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Research Article

Geo-ontology Tools: The Missing Link

Jochen Albrecht
Department of Geography
Hunter College, CUNY

Brandon Derman
Department of Urban Affairs and Planning
Hunter College, CUNY

Laxmi Ramasubramanian
Department of Urban Affairs and Planning
Hunter College, CUNY

Abstract
Numerous authors have presented ontology building tools that have all been developed as part of academic projects and that are usually adaptations of more generic tools for geo-spatial applications. While we trust that these tools do their job for the special purpose they have been built, the GIScience user community is still a long way away from off-the-shelf ontology builders that can be used by GIS project managers. In this article, we present a comparative study of ontology building tools described in some twenty peer-reviewed GIScience journal articles. We analyze them from the perspective of two application domains, crime analysis and transportation/land use. For the latter, we developed a database schema, which is substantially different from the three main templates commonly used. The crime analysis application uses a rule base for an agent-based model that had no precursor. In both cases, the currently available set of tools cannot replace manual coding of ontologies for use with ESRI-based application software. Based on these experiences, we outline a requirements list of what the tools described in the first part of the article are missing to make them practical from an applications perspective. The result is an R&D agenda for this important aspect of GIScience.

1 Introduction

Ontologies are en vogue. Many conferences such as GIScience or AGILE are dominated by ontology papers and most relevant journals have had special issues on this topic. Even trade magazines have jumped onto the bandwagon, and it is now considered to be

Address for correspondence: Jochen Albrecht, Department of Geography, Hunter College, City University of New York, 695 Park Avenue, New York, NY 10065, USA. E-mail: jochen@hunter.cuny.edu

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good practice to develop domain-specific data models by paying at least lip service to the underlying ontology. "Traditional" (what is traditional in a discipline that was virtually non-existent 10 years ago?) ontology building tools such as OilEd, OntoEdit, PowerLoom, Protégé, or WebODE are (1) not geared towards geo-spatial phenomena, and (2) are not exactly aimed at end users such as GIS managers in a regional authority. The situation is similar to the fashion industry, where the models on the runway have little to do with Joe or Jane Public. Even the result is the same, in that we are (all made to) feel bad about our ineptitude to develop sound database and service schemas while we are made to believe that this is what we ought to do.

We now have a generation of peer-reviewed articles that describe ontology building tools for geo-spatial applications and the next section will review them to take stock of what may be regarded as the current state of the art. There is, however, an obvious disconnect between these special purpose built tools and off-the-shelf or preferably public domain ontology builders that can be used by GIS project managers. Section 3 describes two projects, where the authors developed complex schemas that on the one hand are based on very reasonable needs of the practice, while on the other hand are completely beyond the scope of what could be produced by currently existing tools. This suggests a gap in current applied research and we therefore conclude this article with a list of recommendations on how to address this mismatch.

2 State of the Art: In Theory

General purpose ontology builders and editors have matured, at least from an information scientist's perspective (Duineveld et al. 2000, Escórcio and Cardoso 2007). Within academia and in the open source world, Protégé (2007) has become the tool of choice for close to 100,000 registered users, who (in addition to it being free) appreciate its many extensions for different paradigms (frames vs. OWL), multiple APIs, many export formats, and several different editing tools. Originally developed for the medical community, it is now widely used, even in geospatial communities (Souza et al. 2006, Lüscher et al. 2007). However, Protégé has its limitations. As Lüscher et al. (2007, p. 9) point out, "Protégé may be too complex for domain experts". They therefore employed a special user interface for creating spatial patterns. Another issue is that while Protégé is well suited for the development of Semantic Web applications, most GIS are still desktop- or heavy server-based, i.e. they require a database schema. Protégé can read database schemas but the only way to export to them is through XML.

One solution to this is to move to another public domain ontology editor called WebODE (2003). As the name suggests, WebODE is the web-based front-end to what the authors call an Ontology Development Environment (ODE). In its latest incarnation as ODE Semantic Web Services designer (Gómez Pérez et al. 2004a, b), this tool limits itself to the creation of OWL-S services, albeit in a very comfortable manner. Of higher value for our purposes here is the still available version of WebODE 2.0, which exports to a wide range of data exchange standards such as XML, RDF, OWL, Java/Jess, and UML. The latter two can be used then to create database schemas in, for example, Oracle or MySQL (Corcho et al. 2002). This gets us a long way towards linking original geospatial ontology development with the creation of professional GIS database schemata.

2.1 From Ontologies to Spatial Data Models

Database systems can be conceptualized at three different levels: the conceptual, the logical and the physical level (Jardine 1977). Especially in our geospatial application areas, the first of these is often based on a domain ontology that defines concepts and their relationships; the ESRI geodatabase schemas are widely used examples. These conceptual models are usually documented in the form of UML diagrams. At the logical level, the formalized concepts are represented symbolically, for example as objects versus fields. At the physical level, we specify the implementation in form of low-level software structures and data serialization. A crime event may hence be described in formal (legal) terms as a burglary, in logical terms as the intersection of behavioral strains of various actors (the burglar and the victim leaving their house), and in physical terms as an event object that waits to be triggered until the opportunity arises.

Lemmens et al. (2007) and Staub et al. (2008) in this journal, as well as Pundt (2007) describe the process of ontology generation across different abstraction levels. An analysis of this process is complicated by the fact that different authors use ontologies for different purposes, which in turn biases their choice of tools and experiences. Visser et al. (2002), for example, separate different ontology uses into benefits of their application (communication, systems engineering, interoperability), and their purpose (shared vocabularies and conceptualizations, specification of context knowledge, etc.). Staub et al. (2008) expand on Obrst (2006) to discuss an "ontology spectrum" that ranges from taxonomies and thesauri to conceptual models and logical theories. Each level requires additional levels of specificity and eventually larger amounts of user interaction. In other words, depending on what we mean by 'ontology' we may be able to do what is needed with some of the general purpose ontology builders, or we may have to use a whole tool chest of software packages, plus a lot of manual coding.

The range of publication outlets for the description of ontology tools in geospatial applications is fairly limited and can be found first and foremost in this journal, but then also in *Computers, Environment and Urban Systems, the International Journal of Geographical Information Science*, and several online conference proceedings. Of these, most of the authors (e.g. Visser et al. 2002, Linková et al. 2005, Pundt 2007, Lemmens et al. 2007, McCarthy et al. 2008) prefer Protégé over all other tools. This is consistent with the use of ontology editors in general IT (Nieto 2003, Cardoso 2007). Protégé has a wide range of import and export options and a good effort/result ratio, meaning that while it is not the most powerful tool it provides many users with as many capabilities as they need for an acceptable amount of learning. Purists, and information scientists who have experience with knowledge-based systems, prefer OntoLingua (Gruber 1993), which is based on the knowledge interchange format (KIF), which reaches into the top end of the abovementioned ontology spectrum by making use of more contextual information. The discipline is maturing enough to now allow for commercial products such as Altnova™, Ontoprise™, TopBraid Composer™, or SemTalk™, to enter the market; here the learning curve is often less steep and eased with a comfortable user interface – albeit at the price of real dollars or Euros rather than student labor.

However, Cardoso (2007) reports that still four out of five users of ontology editors work in academia, where the working conditions differ considerably from those in non-research oriented companies or public agencies at local or regional levels. It deserves mentioning that the majority of recent articles on ontology building in the recent GIScience literature (Visser et al. 2002, Dolbear et al. 2006, Hart and Dolbear 2006, Lemmens et al. 2007, Staub et al. 2008) originate in Europe and typically involves partnerships between universities and national agencies. They all describe projects involving many person years of effort, where ontology editors, regardless of which ones were employed, cover only a small part of the effort.

One of the reviewers of this article asked for a table that compares various editors by their features. Just limited to the editors themselves, this request is well covered by Duineveld et al. (2000) and more recently Escórcio and Cardoso (2007). However, the discussion above alludes to the fact that an editor is only a small component in the workflow underlying an ontology-driven GIS (Fonseca et al. 2002, Cruz et al. 2005). After looking at another major aspect of ontology building on the immediately following pages, we will therefore work in section 3 through two examples to discuss the gaps in the workflow with ontology building tools.

2.2 Process Model Specifications

GIS is more than just a data repository. As Noy and Guinness (2001) point out, programmers make design decisions based on the operational properties of a class, whereas an ontology designer makes these decisions based on the structural properties of a class. In consequence, we are still short of ontologies of geographic processes, and ontologies are much easier translated into a database schema than into process models – although the most recent crop of articles (Klien and Probst 2005, Lemmens et al. 2007, Peachavanish and Karimi 2007, McCarthy et al. 2008) attempts to address the problem.

Both Protégé and WebODE allow for OWL-S output, i.e. the specification of services, which according to the WorldWideWeb Consortium (W3C 2004) can in turn be modeled as processes. We have, however, yet to see the development of geographic process libraries, notwithstanding the efforts of NASA (Raskin 2004), a few intrepid companies (GOL 2004), and the odd GIScientist (Reitsma and Albrecht 2005, Peachavanish and Karimi 2007), the formal specification of geographic processes is at this point restricted to web services and queries á la Google Maps. This should come as no surprise because the ontology community has not really gone beyond the SNAP/SPAN view introduced by Grenon and Smith (2003). We are still missing a practical ontology of process that is both proven to be formally correct and at the same time well enough developed to reach to the level of real world applications.

The best we have at this point is UML output based on OWL-S encoded ontologies. As mentioned above, (web) services, the usual target of OWL-S ontologies are a far cry from the complexities of desktop-based spatial decision support systems. The best link that these authors have found so far, is a commercial ontology editor called SemTalk (2008). Originally designed for business workflows, it is an OWL interpreter developed as an extension to MS Visio. Formal consistency is assured with the open source OWL reasoner PELLET (2008). Pre-existing ontologies such as SWEET (Raskin 2004) can be imported and form the foundation for subsequent user-defined extensions. One of the advantages of this tool is its relationship with MS Visio, a widespread software package that is also commonly used to define the data models for various ESRI communities (ESRI 2008). This allows for using one and the same tool to define both geospatial data structures and processes. It is no coincidence that SemTalk has been designed for and is most widely used for business process models. In the following, we will revisit the notion of workflows, originally introduced in a GIScience context by Smith et al. (1995) and revisited by Lemos-Dias et al. (2004).

In GIScience, we distinguish between two different notions of 'process' (Albrecht 2008). One is the notion of GIS as a sequence of operations with the goal to fulfill a specific set of tasks. The other is the attempt to represent dynamic geospatial phenomena (Reitsma and Bittner 2003). The dynamic phenomenon aspect was revisited for individual applications (Feng et al. 2004, Raubal and Worboys 1999) but conceptually remains with the representation of processes as a sequence of events (Worboys and Hornsby 2004, Worboys 2005, Galton and Worboys 2005). Medeiros must be credited as being just about the only one who looked beyond the realm of traditional GIScience (Weske et al. 1998, Russell and Norvik 2003, Ghallab et al. 2004) to work with plan synthesis.

Plan synthesis is a mature area in information science, with well-studied algorithms applied to manufacturing processes and emergency management, among others (Munoz-Avila et al. 2001, Nau et al. 2003). Recent research efforts have investigated the use of plan synthesis to solve the problem of automatic composition of web services (Ambite and Kapoor 2007). This requires the consideration of additional factors such as complex control structures with loops, non-determinism and conditionals (Srivastava and Koehler 2003). None of the plan synthesis methods treats complex objects or objects created dynamically.

In contrast to the primitive analysis of user tasks in a GIS workflow (Albrecht 1995) we now find solid applications for different user communities (Jayavarapu 2007) that are based both on a deeper understanding of the communication process (MacEachren et al. 2003) and new standards for business applications (Fillies et al. 2003). Notwithstanding the advent of web and location-based services (Lemmens 2006), much of the GIScience standardization community is still stuck in the surveying perspective (Albrecht 1999). This contrasts with the development of the Object Management Group's business process modeling notation (Thiagarajan et al. 2002, BPMN 2008), which has been widely adopted and could easily be applied to the OGC's information communities (Kottman 1999). A direct outflow of that framework is the XML process definition language (Hollingsworth 2004, WFMC 2008), which together with the asynchronous service access protocol (Ricker et al. 2008, Swenson et al. 2008) forms the basis of Workflow-XML.

Using the BPMN framework, XPDL and Wf-XML are now widely accepted standards that are applied in dozens of software packages such as SemTalk, and are used for the formal specification of workflows in neighboring disciplines such as bioinformatics (Digiampietri et al. 2007). Formally, each of these can be proven using Petri Nets (van der Aalst and Ter Hofstede 2000), which are increasingly being supported/implemented in process modeling software packages.

In the next section, we will discuss two larger application examples, where the authors struggled with the definition of new data and process models. This discussion is intended to illustrate the needs from an applied perspective, in this case two university/public agency partnerships.

3 Practical Experiences Highlighting Gaps between Theory and Practice

This section consists of two parts. In the first, we describe and analyze the needs of an agent-based GIS model developed by Groff and described across a range of publications (Groff 2007a, b; 2008). The emphasis in this discussion is on the formal specification of agent behavior in a geographic context – thereby addressing the process perspective discussed in section 2.2. In the second part, we look at a transportation/land use model developed for a regional planning authority that builds on a new and rather involved database schema beyond the scope of what is publically available in this application domain. In both cases, the authors are forced to manually code their ontologies rather than using any of the above mentioned tools, underlining the assertion made at the end of section 2.1 that the current tools are of limited use in "the real world".

3.1 Formal Specification of Actions in an Agent-based GIS

This model has been described in detail in Groff (2007a, b). We will here instead focus on the process of agent specification, which is the foundation for what eventually was implemented in AgentAnalyst (2008), a Python interface between the agent-based modeling environment Repast (North et al. 2006) and ERSI's ArcGIS. Following the logic of Kuhn (2001) Groff develops a formal framework of agent actions within a well-defined context, in this case crime analysis. 'Context' is a useful feature in database reasoning that allows adding some depth beyond mere descriptors (Visser et al. 2002). But it becomes absolutely essential in the definition of agent behavior when those agents represent human decision making. As Cai (2007, p. 255) describes persuasively, the concept of 'near' is dependent on the context of what mode of travel we are talking about. Analyti et al. (1999) and subsequently Cai (2007) describe how context specifications and ontologies can be linked and Bouquet et al. (2004) have even developed an OWL dialect to accomplish just that, however, there is no tool that the authors of this article are aware of that (1) implements C-OWL and (2) does so with a comfortable user interface. Groff (2008) therefore develops her specifications the way a programmer would: defining in a painstaking iterative process all the variables and actions of the agent-based model (Figure 1) and arranging them in the complex schedule that operates at four different hierarchical levels.

The total model consists of four types of agents (places, citizens, cops, and activity nodes) that perform 35 defined activities based on the state of 64 variables. It took Groff a good year of her PhD to develop this model, which is a lot less than most of the projects described in the cited literature but a lot more than the average GIS consultant or employee in a regional authority could devote. The closest to a tool that assists in the setup of the model logic would be something like Stella® (ISEE 2008) or a UML editor that supports the BPMN framework such as SemTalk. The same tools could also be used for checking the formal consistency of the model. If the agents could be defined within a GIS, then the resulting UML could be used to at least create a database schema. We do not have any tools though that read BPMN notation and translate it into GIS procedures. Jäger et al. (2005) and Bambacus et al. (2007) provide examples of how to do this for semantic web services but neither incorporate domain knowledge (Pike and Gahegan 2006) nor allow access to functional levels of desktop GIS software. As agent-based systems are not yet a feature of GIS but exist only in a coupled environment, we would have to follow the path mapped by Endert et al. (2007) to theoretically relate BPMN to a highly abstract definition of (JIAC) agents. This is not particularly practical either though; to quote Endert et al. (2007, p. 55):

> "Since there is no XML schema or similar given for BPMN, the editor's domain model had to be created from scratch and thus is not compatible with other

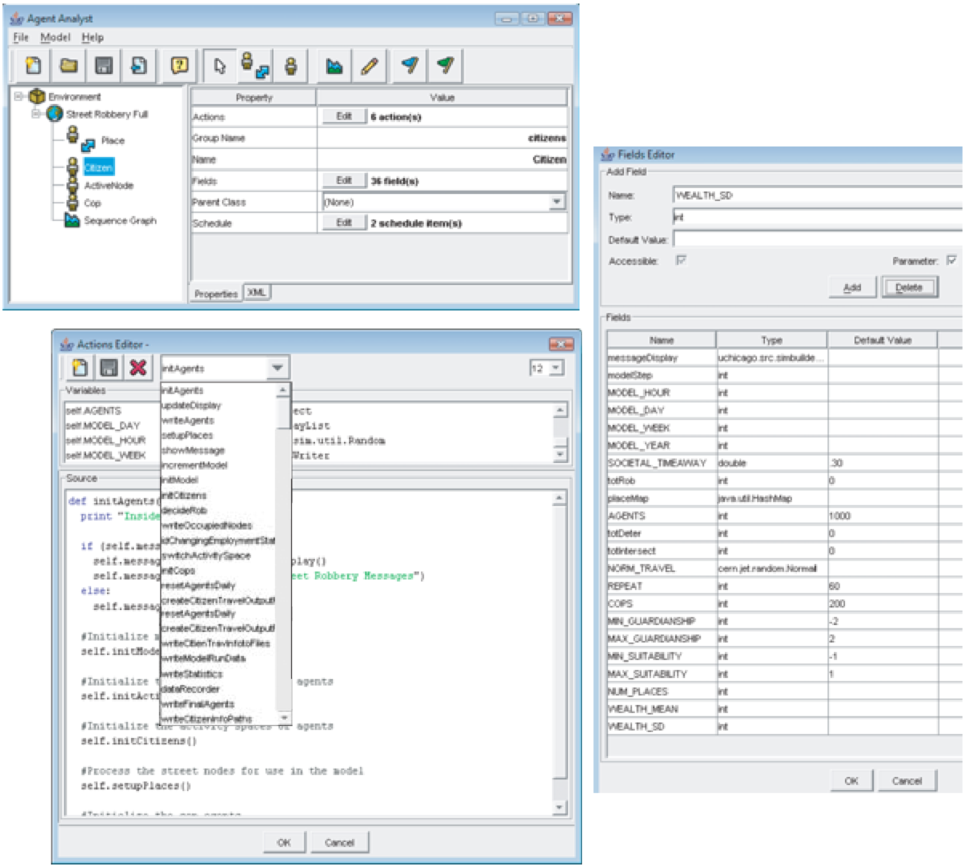

Figure 1 Top-level view of the variables and activities of a street robbery model. The Edit buttons in the top left window open the respective Actions and Fields (variable) editor windows displayed on the bottom and right. The Actions Editor in turn creates the stubs for Java classes and methods

> BPMN editors" . . . (and) . . . "Although the mapping from BPMN to JIAC is not yet fully specified and there is still some work to do to support the transformation of unstructured workflows, the basics are working fine and simple BPMN diagrams can be transformed to JIAC multi-agent systems".

On an earlier page, we argue that agents are supposed to act depending on context and introduced the notion of context ontologies. From a developer's perspective however, this context quickly gets out of hand because of the combinatorial explosion of possible situations among the many dimensions that Groff's model spans. A more practical solution is described by Ali et al. (2007) who address this problem with a spatial variant of an online analytical process (OLAP) to keep track of the complexities in the real-time analysis of their multi-agent geosimulation software decision making process. This takes care of some of the implementation issues but leaves the question of ontology-based design tools that this article is about unresolved.

3.2 Formal Specification of a Land Use-based Transportation Model

The second model to be discussed here has not yet been released to the general public and the description is purposefully general as to not identify the agencies involved. The goal of this spatial decision support system (SDSS) is to model existing flow in a multimodal network and to find optimal locations for a transit hub based on existing parcel-level land use. The resulting geodatabase (all vector data) is approximately 2 GB in size, and the procedures of the SDSS combine many hundreds of GIS operations for a single model iteration. A top view of the underlying database schema is depicted in Figure 2, while Figure 3 provides a superficial view of the geoprocessing model.

At first sight one would think that a land use-based transportation model is a lot easier to develop than the agent-based model described above because everything can be implemented under the hood of a single software package such as ArcGIS. GIS databases are often treated as mere repositories that once created are frozen in time and form a stable basis for subsequent analysis. The efforts of creating a database are hence neglected in the academic literature (notwithstanding publications on management (Huxhold and Levinsohn 1994, Tomlinson 2003, Watson 2005, Obermeyer and Pinto 2007, Yeung and Hall 2007), metadata (Williamson et al. 2003, Nogueras-Iso et al. 2005, Wootton 2007) or spatial decision support (Geertman and Stillwell 2002).

Similar to the crime model of the previous section although not at the fine-grained individual level of perpetrators and victims, our model *structure* is dynamically changing as we run the model. For instance, the choice of a commuter's mode or route is influenced by how many other commuters crowd one's first or second option. Many train riders in Seattle, for example, are familiar with the added number of passengers when flooding closed a highway during exceptional rainstorm in fall of 2007. The same happens on a smaller but cumulatively as effective scale every day in metropolitan areas around the world. From an abstract perspective, the phenomenon is well studied and has become a popular example in complexity theory (Qiu et al. 2000, Shen et al. 2005; Selçuk 2007). As a matter of fact, it is one of the hallmarks of complexity theory (Gimblett 2002) that its objects arise from innocent looking simple setups. With the exception of a draft paper by Line (2004), there is no ontology of complex systems and we are left with basic tools such as the Unified Modeling Language (Tsang et al. 2006), which lacks the mechanisms to deal with complex systems.

Still, the outlook is not as bleak as it is for the attempt to find a working environment for the development of a multi-agent GIS. At least for the development of database schemas we now have comfortable tools that create UML code that can be used to automatically generate the desired schemas. Using BPML-aware editors, we can even generate process models that at least from a conceptual modeling perspective allow for comfortable model development and consistency checking. As mentioned above, however, there is currently no interface to any of the mainstream GIS software packages and there is no reason to expect manufacturers to jump into the gap because we are lacking application schema standards (ISO 19109 2005) at this higher level. The GML (OGC 2007) is at least a common denominator but has no chance to cover the wide range of functionality that a standard desktop GIS offers. The proliferation of add-on packages such as CityGML (OGC 2008), LandGML, etc. serves as an indicator, although recent developments such as a schema definition for moving features (ISO 19141 2008) promise interesting perspective in the long run.

This then leads us to a call for an applied research agenda that we outline in the concluding section.

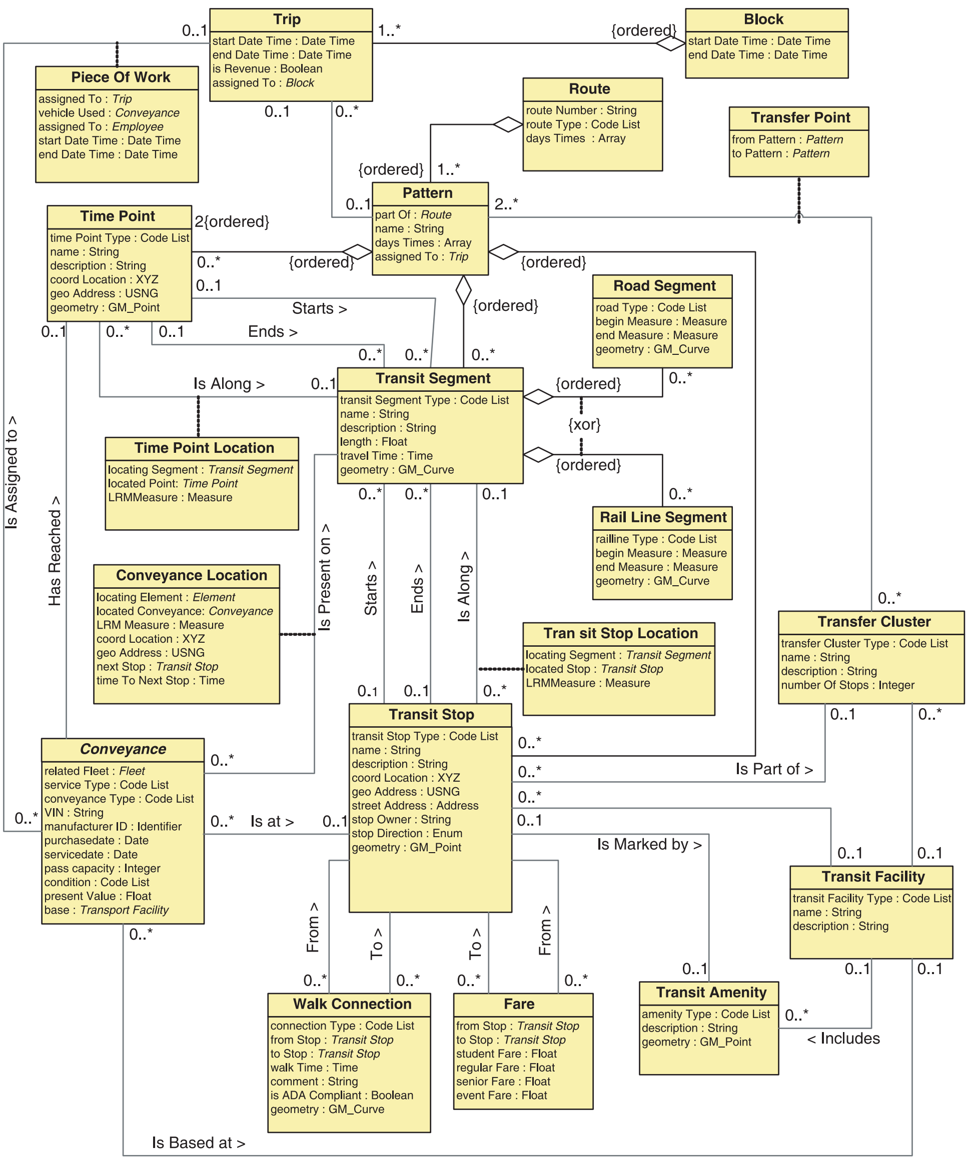

Figure 2 Top-level view of a land use-based transportation hub siting database schema. The full schema has over two hundred feature classes

4 Conclusions

Based on the above examples we outline a requirements list of what the tools described in the first part of the article are missing to make them practical from an applications perspective. Klien and Probst (2005), as well as da Silva et al. (2005) call for research on methods and tools that support application ontology engineering, e.g. by automating

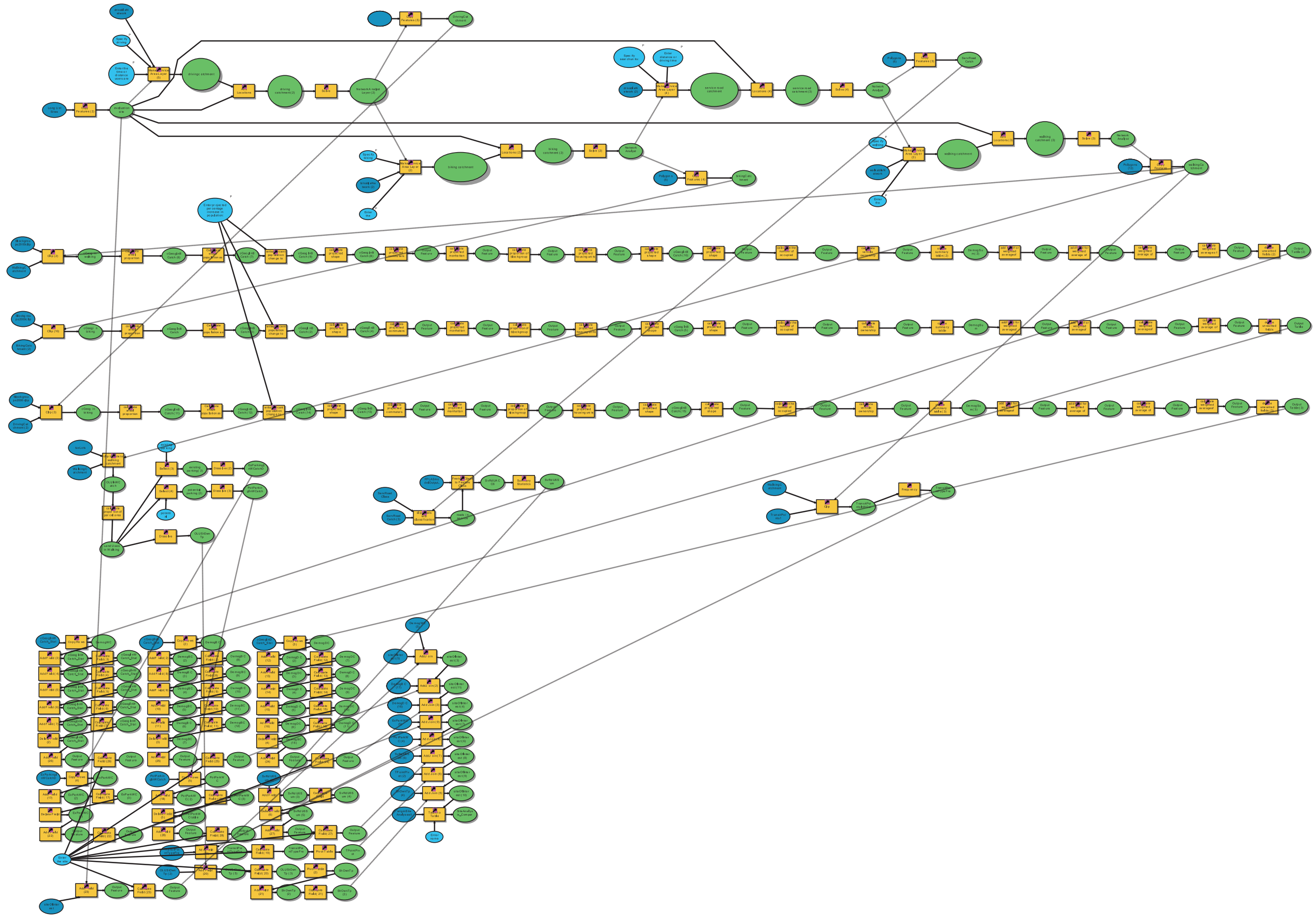

Figure 3 Top-level view of a land use-based transportation hub siting model

the process of creating application ontologies. We cannot agree more. So, how do we get there? Apparently, the problem is non-trivial; the authors are not aware of any solutions in the wider non-spatial realm.

In a first step, we need to increase our efforts on the low-level ontology side. Grenon and Smith's (2003) SNAP/SPAN dichotomy is a neat logical device to compartmentalize views of dynamic phenomena but we need a unified view that allows for the application of one methodology rather than the continued parallel use of two. Reitsma and Albrecht (2005) introduced a radical approach, which does not seem to have found too big a following, yet they seem to have been onto something: Line (2004) and Raskin (2004) independently came up with similar notions of 'flux' and 'trajectory' that do away with the idea that we can capture processes in the form of discrete automata steps. In information science, the solution to the latter was introduced by Petri (1962). Petri nets, also known as place/transition nets allow for formally complete specifications, are uniquely suited for dynamic phenomena, and could conceivably be linked with network- as well as with Voronoi-based GIS (e.g. Gold and Cormack 1987). The International Standards Organization (ISO/IEC JTC1 2005) is about to accept a Petri Net markup language that will go a long way towards public access to what used to be a rather theoretical tool. Galton and Worboys (2005) use similar directed multi-graphs to represent processes and Worboys and Hornsby (2004) provide an application-oriented UML-based notation of objects and processes. This is a good start; what we need next are industry-strength tools that implement the ideas put forward in those papers.

Second, we need spatio-temporal schema editors that assist with the development of complex scheduling and update routines in dynamic models. Even industrial-strength UML tools like Rational Rose (2003) cannot cope with the spatio-temporal granularity of models such as those described in the previous section. SemTalk (2008), described in section 2, comes closest so far, but its BPML output cannot yet be readily translated into specifications that a GIS or an agent-based modeling system can read. An immediate solution for this problem is not visible, as this kind of optimization of a geospatial process model specification is not an inherently academic endeavor. Similar to the development of true three-dimensional GIS, we may even miss the inauguration of such tools because they remain behind the closed doors of the defense and oil industry.

Finally, and here we join the tenor of Klien and Probst (2005), a widespread move from static GIS repositories to GIS-based process modeling systems requires the development of reusable libraries of process model specifications, similar to their counterpart in the data model world. This is of course dependent on the availability of standardized tools and methodologies – the steps one and two from above. Until then, the conceptual difficulties of bridging domain-specific models (Albrecht 2007) as well as the sheer effort required to develop real-world dynamic GIS will render them a rare and endangered species.

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