# Chapter 7
# Ontologies for Interconnecting Urban Models

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## 7.1 Introduction

Various accurate urban models have been developed and are used in the urban field, to perform for example air quality calculation, building energy consumption or traffic simulation. 3D city models representing the structure of a city in three dimensions are special urban models issued from 3D GIS (3 Dimensional Geographic Information Systems). The use of urban models, particularly 3D city models, is increasing in urban planning. The consequence of an integrated approach in urban planning is the use of different models, most of the time in an interconnected way able to simulate the urban issues together with their inter-relations.

In the first part of the chapter, we will present our needs and expectations in terms of urban information: modelling and interconnection of the information. An important issue related to the representation of urban information is then discussed: the comparison of the role of conceptual schemas and ontologies, since strong links do exist between the two approaches. The chapter then analyses three ontology-based approaches in relation with urban modelling. The interconnection of urban models through ontologies is described in the last part of the chapter and examples are given on the basis of real case studies.

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## 7.2 Urban Information: Modeling and Interconnection Issues

Urban models have a long history beginning in the 1960s. Since this period, the term urban model has usually been 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 et al. 2008), building energy consumption (Jones et al. 2000), water quality calculation (Kianirad et al 2006) or air quality estimation (Moussiopoulos et al. 2006).

3D numerical models generally come from the CAD (Computer-Aided Design) field or from the GIS field as for 3D city models. In the first case they usually have no functionality beyond display while, in the latter case, they can be associated with spatial queries. In fact 3D models are named mock-ups while the term urban models usually refer to dynamic models. 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.

According to the point of view and the purpose, the same reality can give rise to different models: for example a physical or a numerical mock-up, an information model associated with geo-data or a mathematical model of in-play processes represented through differential equations, as shown on the Fig. 7.1 below (issued from a personal discussion with Professor François Golay from EPFL-Switzerland).

If urban models can be seen 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 being directly available within 3D city models while providing results which could, in return, 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. They also allow urban actors to explore the city and to plan it (prior to acting on it) in a more global way.

On the basis of case studies related to the urban field, this chapter will explain how domain ontologies can provide a robust and reusable method to interconnect urban models.

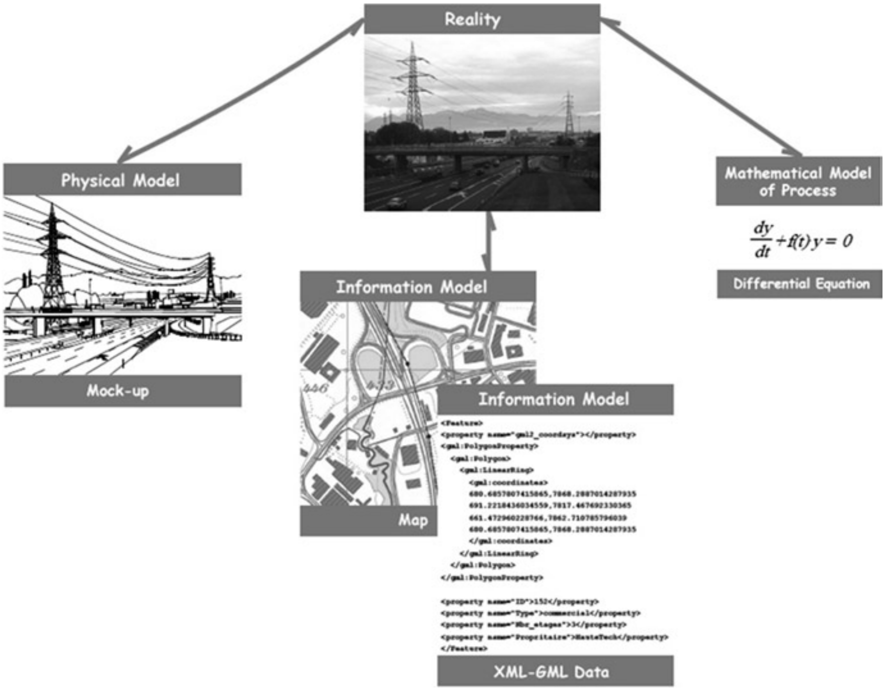


**Fig. 7.1** Different models of different types for the same reality

## 7.3 Urban Information: Ontologies or Conceptual Schemas?

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. If the ontology, based on the user's view of the world, is previously generated and formalised so that it can be used in the development process, such conflicts would be less likely to happen.

On the other hand, the consolidation of concepts and knowledge represented by a conceptual schema can be useful in the initial steps of ontology construction.

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.

In the past few years, since ontologies have gained the attention of the GIS research community (Smith and Mark 1998, 1999, 2001; Smith 1998; Mark 1993; Frank 1997, 2001; Fonseca and Egenhofer 1999; Bittner and Winter 1999; Câmara et al. 2000; (Rodríguez et al. 1999), many researchers have asked themselves whether ontologies were actually the well-known conceptual data modeling techniques in disguise (Winter 2001). Guarino (1998) advises against using ontology as just a fancy name denoting the result of activities like conceptual analysis and domain modelling.

Fikes and Farquhar (1999) consider that ontologies can be used as building block components of conceptual schemas. Fonseca et al. (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.

Ontologies are semantically richer than database conceptual schemas, and thus closer to the user's cognitive model. Conceptual schemas are built to organize what is going to be stored in a database, and then are used to document it. An ontology represents concepts in the real world. For instance, a `reservoir` can be represented differently in diverse databases, but the concept is only one, at least from one community's point of view. This point of view is expressed in the ontology that this community has specified. For instance, a reservoir is a reservoir, regardless of whether it is represented, for the purposes of an information system, by an aerial photograph, a polygon, or a digital terrain model. A conceptual schema that intends to capture all the peculiarities of geographic data should specify differently each of the three representations.

For the same author, this debate on the differences between ontologies and conceptual schemas was partially motivated by the lack of practice in the use of ontologies for real-world problem solving, along with the scarcity of consistent ontologies. In fact, the theory on the use of ontologies is being developed with the broader intention of providing a basis for knowledge consolidation and exchange, a goal that is far beyond the capabilities of current data modelling tools and techniques. Generally speaking, conceptual schemas correspond to a certain level of knowledge formalisation, even though they discard a number of concepts and ideas about which the data modeler and the user have agreed upon. On the other way, ontologies facilitate the integration, in the model, of background knowledge about the entire information systems development process. In this chapter, and in order to keep a track of this background knowledge, we will work on ontology-based approaches and on an interconnection of models based on ontologies.

## 7.4 Interconnection of Urban Models Through Ontologies

An ontology-based approach for interconnecting urban models is described in the following sections of this chapter. The general methodology can be summarized in two main steps:

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

The following sections present 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.

## 7.5 Creation of the Ontologies

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

### *7.5.1 Ontology of CityGML*

CityGML is an open information model for the representation and exchange of virtual 3D city models on an international level (OGC 08–007 2008). CityGML defines the most relevant features in cities and regional models with respect to their geometrical, topological, semantical, and appearance properties such as:

– the terrain (named as `Relief Feature`),
– the coverage by land use objects (named as `Land Use`),

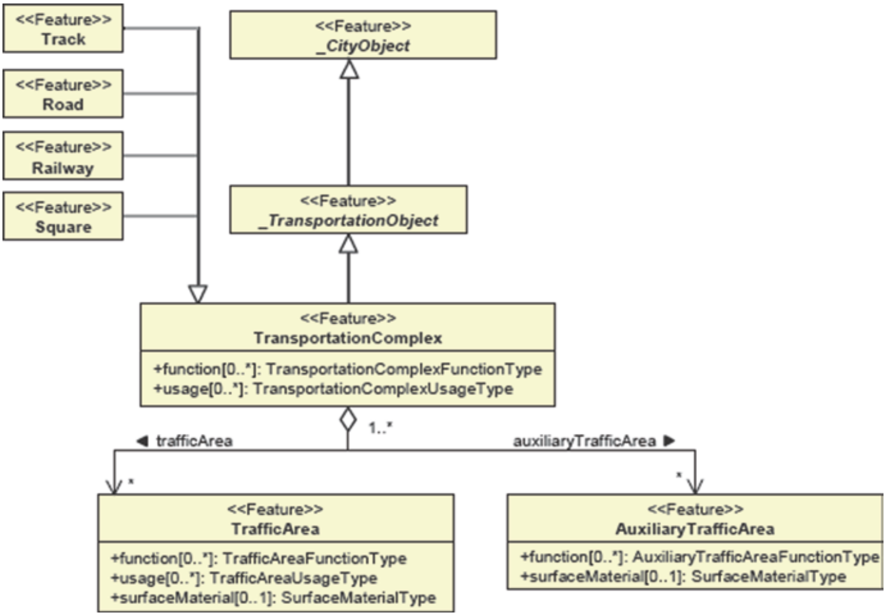


**Fig. 7.2** Part of the UML diagram of the transportation feature of CityGML

– 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 7.2 shows a part of the UML diagram of CityGML.

As we can see, 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;

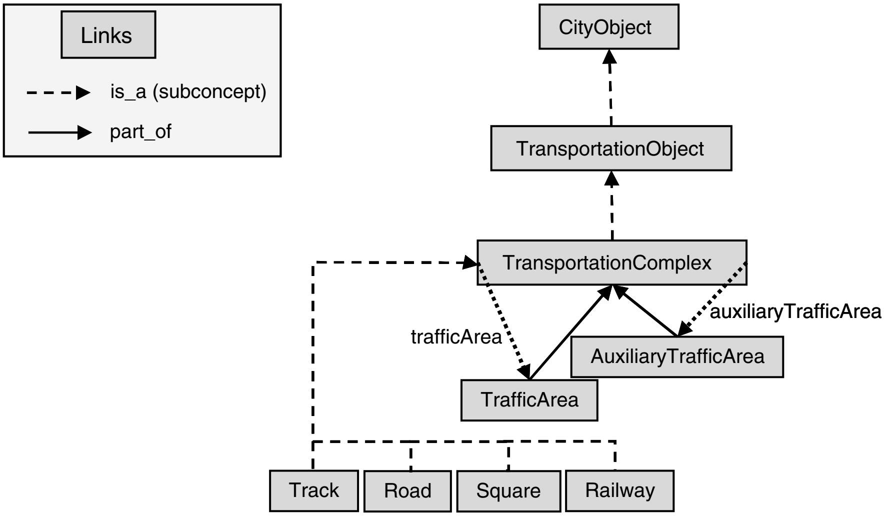


**Fig. 7.3** Part of the ontology of the transportation feature of CityGML

- 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 class attributes will be translated either into concept attributes or into relations between concepts.

Figure 7.3 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 class attributes have been translated:

- `function` as a relation between `TransportationComplex` and `Transportation-ComplexFunctionType` itself defined as a concept;
- `surfaceMaterial` also as a relation between the concepts `TrafficArea` and `TrafficSurfaceMaterialType` but with the following restriction: a `TrafficArea` has at most one `TrafficSurfaceMaterialType`.

### *7.5.2 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. To define this ontology we have used the method proposed by

Uschold and King (1995) extended by Uschold and Grüninger (1996). This method is composed of four phases: (1) identify the purpose of the ontology, (2) build it, (3) evaluate it, (4) document it.

#### 7.5.2.1 Identification of the Purpose and the Scope of the Ontology

In this phase we have to define the purpose of the ontology.

In our case and as described in (Métral et al 2009b) the purpose is to promote such a way of travelling. 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.).

#### 7.5.2.2 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.

Ontology Capture

This means identify 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 Grüninger (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 were 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`.

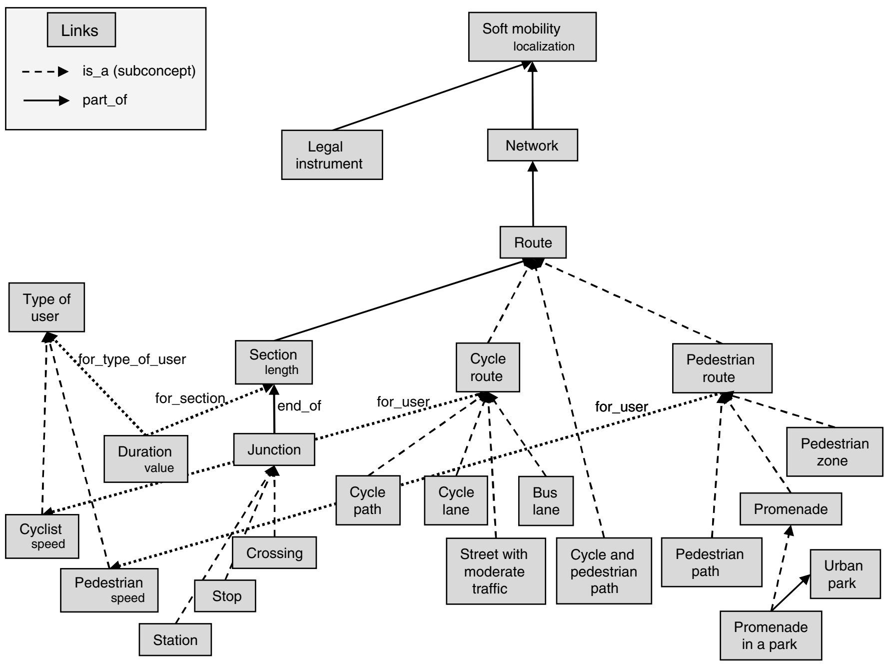


**Fig. 7.4** Part of OUPP related to soft mobility aspects

Then the different kinds of Routes (Cycle_route, Pedestrian_route, etc.) and the different kinds of Junctions (Crossing, Stop, etc.) were defined.

## Ontology Coding

As quoted by (Gómez-Pérez 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 Fig. 7.4 below shows as a graph the ontology defined for representing soft mobility aspects within OUPP.

## Integration of Existing Ontologies (If Any)

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.

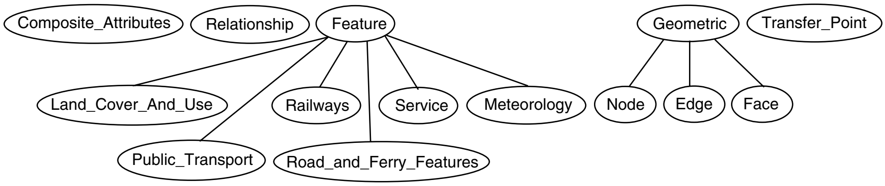


**Fig. 7.5** Basic classes in OTN

In our case study, an Ontology for Transportation Systems (OTN) was identified (Lorenz et al 2005). The main classes in OTN are shown in Fig. 7.5 above:

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 (see next section).

#### 7.5.2.3 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.

#### 7.5.2.4 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. Furthermore a knowledge base composed of the source documents associated with the ontology is on-going.

### *7.5.3 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 and Kim 1999), (Huang et al 2000), there exists some three-dimensional models such as (Kim and 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. The Fig. 7.6 below shows it in a graph form.

All those ontologies have been coded into OWL using the Protégé editor.

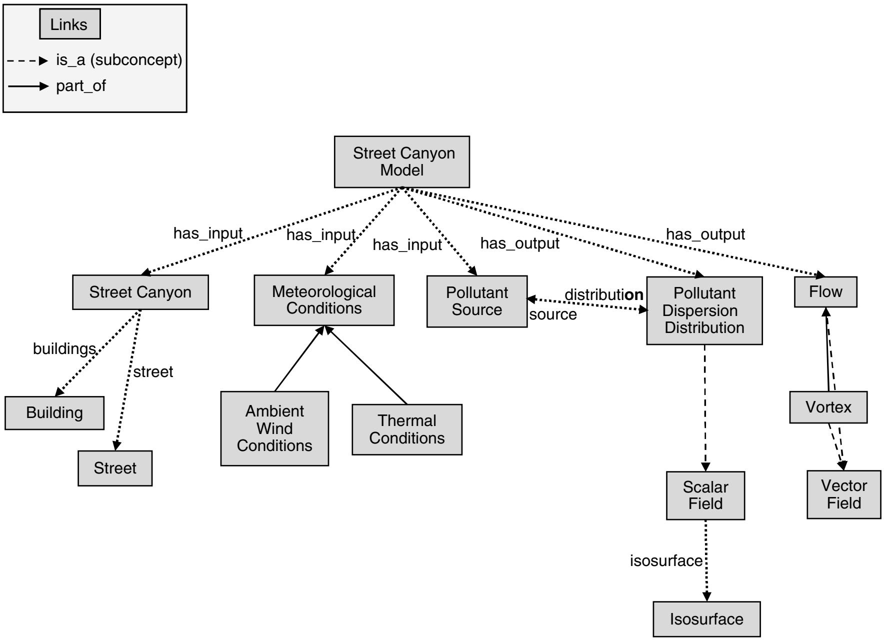


**Fig. 7.6** Part of the ontology of a Street Canyon Model

## 7.6 Interconnection of the Ontologies

In the simplest 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.

### *7.6.1 Simple Case: Direct Interconnection*

The direct interconnection of ontologies can be done either through an equivalence link or through an inclusion link. Figure 7.7 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`

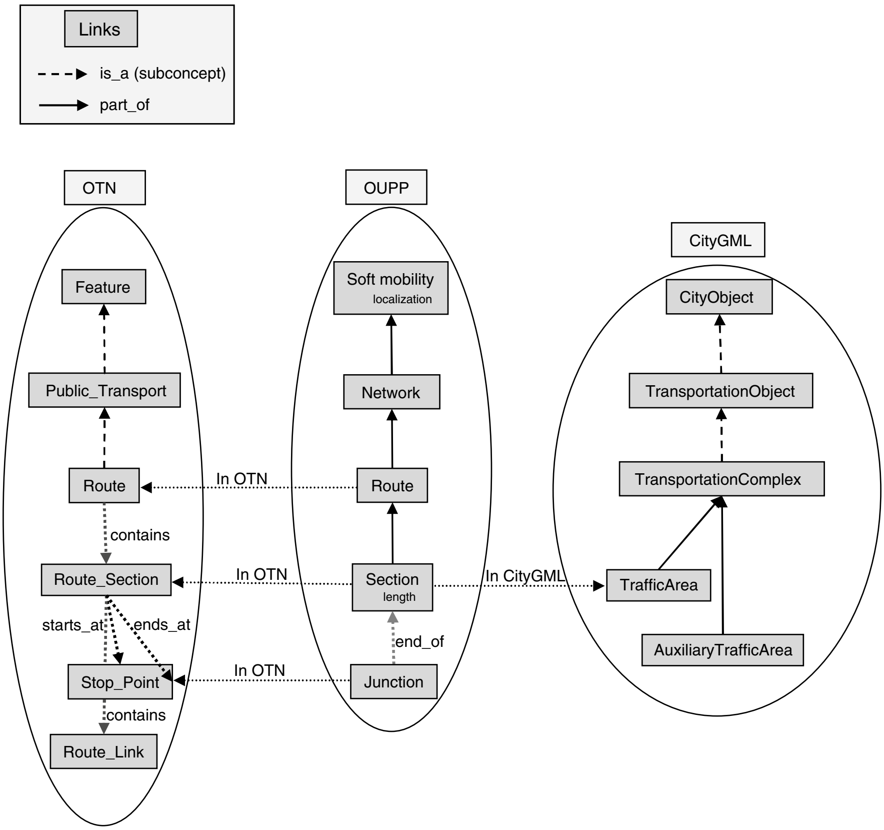


**Fig. 7.7** Direct interconnection of ontologies

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.

### 7.6.2 *Complex Case: Interconnection Through an Articulation or Mediator Ontology*

Some approaches such as (Mitra et al 2000) propose the construction of articulation ontologies where articulation rules (implications between concepts of the two ontologies) describe the semantic relationships between the two source ontologies. These articulation rules are generated using a semi-automatic articulation engine with the help of a domain expert then translated into yield concepts in an articulation ontology and semantic implication edges between the articulation ontology and the source ontologies. The authors also propose functional rules that are intended to normalize values expressed in different systems of measurement. Other approaches such as (Métral et al 2008) extend the previous approach by defining a mediator ontology containing either interconnection concepts that may have different types of semantic links with the source ontologies, or true concepts that may not exist in the source ontologies. These approaches can support sophisticated interconnection patterns between urban ontologies, and formally define them. In addition, they are particularly suited to ontologies that are developed and maintained independently, as this is usually the case for urban ontologies.

As an illustration of this method, we will present here the interconnection of an air quality (AQ) model with CityGML (CGML), which is a complex interconnection involving computations and aggregations. Here are the main phases to define this interconnection:

A concept instance in an ontology corresponds to a set of concept instances in the other one. For example a Street_Canyon in AQ exists only if, in CGML, there is a Road bordered by Buildings in a particular configuration:

```
OUPP:Street_Canyon
    in_AQ            a AQ:Street_Canyon
    street       a CGML:Road
    buildings_1  a set of CGML:Building
    buildings_2  a set of CGML:Building
```

where buildings_1 and buildings_2 refer to the set of buildings that border the street on both sides.

Furthermore, these `buildings` must be continuously aligned:

```
for all s in OUPP:Street_Canyon
  for all x in s.buildings_1
    borders(x,s.street)
  and for all y in s.buildings_2
    borders(y,s.street)
  and continuously_aligned (s.buildings_1)
  and continuously_aligned (s.buildings_2)
```

where `borders` and `continuously_aligned` are geometric predicates.

In addition, the properties of concepts in AQ can be computed from the properties of concepts that exist in CGML.

For example, the `height-to-height ratio` of a `Street_Canyon` in AQ can be computed from the properties defined in CGML and by defining a function named `average_height`:

```
for all s in OUPP:Street Canyon
  s.in_AQ.height-to-height_ratio=
  average_height(s.buildings_2)/
    average_height(s.buildings_1)
```

where:
`in_AQ=a AQ:Street Canyon`
`average_height` is a geometric predicate
`buildings_2` and `buildings_1` refer respectively to the buildings on the windward side and the buildings on the leeward side of the canyon.

Figure 7.8 below shows an illustration of this complex interconnection pattern.

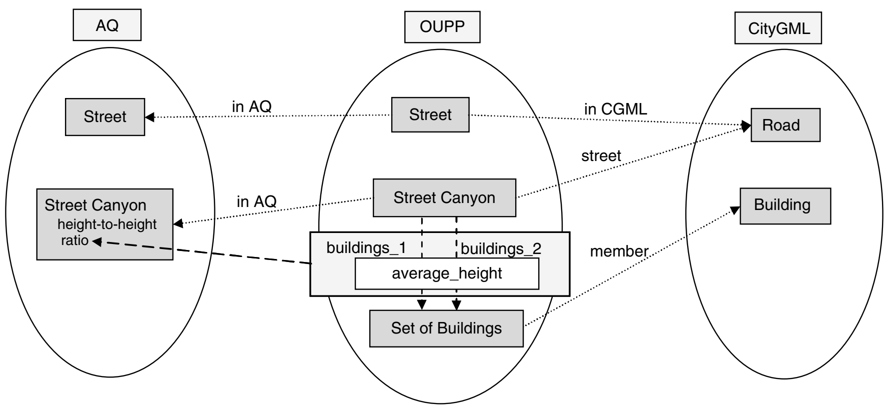


**Fig. 7.8** Interconnection of ontologies performed through a mediator ontology

## 7.7 Open Problems and Research Challenges

Despite the significant number of research activities in this domain, a number of problems still remain open – thus creating important challenges in terms of research opportunities.

Among the open issues, we can mention:

- the big diversity of languages, formalisms, methodologies and tools that can be used to express and to formalise ontologies, most of them being neither equivalent, nor even compatible (see the COST TU0801 project wiki : http://isis.unige.ch/semcity/);
- numerous research papers refer to ontologies, either specific to a domain, or else more generic ; some of them are data ontologies, others are process ontologies. However most of the ontologies mentioned in those papers cannot directly be used for interconnection purposes, since the concepts developed remain theoretical and abstract, and the ontologies often kept at a basic level of description;
- the interconnections between models can be difficult to set up into details, in particular when correspondences between concepts are not one-to-one or else when the interpretation of the terms used is ambiguous. The expression of instance matching and adaptation can also be difficult to perform;
- in the urban field we can have, in both ontologies, similar concepts referring to the same real object but with different geometrical representations (plane representations, 3D, B-REP, CSG, … ) or when different representation scales are used without being explicitly mentioned.

Based on the previous issues, several research themes can be proposed, among which we will mention – without any attempt to sort them out between more theoretical or more applied topics:

- the elaboration of real ontologies relevant to the domains of urbanism, urban planning and urban management, fully documented and formalised;
- a comparison of ontology tools based on the development of urban ontologies, thus enabling the user to find out the tools that are more suited to the urban sector. This comparison can also help to highlight or to define the tool functionalities that are really useful for the urban domain;
- the development of domain-specific ontological languages, in particular of graphical languages able to visualise the geometrical aspects of the concepts;
- the development of tools facilitating the measure of the geometric heterogeneity, thus leading to better and more reliable alignment processes specific to urban ontologies;
- an analysis of the paradigm of data ontologies, process ontologies, domain ontologies and foundational ontologies, with their domain of interest, their benefits/drawbacks and the best use that can be made for each of them in an urban project – which of them is the most suited to the kind of use that is planned.

## 7.8 Conclusion and Perspectives

Integrating or interconnecting urban data or information is a crucial problem, 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 conceptual model-based and ontology-based approaches, an ontology-based approach has been described to interconnect urban models and information. 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 3 dimensions soft mobility routes or routes accessible partly by foot and partly with public transportation systems;
– compute the duration of a particular route for a type of user (see (Métral et al 2009a));
– visualize within 3D city models based on CityGML the pollution induced by vehicle traffic in street canyons;
– identify the best positioning of a sidewalk or a cycle path, for example;
– visualize within 3D city models based on CityGML the decrease of pollution induced by the travelling of n vehicles replaced by soft mobility travelling.

As this methodology is not related to one kind of model, it can be used for multiple interconnections of urban models, for example transportation or building energy consumption models.

It is the first step towards what can be called semantically enriched 3D city models (based on CityGML) with an improved semantics and thus an improved adequacy to urban planning purpose (see (TU0801 2008)).

## References

Anselin, L.: What is special about spatial data? Alternative perspectives on spatial data analysis. NCGIA, Santa Barbara (1989)

Baik, J.-J., Kim, J.-J.: A numerical study of flow and pollutant dispersion characteristics in urban street canyons. J. Appl. Meteorol. **38**(11), 1576–1589 (1999)

Bishr, Y.A., Kuhn, W.: Ontology-based modelling of geospatial information. In: AGILE Conference on Geographic Information Science, Helsinki, 2000

Bittner, T., Winter, S.: On ontology in image analysis in integrated spatial databases. In: Agouris, P., Stefanidis, A. (eds.) Integrated spatial databases. Digital Images and GIS. Lecture Notes in Computer Science, vol. 1737, pp. 168–191. Springer, Berlin (1999)

Câmara, G., Monteiro, A., Paiva, J., Souza, R.: Action-driven ontologies of the geographical space: beyond the field-object debate. In: GIScience 2000, First International Conference on Geographic Information Science, Savannah, 2000

Cui, Z., Jones, D., O'Brien, P.: Semantic B2B integration. Issues in ontology based applications. ACM SIGMOD Rec. Web Edn. **31**(1), 43–48 (2002)

Egenhofer, M.: What's special about spatial? Database requirements for vehicle navigation in geographic space. SIGMOD Rec. **22**, 398–402 (1993)

Fikes, R., Farquhar, A.: Distributed repositories of highly expressive reusable ontologies. IEEE Intell. Syst. **14**, 73–79 (1999)

Fonseca, F., Egenhofer, M.: Ontology-driven geographic information systems. In: 7th ACM Symposium on Advances in Geographic Information Systems, Kansas City, 1999

Fonseca, F., Davis, C., Camara, G.: Bridging ontologies and conceptual schemas in geographic applications development. Geoinformatica **7**(4), 355–378 (2003)

Foot, D.: Operational urban models: an introduction. Taylor & Francis, London (1981)

Frank, A.: Spatial ontology. In: Stock, O. (ed.) Spatial and temporal reasoning, pp. 135–153. Kluwer, Dordrecht (1997)

Frank, A.: Tiers of ontology and consistency constraints in geographical information systems. Int. J. Geogr. Inf. Sci. **15**, 667–678 (2001)

Gómez-Pérez, A., Fernández-López, M., Corcho, O.: Ontological engineering. Springer, London (2004)

Guarino, N.: Formal ontology and information systems. In: Guarino, N. (ed.) Formal ontology in information systems, pp. 3–15. IOS Press, Amsterdam (1998)

Huang, H., Akutsu, Y., Arai, M., Tamura, M.: A two-dimensional air quality model in an urban street canyon: evaluation and sensitivity analysis. Atmos. Environ. **34**(5), 689–698 (10) (2000)

Jones, P., Williams, J., Lannon, S.: Planning for a sustainable city: an energy and environmental prediction model. J. Environ. Plann. Manage. **43**(6), 855–872 (2000)

Kianirad, E., Bedoya, D., Ghosh, I., McGarvey, K., Novotny, V.: Review of watershed ecological models. Technical report no 7, Center for Urban Environmental Studies, Northeastern University, Boston. www.coe.neu.edu/environment/DOCUMENTS/TR-7-Review%20of%20Watershed%20Ecological%20Models.pdf (2006). Accessed 31 Jan 2011

Kim, J.-J., Baik, J.-J.: A numerical study of the effects of ambient wind direction on flow and dispersion in urban street canyons using the RNG k–e turbulence model. Atmos. Environ. **38**(19), 3039–3048 (2004)

Lorenz, B., Ohlbach, H.J., Yang, L.: Ontology of transportation networks. In: Lorenz, B. (ed.) Deliverables of the project REWERSE (Reasoning on the Web with Rules and Semantics), REWERSE-DEL-2005-A1-D4. EU FP6 Network of Excellence (NoE). http://rewerse.net/deliverables/m18/a1-d4.pdf (2005). Accessed 31 Jan 2011

Mark, D.: Toward a theoretical framework for geographic entity types. In: Franck, A., Campari, I. (eds.) Spatial information theory. Lectures notes in computer science, vol. 716, pp. 270–283. Springer, Berlin (1993)

Métral, C., Falquet, G., Karatsas, K.: Ontologies for the integration of air quality models and 3D city models. In: Teller, J., Tweed, C., Rabino, G. (eds.) Conceptual models for urban practitioners, pp. 27–42. Società Editrice Esculapio, Bologna (2008)

Métral, C., Billen, R., Cutting-Decelle, A.-F., Van Ruymbeke, M.: Ontology-based models for improving the interoperability of 3D urban information. In: Teller, J., Cutting-Decelle, A.-F., Billen, R. (eds.) Urban ontologies for an improved communication in urban development projects, pp. 69–83. Les Editions de l'Université de Liège, Liège (2009a)

Métral, C., Falquet, G., Cutting-Decelle, A-F.: Towards semantically enriched 3D city models: an ontology-based approach. In: Kolbe TH, Zhang H, Zlatanova S (eds.) Academic Track of GeoWeb 2009 – Cityscapes, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS), vol. XXXVIII-3-4/C3, Vancouver (2009b)

Mitra, P., Wiederhold, G., Kersten, M.: A graph-oriented model for articulation of ontology interdependencies. In: Proceedings of Conference on Extending Database Technology 2000 (EDBT'2000), Konstanz (2000)

Moussiopoulos, N., Berge, E., Bøhler, T., de Leeuw, F., Grønskei, K.E., Mylona, S., Tombrou, M.: Ambient air quality, pollutant dispersion and transport models. Report of the European Topic Centre on Air Quality, prepared under the supervision of G. Kielland, Project Manager, European Environment Agency, Copenhagen (2006)

OGC 08-007r1: OpenGIS city geography markup language (CityGML) encoding standard. In: Gröger, G., Kolbe, T.H., Czerwinski, A., Nagel, C. (eds.) Open Geospatial Consortium. www.opengeospatial.org/standards/citygml (2008). Accessed 31 Jan 2011

Rodríguez, A., Egenhofer, M., Rugg, R.: Assessing semantic similarity among geospatial feature class definitions. In: Vckovski, A., Brassel, K., Schek, H.-J. (eds.) Interoperating Geographic Information Systems – Second International Conference, INTEROP'99. Lecture Notes in Computer Science, vol. 1, pp. 1–16. Springer, Berlin (1999)

Santiago, J.L., Martilli, A., Martin, F.: CFD simulation of airflow over a regular array of cubes, Part I: Three-dimensional simulation of the flow and validation with wind-tunnel measurements. Bound. -Lay. Meteorol. **122**(3), 609–634 (26) (2007)

Smith, B.: An introduction to ontology. In: Peuquet, D., Smith, B., Brogaard, B. (eds.) The ontology of fields, pp. 10–14. National Center for Geographic Information and Analysis, Santa Barbara (1998)

Smith, B., Mark, D.: Ontology and geographic kinds. In: International Symposium on Spatial Data Handling, Vancouver 1998

Smith, B., Mark, D.: Ontology with human subjects testing: an empirical investigation of geographic categories. Am. J. Econ. Sociol. **58**, 245–272 (1999)

Smith, B., Mark, D.: Geographical categories: an ontological investigation. Int. J. Geogr. Inf. Sci. **15**, 591–612 (2001)

TU0801: Semantic enrichment of 3D city models for sustainable urban development. Memorandum of Understanding (MoU). http://w3.cost.esf.org/index.php?id=240&action_number=TU0801 (2008). Accessed 31 Jan 2011

UML-Unified Modeling Language, UML Resource Page. http://www.uml.org/. Accessed 31 Jan 2011

Uschold, M., Grüninger, M.: Ontologies: principles, methods and applications. Knowl. Eng. Rev. **11**(2), 93–155 (1996)

Uschold, M., King, M.: Towards a methodology for building ontologies. In: Skuce, D. (ed.) IJCAI'95 Workshop on Basic Ontological Issues in Knowledge Sharing, Montreal, pp. 6.1–6.10 (1995)

Waddell, P., Wang, L., Liu, X.: UrbanSim: an evolving planning support system for evolving communities. Preprint of paper forthcoming. In: Brail, R. (ed.) Planning support system. Lincoln Institute for Land Policy, Cambridge (2008)

Winter, S.: Ontology: buzzword or paradigm shift in GI science? Int. J. Geogr. Inf. Sci. **15**(7), 587–590 (2001)