene. This visualization can be adapted to the profile and the centers of interest of the user [7].

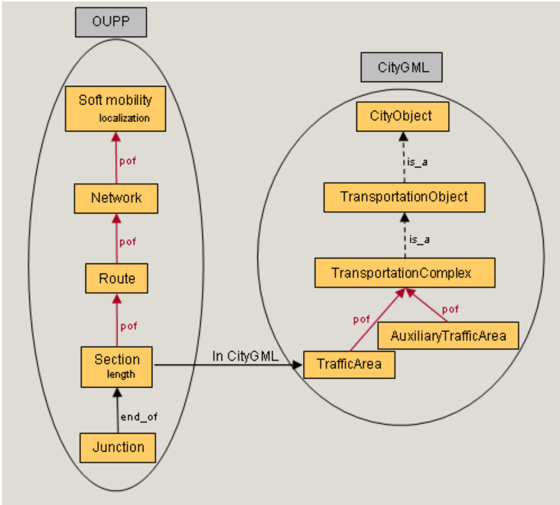

Fig. 7 : Interconnection between OUPP and CityGML

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 [8]. 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. The Figure 8 below shows an excerpt of the OTN ontology represented in OWL with Protégé.

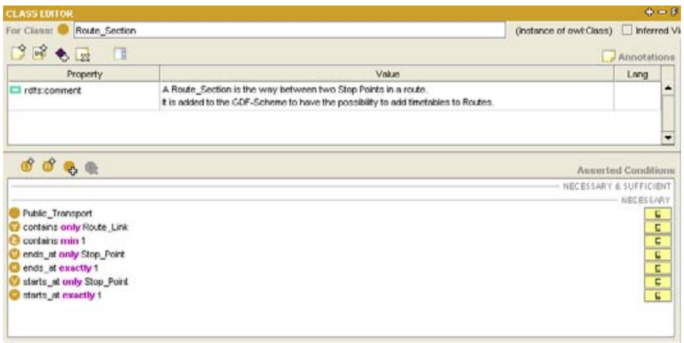

Fig. 8 : Excerpt of the OTN ontology defined in OWL with Protégé

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` ended by `Stop_Points` in OTN, `Routes` composed of `Sections` ended by `Junctions` in OUPP, as shown on Figure 9. The main difference is that OUPP is related to soft mobility issues while OTN represents public transport.

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 associate those concepts to an extra-attribute indicating, at the instance level, whether we are considering soft mobility, public transport or other means of transport or not. When OUPP and OTN are interconnected, it is possible to define routes partly by foot and partly with public transportation systems.

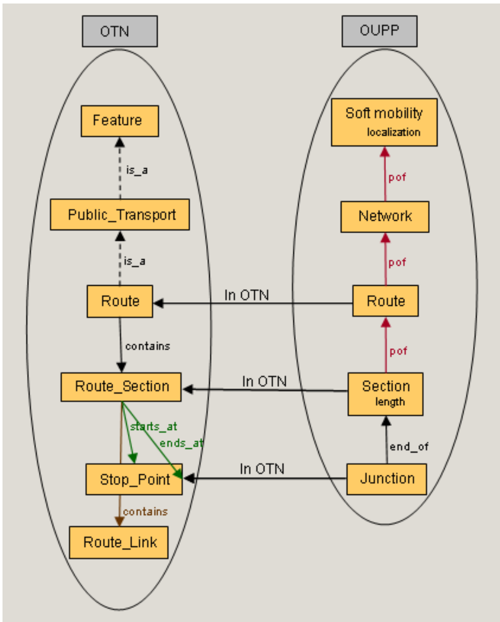

Fig. 9 : Interconnection between OUPP and OTN

3.4 Interconnection between OUPP, OTN and CityGML

With OUPP, OTN and CityGML interconnected (see the Figure 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 `TrafficAreas` is associated to `MultiSurface` geometries.

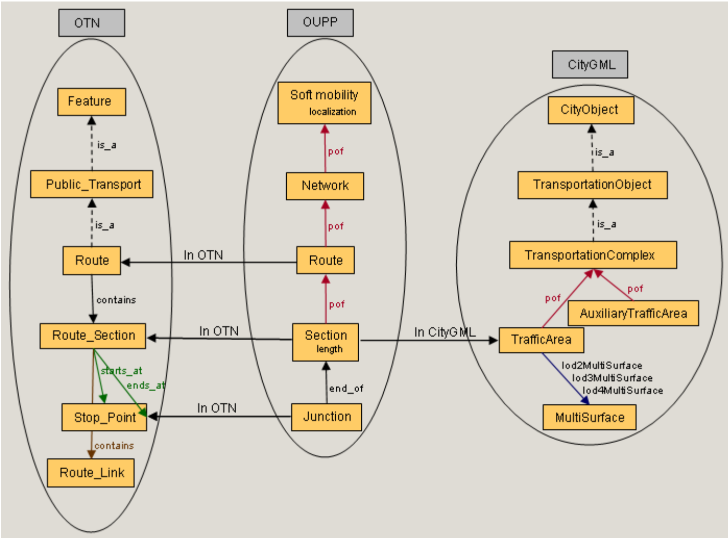

Fig. 10 : Interconnection between OUPP, OTN and CityGML

4. An Ontology-based Model for archaeological purpose

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 other, more recent. Sometimes they have disappeared. Besides, archaeological data are known for their complex semantics. 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 [9]. For this reason, we believe that 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 has been adopted in the case of the Structure II Sub C of Calakmul (Yucatan, Mexico) (see Figure 11). It is the oldest building of a very important Maya city, founded during the Late Pre-classical period (between - 300 and + 250) and left at the beginning of Post-Classic (at the end of the 1st millenary). This building consists in two superimposed platforms, on which a space decorated with red stuccos rests. A monumental central staircase, surrounded by macaroons, goes to a large vaulted room, the only example of barrel vault known for all Maya architecture.

Lastly, a summit crest probably tops it off. For the current specialists of Maya world, this building giving off monumentality and verticality is interpreted like a temple - mountain. The macaroons feature the supernatural powers, undoubtedly of the gods. The vaulted room symbolizes the *Xibalba* (the infra-world). The crest, an openwork, is designed to create sets of shades and light. In the history of Calakmul, this building certainly played the following role: 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 [10].

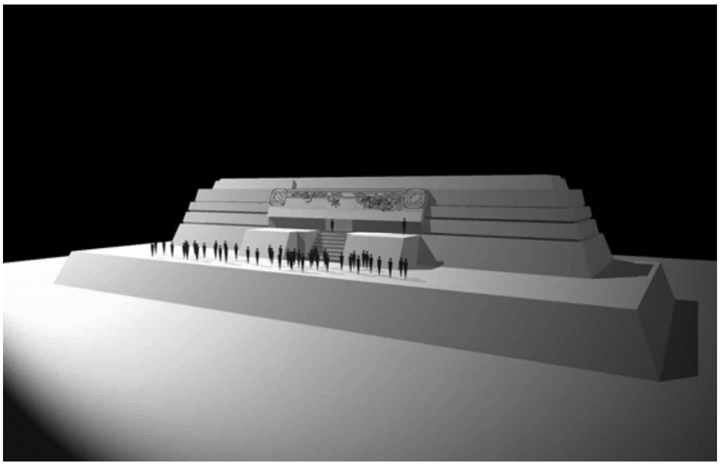

Fig. 11 : A vision, without crest, of the Structure II Sub C of Calakmul
© Massimo Stefani - animasalva@tin.it [11]

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. To illustrate our approach, we consider a schematic semantic net involving a very small number of concepts, see Figure 12. In addition to the link between archaeological concepts, we wish to use existing models, such as CityGML, 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.

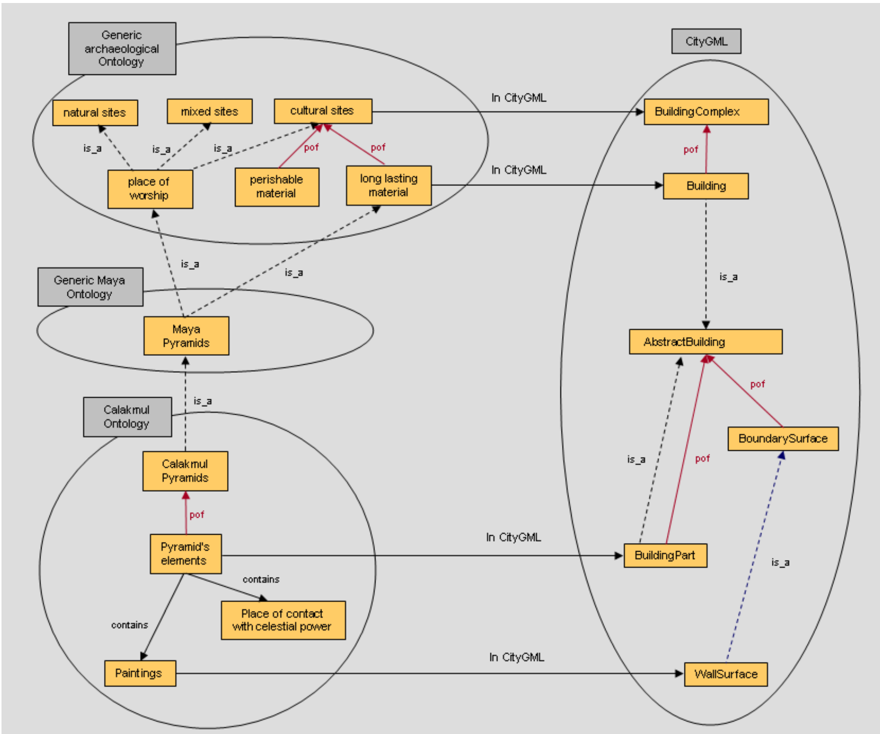

Fig. 12 : Schematic semantic net of the different ontologies

5. Towards Generic Models based on urban ontologies

5.1 Specificities, problems, stakes for the future

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 the OUPP project and the CALAKMULL project can be generalised; interconnecting models by means of ontologies in order to gradually build a strongly interconnected set of models representing different perceptions of urban environment. Such an interconnected set of models could be built around the CityGML model, as proposed on the Figure 13.

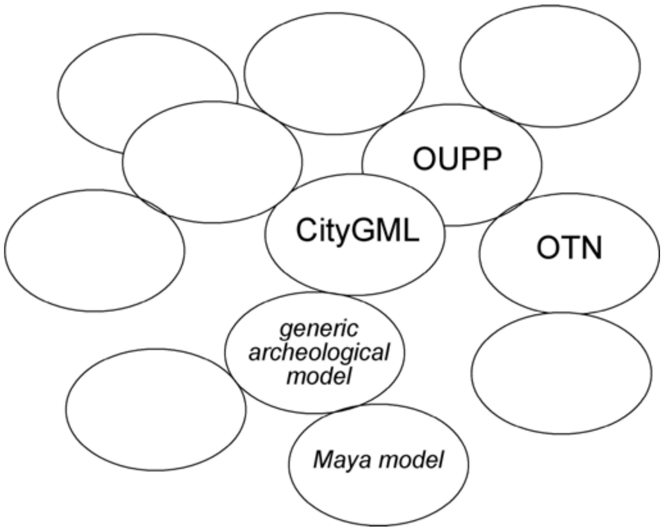

Fig. 13 : A set of models around CityGML

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 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 Figure 14).

CityGML seems to be a good candidate as a central model dealing with urban fabric and geometry. It however shows some conceptual drawbacks which should be overcome. As mentioned above, models must be strictly described to allow for 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 *et al.* [12]. In this position paper, the authors show that some CityGML's objects could be retrieved from the associated hierarchical meta-model.

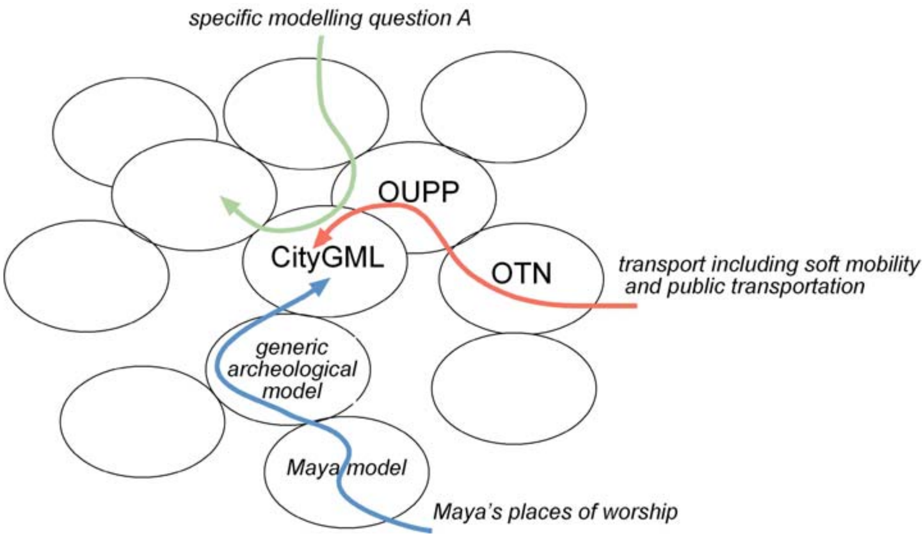

Fig. 14 : Towards an interconnectet set of models around CityGML

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 explicitly 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 are working together to build up a representation of the different kinds of urban information that is common and ontology-based. For this development, they need 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 [13].

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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