Environmental Modelling & Software 33 (2012) 80–91

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Entity-relationship and object-oriented formalisms for modeling spatial environmental data

François Pinet

Irstea, UR TSCF, 24 avenue des Landais, 63172 Aubière, France

ARTICLE INFO

Article history:
Received 15 April 2011
Received in revised form
3 January 2012
Accepted 13 January 2012
Available online 15 February 2012

Keywords:
Software engineering
Object-oriented design
Geographic information system
Environmental data
Entity-relationship formalism

ABSTRACT

Entity-Relationship (ER) and Object-Oriented (OO) formalisms are often used to model environmental information of databases or computer programs. The majority of the environmental information is georeferenced. However, for 20 years, researchers have proposed different methods to adapt ER and OO to model spatial data. Spatial information is complex, and the goal is to simplify its representation in conceptual models. The goal of this paper is to propose a classification and a list of work in the area of ER and OO formalisms for spatial information. Numerous bibliographical references on the subject are also provided. The article targets mainly researchers working in the area of environment domain hoping to find a bibliographical entry to the subject. We present here a synthesis of the principal advances in the field.

1. Introduction

Entity-Relationship (ER) (Chen, 1976) and Object-Oriented (OO) formalisms (Din and Idris, 2009) are widely used to describe environmental information of databases or computer programs. Numerous recent examples are available, including (Almeida et al., 2010; Anselme et al., 2010; Bimonte, 2010; Campo et al., 2010; Kraft et al., 2011; Miralles et al., 2010; Moglia et al., 2010; Papajorgji et al., 2010; Parent et al., 2006a,b; Raffaetà et al., 2008; Spaccapietra et al., 2007; Stempliuc et al., 2009).

The majority of the environmental data presented in these articles are georeferenced. This is an important feature of environmental information. In order to model the spatial components of objects more easily, some of these articles use specific extensions of ER or OO formalisms (Miralles et al., 2010; Papajorgji et al., 2010; Parent et al., 2006a,b; Raffaetà et al., 2008; Spaccapietra et al., 2007; Stempliuc et al., 2009).

For 20 years, several research teams adapted first ER formalisms and then OO formalisms to facilitate the modeling of spatial information. Because this type of information is complex, one goal of researchers is to propose specific notations to clarify its representation in models.[1] According to the experiments presented in Parent et al. (1998), using a formalism specifically dedicated to spatial information allows for a 22% reduction in the number of entities and relationships in an ER diagram (without losing semantics), compared to a traditional ER model. Another comparison (Bédard et al., 1996) between a formalism for spatial information and traditional ER/OO methods also shows an important reduction in the size of the models.

The purpose of this paper is to provide a list of the principal proposals in the field of ER and OO formalisms for spatial information. The principal bibliographic references on the subject will also be provided here. This article does not aim to describe and compare in detail the many formalisms that have been proposed. Instead, this article is addressed to researchers working in the environmental field who wish to:

- Learn about the major possibilities that these formalisms offer,
- Find citations that will allow them to learn about these methods in greater detail.

Different methods often provide modeling similar solutions. We analyze here what we believe to be the major advances in the field. As we will show in this paper, our study of the field has led us to propose a classification scheme for formalisms according to seven major design possibilities.

In Section 2, we present a brief history of the field and regroup these formalisms according to our classification of the major possibilities that they offer. Sections 3 through 9 describe each of these possibilities and provide examples of modeling environmental objects.

E-mail address: francois.pinet@cemagref.fr.

[1] Note that in ER and OO approaches, the term "model" is used in the sense of "representation of data or software".

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doi:10.1016/j.envsoft.2012.01.008

2. History of the field and classification of formalisms

The Entity-Relationship (ER) formalism was presented for the first time precisely and in detail in Chen (1976). The ER formalism offers the ability to build conceptual and semantic representations of data through diagrams. These representations are abstractions of the real world, which is modeled by entities and their associations (their semantic links). Each entity and its associations are described by a set of features (properties or attributes). The ER formalism is often used to model databases.

The object paradigm was first popularized through OO programming, then, to a further extent, by formalisms of OO modeling. Alan Kay (winner of the 2003 Turing Award) is considered the father of the OO programming approach (ACM, 2004). In the early 1990s, several modeling formalisms based on the OO paradigm began to develop; e.g., OMT – Object-Modeling Technique (Rumbaugh et al., 1991) and OOA – Object-Oriented Analysis (Coad and Yourdon, 1991). Unified Modeling Language (UML) would emerge in the second half of the 1990s as the standard for OO modeling (OMG, 2009). In OO, the real world is modeled in terms of object classes. Object classes are linked by associations. An object can encapsulate both data (attributes) and behavior (operations). Unlike in the ER formalism, the instances (objects) have a unique identity independent of the values of their attributes. Classes of objects can be linked by relationships of generalization/specialization. UML offers modelers the opportunity to use different types of diagrams (e.g., class diagrams, use cases, states, and sequences) (Booch et al., 1999; OMG, 2009).

For over the past 20 years, various spatial extensions of the ER and OO formalisms have emerged. The field was started by the work of Bédard and Paquette (1989). Our study has led us to propose a classification scheme for formalisms according to seven design possibilities (or goals). According to our classification, the main objectives of the formalisms for spatial information that have been proposed are to provide specific concepts and notations used in conceptual models to facilitate the following goals:

1. The representation of the types of basic spatial objects (e.g., points, lines, surfaces, multiple points, and multiple lines); it is a goal shared by virtually all of the formalisms proposed,
2. The enumeration of spatial relationships between objects, for example "an embankment is always adjacent to a river"; the knowledge of these relationships allows better understanding of the layout of these objects in space,
3. The description of the evolution of spatial objects over time (e.g., birth and death of objects, their shape changes, and their movements in space),
4. The modeling of multi-representation, the objects may have several different spatial representations according to their geographical scale of study,
5. The description of objects with uncertain boundaries or positions (e.g., rivers, forest stands, wetlands, and areas of pollution),
6. The representation of continuous spatial data; the term "continuous" means that a variable of interest (temperature, elevation, pollution level, vegetation cover density, etc.) can be measured in any location in the study area (Saveliev et al., 2007),
7. The modeling of the structure of networks (such as water systems).

Table 1 ranks the ER and OO formalisms for spatial information in terms of these seven modeling possibilities. Our study of the field has led us to propose this classification scheme. The main references are listed in the table along, with the periods when these formalisms appeared. We see that shortly after the emergence of research in this topic in the late 1980s/early 1990s, many studies were initiated.

Several software tools have been produced over time to support these formalisms. Their descriptions can be found in the articles listed in Table 1. Today, the formalisms that have a significantly maintained software solution are: PVL, MADS, UML-GeoFrame, and the STGL profile. The software solutions associated to these formalisms are used primarily to create models of spatial data using a specialized graphical interface and to generate code – for example, scripts for creating database tables or Java code.

The tool Perceptory is based on the PVL formalism. Perceptory is a freeware plugin for Microsoft Visio that is used to create models in PVL. Perceptory had resounding success, which illustrates the real need for formalisms dedicated to spatial information. Perceptory can be downloaded free from Laval University (2011). Bédard et al. (2004) cites more than 300 freeware downloads per month, as well as evidence of use in more than 40 countries. Perceptory has been used in numerous applications (management of natural resources, health, archaeology, sports, etc.) (Bédard et al., 2004).

A tool based on the MADS formalism has been developed and tested on the European project MurMur (Parent et al., 2006a), a project that focused on the multi-representation of spatial objects. A portion of the project data involved avalanches. This tool is described in detail in Parent et al. (2006b). It is not available on the Web.

UML-GeoFrame has been implemented in a code generator called ArgoUML (Victor de Freitas et al., 2005). ArgoUML is a well-known open source tool, a forerunner of the commercial tool Poseidon. It is simple to use and yet relatively efficient for code generation. The version of ArgoUML extended for spatial data was called ArgoCASEGEO (Victor de Freitas et al., 2005). This freeware can be downloaded from (UFV, 2011).

The STGL profile proposed in Miralles and Libourel (2008); Miralles et al. (2009a,b) is partially inspired from PVL. It has been implemented in the commercial CASE tool Objecteering. The developed tool is based on the model driven architecture (Kleppe et al., 2003). It was tested during the design of an application for the maintenance of dikes, and in the context of a project to design observatories for agricultural practices. Recently, the tool is used in an information system project integrating data on pesticide usage in agriculture (Pinet et al., 2010). This tool is not available on the Web but it can be used in collaboration with the research team that maintains the STGL profile (Miralles and Libourel, 2008; Miralles et al., 2009a,b).

Note that these four software tools are currently neither commercial nor open source.

Several formalisms for spatial information are aligned with international standards in GIS (ISO and OGC – Open Geospatial Consentium) (Brodeur et al., 2000; OGC, 2011; Percivall, 2010). These standards facilitate geospatial data interoperability (web services, metadata, etc.); as shown in OGC (2011); Frehner and Brändli (2006); Granell et al. (2010); Huang et al. (2011), they are often used in environmental applications. The authors of Brodeur et al. (2000) and Belussi et al. (2004) present the mappings between PVL/GeoUML and these standards. They show how the spatial concepts defined by ISO and OGC can be integrated into OO formalisms.

3. Representation of basic types of spatial objects

Spatial objects stored in information systems are of different types, for example:

- points, lines, or surfaces,
- multiple points, multiple lines, or multiple surfaces,
- sets of objects of various types.

Almost all of the formalisms dedicated to spatial information provide a simplified representation of these data types in the ER

Table 1
ER and OO formalisms for representing spatial information.

Objectives Formalisms	Representation of basic types of spatial objects	Specification of spatial relationships	Description of the evolution of spatial objects over time	Modeling multi-representation	Description of objects with uncertain boundaries or positions	Representation of continuous spatial fields	Modeling of network structure
Formalisms appearing from the end of the 1980's to the beginning of the 1990's							
Modul-R *(based on an ER approach)*	(Bédard and Paquette, 1989; Brodeur et al., 2000)		(Bédard et al., 1992)				
Congoo *(based on OOA)*	(Pantazis, 1995, 1997; Pantazis and Cornélis, 1997; Pasquasy et al., 2005)	(Billen et al., 2004)					
Formalisms appearing in the second half of the 1990's							
GeoOOA *(based on OOA)*	(Kosters et al., 1995; Kosters et al., 1996; Kosters et al., 1997)	(Kosters et al., 1995; Kosters et al., 1996; Kosters et al., 1997)	(Kosters et al., 1996; Kosters et al., 1997)				(Kosters et al., 1995; Kosters et al., 1996; Kosters et al., 1997)
GISER *(based on an ER approach)*	(Shashi et al., 1997)						
GeoER *(based on an ER approach)*	(Hadzilacos and Tryfona, 1997)	(Hadzilacos and Tryfona, 1997)					
MADS *(based on an ER-OO approach)*	(Parent et al., 2006a; Parent et al., 1998)	(Parent et al., 2006a; Parent et al., 1998)	(Claramunt and Parent, 2003; Claramunt et al., 1999; Parent et al., 1999; Parent et al., 1997)	(Balley et al., 2004; Parent et al., 2006b; Spaccapietra et al., 2007)	(Shu et al., 2003)	(Parent et al., 2006b; Parent et al., 1998; Zimanyi and Minout, 2005)	
Omega *(based on UML)*	(Laurini, 2001; Lbath, 1997, 2002)	(Lbath and Pinet, 2000)					
GeoOM *(based on OMT)*	(Tryfona et al., 1997)	(Tryfona et al., 1997)				(Tryfona et al., 1997)	
STER *(based on an ER approach)*	(Tryfona et al., 1999; Tryfona and Jensen, 1999)		(Tryfona et al., 1999)				
PVL - Plug-in for Visual Languages *(based on UML)*	(Bédard, 1999; Bédard et al., 2004)		(Bédard et al., 2004; Brodeur et al., 2000)	(Bédard et al., 2004; Proulx et al., 2002)			
Extended Spatio-temporal UML *(based on UML)*	(Price et al., 1999)		(Price et al., 1999)				
UML-GeoFrame *(based on UML)*	(Lisboa Filho et al., 1998)	(Lisboa Filho and Cirano, 2008)	(Lisboa Filho et al., 2007; Rocha et al., 2001)			(Lisboa Filho and Cirano, 1999)	(Stempliuc et al., 2009)
OMT-G *based on OMT)*	(Borges et al., 1999)	(Borges et al., 1999; Borges et al., 2001)		(Davis and Laender, 1999)		(Borges et al., 2001)	(Borges et al., 2001)
Formalisms appearing after 2000							
Icons for GIS *based on ER-UML)*	(Tveite, 2001)						
Semantics data model of spatio-temporal database *(based on UML)*	(Yazici et al., 2001)				(Sözer et al., 2008; Yazici et al., 2001)		
Multiple Representation Schema Language *(based on UML)*				(Friis-Christensen and Jensen, 2003; Friis-Christensen et al., 2002)			
T-Omega *(based on UML)*	(Ben Youssef et al., 2010; Pinet and Lbath, 2003)	(Pinet and Lbath, 2003)					
Conceptual framework for Spatio-temporal data modeling *(based on an OO approach)*	(Wang et al., 2003)	(Wang et al., 2003)	(Wang et al., 2003)				
ST USM *(based on an ER approach)*	(Khatri et al., 2004, 2006)		(Khatri et al., 2006)				
GEOUML *(based on UML)*	(Belussi et al., 2004)	(Belussi et al., 2006)					(Belussi et al., 2004)

STGL Profile - Spatio-temporal Geographic Language Profile *(based on UML)*	(Miralles and Libourel, 2008; Miralles et al., 2009a)				(Miralles, 2006)
ChronoGeoGraph *(basé sur une approche ER)*	(Gubiani and Montanari, 2007)	(Gubiani and Montanari, 2008)	(Gubiani and Montanari, 2007)	(Gubiani and Montanari, 2008)	

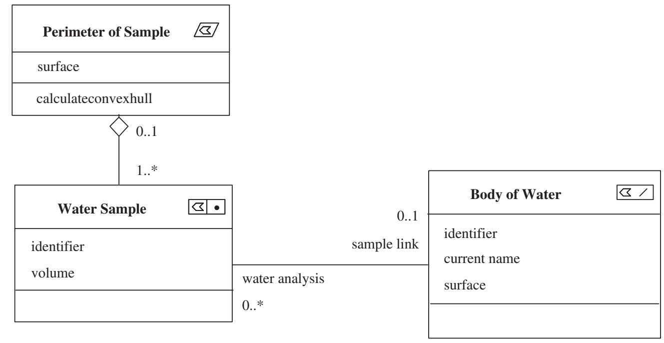

Fig. 1. Example representation of spatial environmental objects with PVL.

and OO models. More precisely, the different formalisms propose to use specific graphical notations in the entities/classes or attributes of OO or ER diagrams in order to model spatial objects. Fundamentally, there are two main approaches to represent spatial types in diagrams: spatial types can be associated to classes (as in PVL) or to attributes (as in MADS).

We will take the example of PVL, which is fairly representative of the general spirit of the modeling techniques proposed by the formalisms. Fig. 1 illustrates the modeling in PVL of geolocalized environmental objects. The class diagram shows that water samples were taken (in order to be analyzed in the laboratory). In accordance with the PVL formalism, icons indicate the type of spatial objects. The semantics of the different PVL notations can be found in Bédard et al. (2004). The pictogram [pictogram] has two shapes in the same rectangle, indicating that the same water body may be composed of several parts that can be surface or linear. The pictogram [pictogram] presents two shapes in separate squares, which means that the point of sampling is either represented by a point, or otherwise, by a surface. The symbol in italics [pictogram] indicates that the spatial representation of the perimeter of the samples is calculated from the other data modeled in the diagram. We consider in this example that the perimeter of the samples is the convex hull of the sampling sites (Water Sample class).

Note that we are talking about 2-D space objects, but the authors of Larrivée et al. (2005) also propose pictograms to represent 3-D data with PVL.

Several examples of the use of pictograms for the modeling of environmental systems can be found in Claramunt et al. (1999); Lisboa Filho and Cirano (2008); Miralles et al. (2010); Papajorgji et al. (2010); Parent et al. (2006b); Raffaetà et al. (2008); Stempliuc et al. (2009); Zimanyi and Minout (2005).

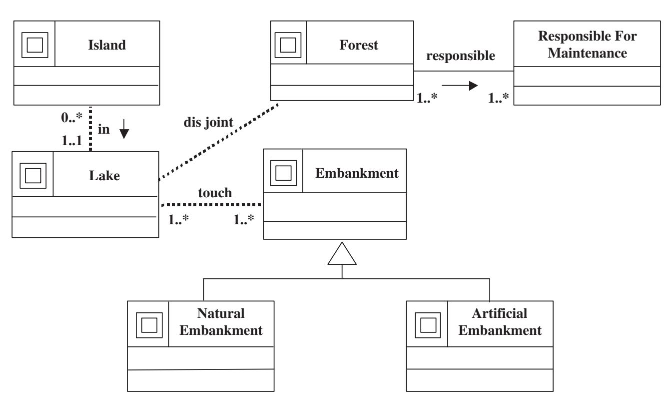

Fig. 2. Diagram of classes described in OMT-G

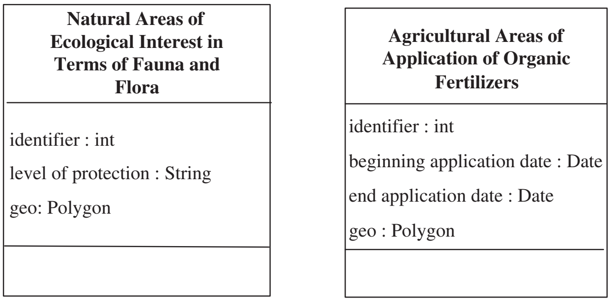

Fig. 3. Two UML classes.

4. Spatial relationships

In Geographic Information Systems, researchers have introduced several sets of relations between spatial objects e.g., between points, lines, surfaces (with or without holes), and composite objects (see for example Clementini and Di Felice (1995); Egenhofer and Herring (1990); Zhong et al. (2004)); for example, an object is spatially within another object, two objects are adjacent, an object is a partition of other objects, an object is north of another, and so on. These studies are based on solid theoretical grounds.

An important contribution of the proposed formalisms concerns the specification of these spatial relationships between objects (Belussi et al., 2006; Billen et al., 2004; Borges et al., 1999, 2001; Gubiani and Montanari, 2008; Hadzilacos and Tryfona, 1997; Kosters et al., 1995, 1996, 1997; Lbath and Pinet, 2000; Lisboa Filho and Cirano, 2008; Parent et al., 2006a, 1998; Pinet and Lbath, 2003; Tryfona et al., 1997; Wang et al., 2003). Many authors consider that specifying the types of spatial relationships in models provides useful semantic information and improves our understanding of the layout of objects in space. In our opinion, the representation of spatial relationships is important in environmental applications. For example, a system called ROSA has been proposed in Le Ber et al. (2003) to help agronomists to compare the spatial organization of farms. In this project, the set of relations proposed in Cohn et al. (1997) has been chosen to represent the land use. ROSA allows agronomists detecting spatial similarities between organizations of farms. Spatial relations have been also modeled in the French information system for agricultural spreading traceability (Pinet et al., 2007). The goal was to detect inconsistent data.

From the onset of formalisms for geographical data, there is the idea of specifying the spatial relationships within the models. In diagrams, the layout of objects can be modeled by relationships between entities or classes. In complex cases, the objects layout can be represented in formal languages.

The method that is found most often in the literature is to represent spatial relationships in ER or OO diagrams by relationships between entities or classes. Fig. 2 shows an example of topological relations present in the formalism OMT-G. In the diagram, the symbol □ of OMT-G indicates that the objects are surfaces. The topological relations are shown by dotted lines. In terms of multiplicities, we can state that:

- an island is located in a lake,
- a lake contains zero, one, or multiple islands,
- forests and lakes are disjoint,
- a riverbank touches one or more lakes, and vice versa.

The formal language OCL (Object Constraint Language) was used to model topological relations between spatial objects described in UML (Kang et al., 2004; Pinet et al., 2009; Pinet et al., 2007; Pinet and Lbath, 2003). OCL allows modeling relations that depend upon more or less complex conditions. For example, consider two classes of UML in Fig. 3: "Natural Areas of Ecological Interest in Terms of Fauna and Flora (NAEIFF)" and "Agricultural Areas of Application of Organic Fertilizers (AAAOF)". The latter involves the spreading of manure or sludge treatment. The NAEIFF can be protected by various governmental measures. The following OCL constraints indicate that AAAOF cannot be spatially within a NAEIFF having an elevated level of protection:

```
  context Natural_Areas_of_Ecological_Interest_in_
Terms_of_Fauna_and_Flora inv:
  self.level_of_protection = 'high'
  implies
  Agricultural_Areas_of_Application_of_Organic_
Fertilizers.allInstances ()
  ->forAll (zone | (zone.geo) .disjoint (self.geo))
```

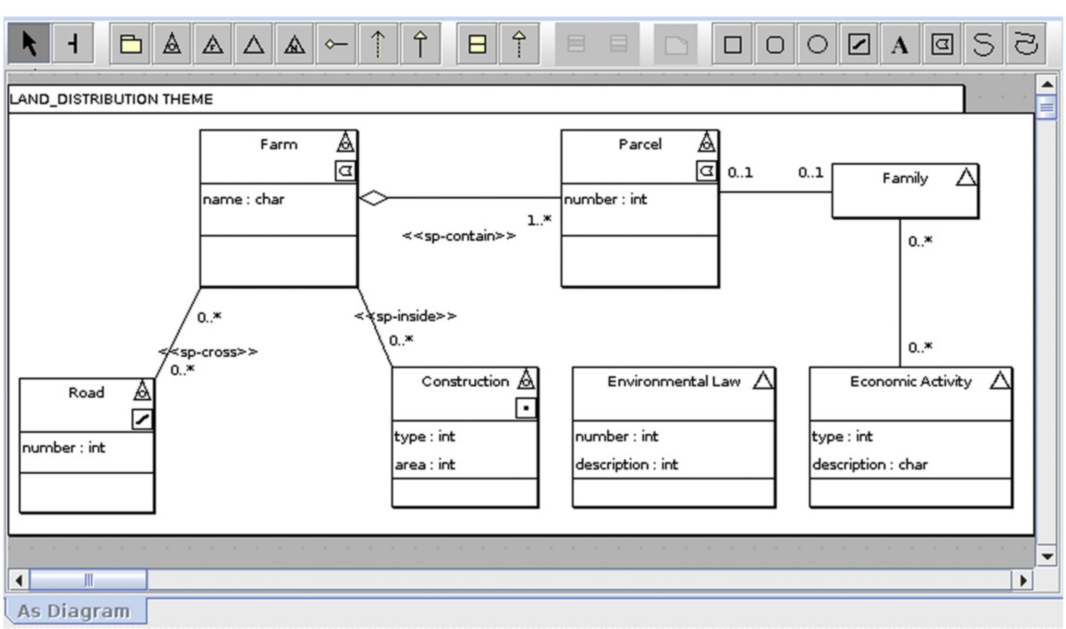

Fig. 4. Part of the example presented in Lisboa Filho and Cirano (2008) – case based on an information system for the Brazilian agrarian reform; this diagram has been created with ArgoCASEGEO (Victor de Freitas et al., 2005; UFV, 2011).

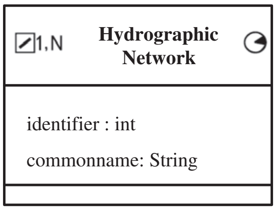

Fig. 5. Example of a temporal pictogram of the PVL formalism.

Thus, OCL enables the formal description of spatial relations, which will facilitate the automatic generation of computer code to control data; see Demuth and Hussmann (1999); Demuth et al. (2001); Pinet et al. (2007, 2005) for more details.

Different examples can be found for modeling OCL constraints in agricultural applications. For instance, Pinet et al. (2009, 2007, 2005) give examples of topological relationships that must be met under French regulations on the sites allowing the land application of sludge treatments.

Lisboa Filho and Cirano (2008) propose a case study based on an information system for the Brazilian agrarian reform. The authors model several spatial relationships with UML-GeoFrame: farms contain parcels and buildings; farms are crossed by roads; etc.; see Fig. 4 – a relationship is rendered as a name enclosed by guillemets on the diagram. Pictograms represent the types of the objects: ⍙ (resp. Δ) models a spatial class (resp. a non-spatial class).

In the field of behavioral ecology, MADS has been used to model a database storing information on the spatio-temporal dynamic of porcupines (Raffaetà et al., 2008). This database contains the porcupines' location. Radio-collars have been used in order to remotely localize the animals. The goal was to analyze the behaviors of the porcupines. The MADS diagrams that model the database show several examples of spatial relationships between the objects stored in the system (e.g., territory of porcupines, habitats, burrows, home ranges, animal transects).

5. Temporal characteristics of spatial objects

Several formalisms can be used to model temporal characteristics of objects (Bédard et al., 2004; Bédard et al., 1992; Brodeur et al., 2000; Claramunt and Parent, 2003; Claramunt et al., 1999; Gubiani and Montanari, 2007; Khatri et al., 2006; Kosters et al., 1996, 1997; Lisboa Filho et al., 2007; Parent et al., 1999, 1997; Price et al., 1999; Rocha et al., 2001; Tryfona et al., 1999; Wang et al., 2003). They allow the modeling of:

- The period of existence of objects (their beginning, their end) (Bédard et al., 2004), and the type of dates that are specified for these periods (date of observation of the phenomenon or when the data are entered in the information system, etc.) (Price et al., 1999),
- The evolution of objects; changing values of their descriptive attributes or their shapes/positions.

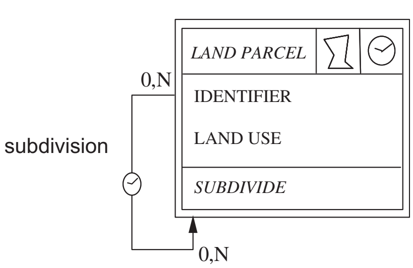

Fig. 6. Example of temporal relationships with GeoOOA.

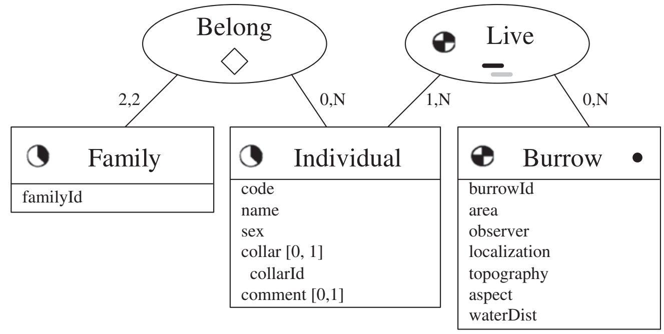

Fig. 7. Part of the example presented in Raffaetà et al. (2008).

The temporality of spatial objects is primarily described by to two methods:

(1) The introduction of temporal pictograms in diagrams. These pictograms are used to indicate a history associated with attributes, classes (or entities), or associations (Bédard et al., 1992; Brodeur et al., 2000; Kosters et al., 1996; Parent et al., 1997; Price et al., 1999; Rocha et al., 2001; Wang et al., 2003). The evolution of attribute values, instances of classes/entities, or relationships will be saved in the modeled information system. Fig. 5 shows an example of a Hydrographic Network class modeled in PVL. You can find to the right, an icon (◔) denoting the temporal feature, and to the left, the icon describing the geometry of the network (1,N meaning "from 1 to N lines"). Water systems can evolve by the addition or destruction of a section, which changes the overall geometry of the networks. The temporal pictogram indicates that the different versions of the water systems will be retained (stored) in the class, each associated with a specific period of time. The implementation of this class will have to allow access to any of these versions. As a function of these formalisms, the pictograms can represent different temporal values, such as the period of validity of the information or the time of the transaction (the insertion) into the system.

(2) The use of temporal relationships between objects. The different formalisms provide lists of possible temporal relationships (and their semantics). These relationships describe the temporal links between the different spatial objects: (a) the evolutionary links, such as the merging of multiple objects into one or the subdivision of one object into many, etc. (Claramunt and Parent, 2003; Kosters et al., 1996), (b) the layout of the periods of existence of objects in time (for example, two types of objects coexist at the same time or the period of existence of an object is included in that of another object) (Raffaetà et al., 2008). The evolution of the temporal links specified in the entity or class diagrams provides important information about state changes of objects. Fig. 6 gives an example of a subdivision relationship in GeoOOA (Kosters et al., 1996). At a given date, a parcel may be subdivided into several plots.

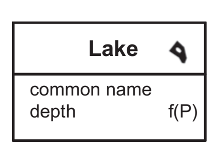

Fig. 8. Example of space-varying attribute (MADS).

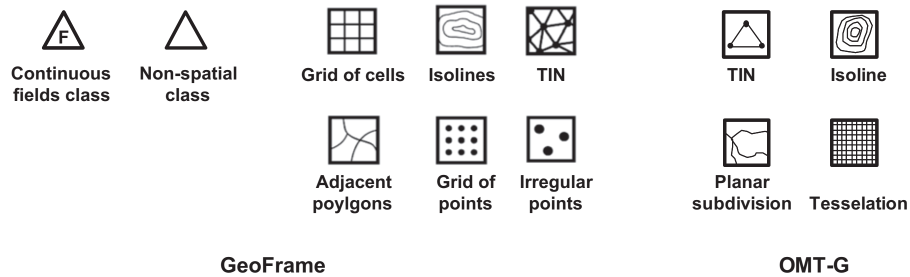

Fig. 9. UML-GeoFrame and OMT-G pictograms for continuous fields – see Borges et al. (2001); Lisboa Filho and Cirano (2008).

Many examples of modeling the temporal dynamics of spatial data are given in Raffaetà et al. (2008). Fig. 7 shows a part of the MADS diagram modeling the database used in this project. The Individual entity represents radio-collared porcupines (see Section 4). The pictogram ◔ indicates that the database stores a time interval for each animal; it corresponds to the (estimated) lifespan of the porcupine. The Family entity represents a couple of porcupines. A set of animals is classified as a family by exploiting the fact that a couple and their cubs are often found together in the same burrow. A family is a temporal object. Its lifecycle is a time interval (◔). The pictogram ◕ indicates that each burrow is associated to a set of time intervals. This set contains the periods during which the burrow is inhabited. The borrows are associated to the point data type (●). The Live relationship can store which porcupines lives in which burrows and when. This relationship contains a set of time intervals (◕); each interval is the time period during which an individual lives in a burrow. A synchronization is also defined (▬) to ensure that a porcupine can be linked to a burrow only if the lifecycles of the individual and the burrow overlap. A detailed description of the spatio-temporal database can be found in Raffaetà et al. (2008).

The authors of Claramunt et al. (1999) propose to use MADS to build a database storing the changes in land use: e.g., fusion or reallocation of agricultural parcels and the evolution (for example, expansion) of urban areas. PVL has been used to model the temporal characteristics of environmental objects in Miralles et al. (2010); Papajorgji et al. (2010).

6. Modeling multi-representation

Depending on the methods of data acquisition or the geographical scale at which they are studied, spatial objects can have multiple representations (e.g., a river can have both a linear and a surface representation). It is sometimes necessary for different types of representation to coexist within a computer system.

Some formalisms propose specific notations to describe spatial data and their multiple representations in models (Balley et al., 2004; Bédard et al., 2004; Davis and Laender, 1999; Friis-Christensen and Jensen, 2003; Friis-Christensen et al., 2002; Gubiani and Montanari, 2008; Parent et al., 2006b; Proulx et al., 2002; Spaccapietra et al., 2007). It is possible, for example, to indicate in the different (class or entity) diagrams, the relationships (spatial, temporal, etc.) depending on the mode of representation of objects (Gubiani and Montanari, 2008; Spaccapietra et al., 2007). In their formalism for multi-representation, the authors of Friis-Christensen and Jensen (2003); Friis-Christensen et al. (2002) use OCL.

For environmental applications, the authors of Parent et al. (2006b) use MADS to model the multi-representation of a spatial database for avalanches. This system stores information on avalanche events and risk zones. The database schema described in MADS indicates the different geographical resolutions of data. The same object can be stored in different resolutions (1:25000, 1:5000 and 1:1000–2000).

7. Description of objects with uncertain boundaries or positions

The boundaries and the positioning of many environmental objects are not well known or imprecise; that is, they are uncertain spatial objects. The author of Miralles (2006) provides illustrations of this type of object. He gives an example of the uncertain boundaries of wheat parcels estimated from satellite images; the contour is not clearly defined because, even with image processing, we cannot be certain of the presence of wheat in some pixels of the image.

Several formalisms propose representation methods for uncertain objects with associated notations that are usable in diagrams (Miralles, 2006; Shu et al., 2003; Sözer et al., 2008; Yazici et al., 2001). In the work of Shu et al. (2003); Sözer et al. (2008); Yazici et al. (2001), the uncertain spatial objects are represented by fuzzy subsets (Schneider, 1999). It is shown how to model these types of objects in class or entity diagrams. The work of Shu et al. (2003) examines random spatial objects. These are objects to which a probability of occurrence is associated.

In Bejaoui et al. (2009); Bejaoui et al. (2008, 2010), OCL are used to describe topological relationships between objects with uncertain boundaries (in a UML diagram). This method was tested on a database storing information on agricultural spreading.

8. Representation of continuous spatial data

Continuous spatial data (also called continuous fields) represent physical phenomena that change in space (Gomez et al., 2010; Kang et al., 2002; Laurini et al., 2004). Continuous spatial data are series of maps, each of them representing the variability of a certain attribute over the earth's surface (temperature, elevation, pollution level, vegetation cover density, etc.) (Mozgeris, 2009). The variable of

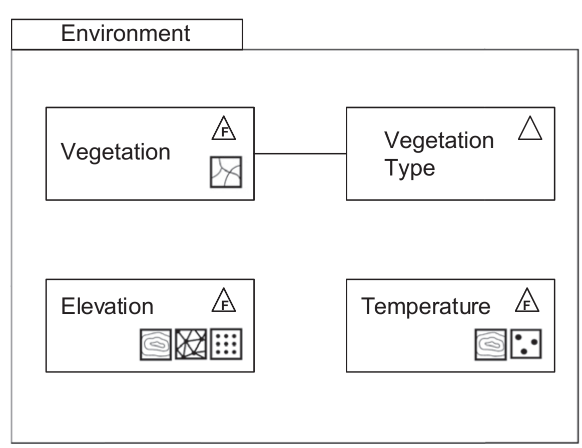

Fig. 10. Example of continuous field classes in UML-GeoFrame (from Lisboa Filho and Cirano (2008)).

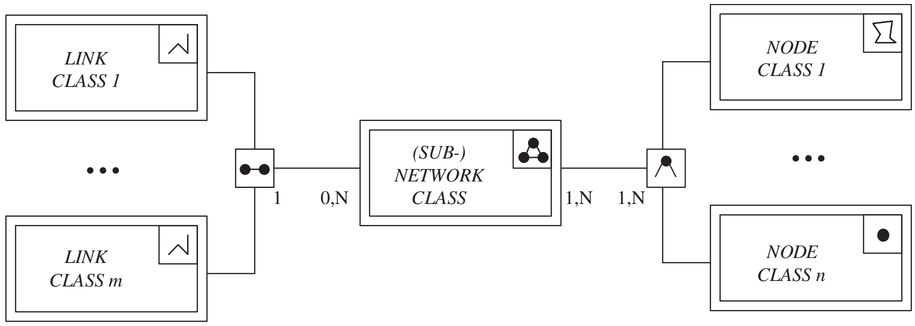

Fig. 11. GeoOOA Notations to describe the network (from Kosters et al. (1996)).

interest can be calculated in any location in the study area (Saveliev et al., 2007). Continuous spatial data can often be found in environmental applications (Fernandes et al., 2004; Kemp, 1993; Lisboa Filho and Cirano, 2008; Mozgeris, 2009; Saveliev et al., 2007).

In MADS and GeoOM, these data are modeled with the concept of space-varying attributes (Parent et al., 2006b, 1998; Tryfona et al., 1997; Zimanyi and Minout, 2005). These attributes vary over space; a function is used to calculate the variable of interest, e.g., f: point → real (Gomez et al., 2010).

For example, the notation "f(P)" models continuous spatial data in MADS diagrams (Parent et al., 2006b), as for the attribute "depth" of the Lake class (in Fig. 8). In this example, this notation indicates that the depth can be calculated in any point of the lake by a function. The pictogram indicates that the lake is a surface. Some examples of space-varying attributes in the environmental field can be found in Parent et al. (2006b); Zimanyi and Minout (2005).

Continuous spatial data may be produced from different data structures: Triangulated Irregular Networks (TIN), isolines, grids of points, etc. (Kemp, 1993; Laurini and Thompson, 1992). UML-GeoFrame and OMT-G propose pictograms to model these data structures (see Fig. 9) (Borges et al., 2001; Lisboa Filho and Cirano, 1999, 2008). These pictograms can be used in classes; see Fig. 10 (Lisboa Filho and Cirano, 2008). In Fig. 10, Elevation and Temperature have several spatial representations.

9. Modeling the structure of networks

Several proposals show how it is possible to formalize networks in diagrams (Belussi et al., 2004; Borges et al., 2001; Kosters et al., 1995, 1996, 1997; Stempliuc et al., 2009). In Kosters et al. (1996), the authors present an example where the integration of new and specific notation considerably clarifies the representation of the network structure in an object-oriented model. For example, Fig. 11 shows the principal notations used in GeoOOA to design networks. A network (or subnet) is represented by a class with the pictogram. The components of the network (the nodes and their links) are then identified. As shown in Fig. 11, these components are formalized in GeoOOA diagrams by node classes () or link classes (). Each node or link class corresponds to a type of node (e.g., a Hydroelectric Power Plant class or a Lake class) or a type of link (e.g., an Artifical Canal class or a Natural Canal class). The type of the spatial object (point, line, surface) is indicated by a pictogram in the class. Every

Table 2
Use of formalisms for the modeling of environmental systems - main references cited in our paper.

Sections References	Section 3) Basic types of spatial objects	Section 4) Spatial relationships	Section 5) Evolution of spatial objects over time	Section 6) Multi-representation	Section 7) Objects with uncertain boundaries or positions	Section 8) Continuous spatial fields	Section 9) Network structure
MADS							
- Database storing information on the spatio-temporal dynamic of hedgehogs (Raffaetà et al., 2008)	X	X	X				
- Database for avalanches (Parent et al., 2006b)	X			X	X		
- River monitoring system (Zimanyi and Minout, 2005)					X		
- Database storing the changes in land use (Claramunt et al., 1999)	X		X				
OCL							
- Examples of topological relationships on the sites allowing the land application of sludge treatments (Pinet et al., 2009; Pinet et al., 2007; Pinet et al., 2005)		X					
- Database storing information on agricultural spreading (Bejaoui et al., 2009; Bejaoui et al., 2008, 2010)					X		
PVL							
- Examples of agricultural systems (Miralles et al., 2010)	X		X				
UML-GeoFrame							
- Case study based on an information system for the Brazilian agrarian reform (Lisboa Filho and Cirano, 2008)	X	X				X	
- Model of a water distribution network (Stempliuc et al., 2009)							X

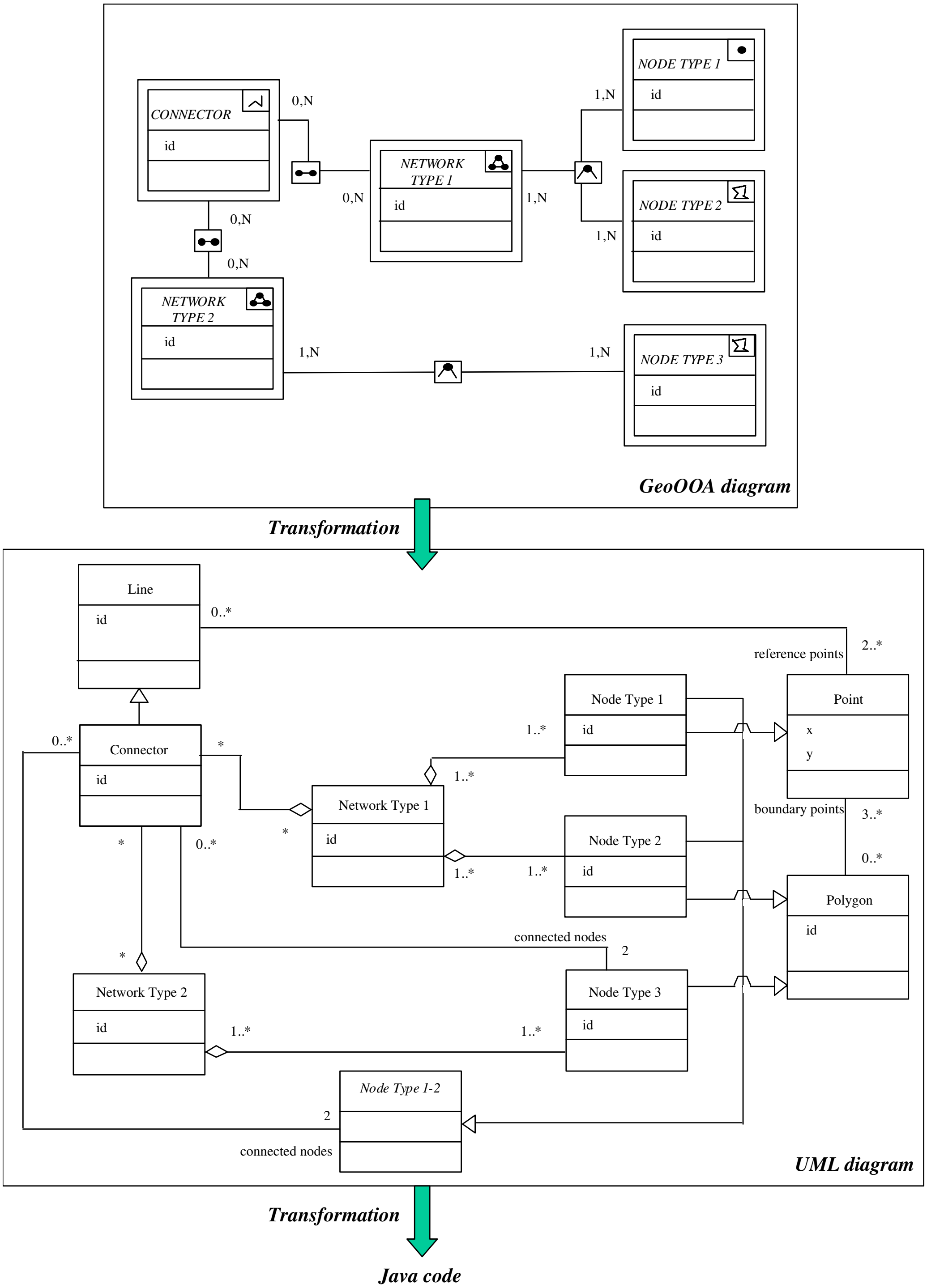

Fig. 12. Example of model transformation.

pair of nodes in a network *R* can be connected by any link in *R*. In the diagrams, the link and node classes can be associated with multiple network classes; it is possible to connect multiple networks or subnetworks.

In Borges et al. (2001), the authors introduce a type of link that might connect not only two nodes but also two links. In Belussi et al. (2004), the authors present an example of network structure with OCL and UML. In Stempliuc et al. (2009), a model of a water distribution network using UML-GeoFrame is presented.

10. Conclusion and outlook

Many ER and OO formalisms have been proposed to facilitate the modeling of spatial information. These types of methods are of evident interest to represent the full complexity of environmental information: the types of spatial objects, their arrangement in space, their temporal evolution, their multiple representations, the uncertainty in their shape and position, and their interconnections within networks.

To sum up, there are several modeling possibilities:

- There are two main approaches to indicate spatial types in diagrams: spatial types can be associated with classes (as in PVL) or with attributes (as in MADS).
- In diagrams, spatial relationships can be modeled by relationships between entities or classes. In complex cases, the objects layout can be represented in the formal language OCL.
- The formalisms can model the period of existence of objects (their beginning, their end) or their evolution (changing their shapes/positions).
- The uncertain objects can be represented by fuzzy subsets or by random spatial objects, e.g. objects to which a probability of occurrence is associated.
- Continuous spatial data are defined by space-varying attributes; the associated structure (TIN, isolines, etc.) can be also represented in diagrams.
- (Sub-) networks, links and nodes can be formalized by specific classes.

Examples of the use of these formalisms for the modeling of environmental systems can easily be found; Table 2 recalls the main references cited in our paper.

OO formalisms allow modelers to represent spatial systems more thoroughly than ER formalisms. OO class diagrams may include operations and relationships of generalization/specialization. Operations can be used to define the processing of spatial data (see Figs. 1 and 6). Relationships of generalization/specialization are used to build hierarchies of spatial objects (see Fig. 2). Also, the Object Constraint Language can model topological relations between objects in UML diagrams (see Section 4).

Today, more and more commercial solutions are available to easily implement UML profiles (i.e., UML customizations) (OMG, 2011), such as the software MagicDraw (www.magicdraw.com) or IBM Rational Rose. These solutions should greatly facilitate the implementation of software tools supporting formalisms for spatial information (e.g., the tools to draw the diagrams and generate code). For example, MagicDraw provides the ability to add new custom notations to UML through stereotypes and tagged values (see Booch et al. (1999) for more details on these concepts). Stereotypes and tagged values can facilitate the implementation of the pictograms presented in this paper. Constraints on the use of these notations can be defined with OCL. For example, these constraints could indicate that in a GeoOOA model, only classes with an icon can be connected to a network by an association class. Once specified, these constraints can be controlled in the diagrams. This helps prevent design errors. Note that some formalisms for spatial information have already been modeled in the form of a UML profile; as an example, see Kang et al. (2004); Lisboa Filho et al. (2010); Miralles (2006). When creating diagrams, it would also be interesting to use multiple profiles simultaneously: for example, when designing a warehouse of spatial data (Malinowski and Zimanyi, 2008; Pinet and Schneider, 2010), the modeler could use a profile dedicated to spatial information and a profile dedicated to the specification of data warehouses (Lujan-Mora et al., 2006).

As indicated in Papajorgji et al. (2010), the Model Driven Architecture (MDA) has made considerable advances in the industrial sector; this approach based on UML is a recent initiative aiming to make development processes independent from changes of implementation technologies. MDA provides an open, vendor-neutral approach to the challenge of business of technology change. The approach starts with a conceptual model expressing the depicted concepts from the problem domain and their relationships; during this phase, no technical details about the implementation environment and the underlying technologies are taken into consideration (Papajorgji et al., 2010). The models are then iteratively refined (e.g., transformed). After all business issues related to the model construction are detailed and well-defined, then considerations about the implementation environment can be taken into account. Different implementation platforms could be used (.NET, Java, etc.). Numerous MDA-based development tools are available.

We can see recent efforts to use the MDA approach in environmental fields. For example, the use of the MDA approach in crop simulation area is described in Papajorgji and Pardalos (2006). The authors of Muzy et al. (2005) propose to use MDA in simulation of ecological propagation processes (applied to fire spread). In the field of spatial environmental information, the Model Driven Architecture approach should also be increasingly used to facilitate the transformation of diagrams to implementation models (Miralles and Libourel, 2008; Miralles et al., 2009b; Papajorgji et al., 2010). Fig. 12 shows an example of model transformation. In our opinion, the MDA approach can provide an efficient method to help designers to implement their spatial information systems.

References

ACM, 2004. Turing Award Honors Alan Kay as Pioneer of Personal Computers. Web page. http://www.acm.org/announcements/turingaward.4-21-2004.html.

Almeida, S.J.d., Martins Ferreira, R.P., Eiras, A.E., Obermayr, R.P., Geier, M., 2010. Multi-agent modeling and simulation of an *Aedes aegypti* mosquito population. Environmental Modelling & Software 25 (12), 1490–1507.

Anselme, B., Bousquet, F., Lyet, A., Etienne, M., Fady, B., Le Page, C., 2010. Modelling of spatial dynamics and biodiversity conservation on Lure mountain (France). Environmental Modelling & Software 25 (11), 1385–1398.

Balley, S., Parent, C., Spaccapietra, S., 2004. Modelling geographic data with multiple representations. International Journal of Geographical Information Science 18 (4), 327–352.

Bédard, Y., 1999. Visual modelling of spatial database towards spatial PVL and UML. Geomatica 53 (2), 169–185.

Bédard, Y., Paquette, F., 1989. Extending Entity/Relationship Formalism for Spatial Information Systems. AUTO-CARTO 9, Baltimore, 818–827 pp.

Bédard, Y., Pageau, J., Caron, C., 1992. Spatial Data Modeling: The Modul-R Formalism and CASE Technology. ISPRS Symposium, Washington, 1–14 pp.

Bédard, Y., Caron, C., Maamar, Z., Moulin, B., Vallière, D., 1996. Adapting data models for the design of spatio-temporal databases. Computers, Environment and Urban Systems 20 (1), 19–41.

Bédard, Y., Larrivee, S., Proulx, M.J., Nadeau, M., 2004. Modeling geospatial databases with plug-ins for visual languages: a pragmatic approach and the impacts of 16 years of research and experimentations on perceptory. Lecture Notes in Computer Science 3289, 17–30.

Bejaoui, L., Pinet, F., Schneider, M., Bedard, Y., 2008. An adverbial approach for the formal specification of topological constraints involving regions with broad boundaries. Lecture Notes in Computer Science (ER) 5231, 383–396.

Bejaoui, L., Pinet, F., Bedard, Y., Schneider, M., 2009. Qualified topological relations between spatial objects with possible vague shape. International Journal of Geographical Information Science 23 (7), 877–921.

Bejaoui, L., Pinet, F., Schneider, M., Bedard, Y., 2010. OCL for formal modelling of topological constraints involving regions with broad boundaries. GeoInformatica 14 (13), 353–378.

Belussi, A., Negri, M., Pelagatti, G., 2004. GEOUML: A Geographic Conceptual Model Defined Through Specialization of ISO TC211 Standards. 10th EC GI & GIS Workshop, ESDI State of the Art, Warsaw, Poland. 23–25 June 2004.

Belussi, A., Negri, M., Pelagatti, G., 2006. An ISO TC 211 conformant approach to model spatial integrity constraints in the conceptual design of geographical databases. Advances in Conceptual Modeling – Theory and Practice, 100–109.

Ben Youssef, M., Lbath, A., Belhadj, Z., 2010. A dedicated UML profile for real time geomantic modelisation and code generation. Journal of Communication and Computer 7 (10).

Billen, R., Pantazis, D., Cornélis, B., 2004. Application of ER and CONGOO Formalisms in a Spatial Database-Reengineering Project.

Bimonte, S., 2010. A web-based tool for spatio-multidimensional analysis of geographic and complex data. International Journal of Agricultural and Environmental Information Systems 1 (2).

Booch, G., Rumbaugh, J., Jacobson, I., 1999. The Unified Modeling Language User Guide. Addison-Wesley.

Borges, K., Laender, A., Davis, C., 1999. Spatial data integrity constraints in object oriented geographic data modeling. In: Proceedings of the 7th ACM International Symposium on Advances in Geographic Information Systems. ACM, Kansas City, Missouri, United States.

Borges, K.A.V., Davis, C.A., Laender, A.H.F., 2001. OMT-G: an object-oriented data model for geographic applications. GeoInformatica 5 (3), 221–260.

Brodeur, J., Bédard, Y., Proulx, M.J., 2000. Modelling geospatial application databases using UML-based repositories aligned with international standards in geomatics.

In: Proceedings of the 8th ACM International Symposium on Advances in Geographic Information Systems. ACM, Washington, D.C., United States.

Campo, P.C., Bousquet, F., Villanueva, T.R., 2010. Modelling with stakeholders within a development project. Environmental Modelling & Software 25 (11), 1302–1321.

Chen, P., 1976. The entity-relationship model: toward a unified view of data. ACM Transactions on Database Systems 1 (1), 9–35.

Claramunt, C., Parent, C., 2003. Modelling concepts for the representation of evolution constraints. Computers, Environment and Urban Systems 27 (3), 225–241.

Claramunt, C., Parent, C., Spaccapietra, S., Theriault, M., 1999. Database modelling for environmental and land use changes. Geographical Information and Planning: European Perspectives, 173–194.

Clementini, E., Di Felice, P., 1995. A comparison of methods for representing topological relationships. Information Sciences – Applications 3 (3), 149–178.

Coad, P., Yourdon, E., 1991. Object-Oriented Analysis. Prentice Hall, Englewood Cliffs.

Cohn, A., Bennett, B., Gooday, J., Gotts, N., 1997. Representing and Reasoning with Qualitative Spatial Relations About Regions, Spatial and Temporal Reasoning. Springer, 97–134 pp.

Davis, C., Laender, A., 1999. Multiple representations in GIS: materialization through map generalization, geometric, and spatial analysis operations. In: Proceedings of the 7th ACM International Symposium on Advances in Geographic Information Systems. ACM, Kansas City, Missouri, United States.

Demuth, B., Hussmann, H., 1999. Using UML/OCL Constraints for Relational Database Design, «UML»'99 — The Unified Modeling Language, 751–751 pp.

Demuth, B., Hussmann, H., Loecher, S., 2001. OCL as a Specification Language for Business Rules in Database Applications, «UML» 2001 — The Unified Modeling Language. Modeling Languages, Concepts, and Tools, 104–117 pp.

Din, J., Idris, S., 2009. Object-oriented design process model. International Journal of Computer Science and Network Security 9 (10), 71–79.

Egenhofer, M., Herring, J., 1990. A Mathematical Framework for the Definition of Topological Relations. Fourth International Symposium on Spatial Data Handling, Zurich, Switzerland, 803–813 pp.

Fernandes, R., Fraser, R., Latifovic, R., Cihlar, J., Beaubien, J., Du, Y., 2004. Approaches to fractional land cover and continuous field mapping: a comparative assessment over the BOREAS study region. Remote Sensing of Environment 89 (2), 234–251.

Frehner, M., Brändli, M., 2006. Virtual database: spatial analysis in a web-based data management system for distributed ecological data. Environmental Modelling & Software 21 (11), 1544–1554.

Friis-Christensen, A., Jensen, C., 2003. Object-Relational Management of Multiply Represented Geographic Entities. In: 15th International Conference on Scientific and Statistical Database Management.

Friis-Christensen, A., Skogan, D., Jensen, C., Skagestein, G., Tryfona, N., 2002. Management of Multiply Represented Geographic Entities. In: International Database Engineering and Applications Symposium (IDEAS'02).

Gomez, L., Vaisman, A., Zimanyi, E., 2010. Physical design and implementation of spatial data warehouses supporting continuous fields. In: Proceedings of the 12th International Conference on Data Warehousing and Knowledge Discovery. Springer-Verlag, Bilbao, Spain, 25–39 pp.

Granell, C., Díaz, L., Gould, M., 2010. Service-oriented applications for environmental models: reusable geospatial services. Environmental Modelling & Software 25 (2), 182–198.

Gubiani, D., Montanari, A., 17–20 June 2007. ChronoGeoGraph: an expressive spatio-temporal conceptual model. In: Proceedings of the Fifteenth Italian Symposium on Advanced Database Systems, SEBD 2007. Torre Canne, Fasano, BR, Italy.

Gubiani, D., Montanari, A., 2008. A conceptual spatial model supporting topologically-consistent multiple representations. In: Proceedings of the 16th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems. ACM, Irvine, California.

Hadzilacos, T., Tryfona, N., 1997. An extended entity-relationship model for geographic applications. SIGMOD Record (ACM Special Interest Group on Management of Data) 26 (3), 24–29.

Huang, M., Maidment, D., Tian, Y., 2011. Using SOA and RIAs for water data discovery and retrieval. Environmental Modelling & Software 26 (11), 1309–1324.

Kang, A.M., Faloutsos, C., Laurini, R., Servigne, S., 2002. Indexing Values in Continuous Field Databases. EDBT.

Kang, M.A., Pinet, F., Schneider, M., Chanet, J.P., Vigier, F., April 29–May 1 2004. How to design geographic database? Specific UML profile and spatial OCL applied to wireless Ad Hoc networks. In: 7th Conference on Geographic Information Science (AGILE'2004), Heraklion, GRC, 289–299 pp.

Kemp, K., 1993. Environmental Modelling and GIS: Dealing with Spatial Continuity. HydroGIS 93, Vienna. 107–115.

Khatri, V., Ram, S., Snodgrass, R.T., 2004. Augmenting a conceptual model with geospatiotemporal annotations. IEEE Transactions on Knowledge and Data Engineering 16 (11), 1324–1338.

Khatri, V., Ram, S., Snodgrass, R.T., 2006. On augmenting database design-support environments to capture the geo-spatio-temporal data semantics. Information Systems 31 (2), 98–133.

Kleppe, A., Warmer, J., Bast, W., 2003. MDA Explained. Addison-Wesley.

Kosters, G., Pagel, B.U., Six, H.W., December 1–2, 1995. Object-oriented requirements engineering for GIS applications. The 3rd ACM International Workshop on Advances in Geographic Information Systems, Baltimore, Maryland.

Kosters, G., Pagel, B.U., Six, H.W., 1996. GeoOOA: object-oriented analysis for geographic information systems. In: Proceedings of the IEEE International Conference on Requirements Engineering, 245–253 pp.

Kosters, G., Pagel, B.U., Six, H.W., 1997. GIS-application development with GEOOOA. International Journal of Geographical Information Science 11 (4), 307–335.

Kraft, P., Vaché, K.B., Frede, H.-G., Breuer, L., 2011. CMF: a hydrological programming language extension for integrated catchment models. Environmental Modelling & Software 26 (6), 828–830.

Larrivée, S., Bédard, Y., Pouliot, J., 2005. How to enrich the semantics of geospatial databases by properly expressing 3D objects in a conceptual model. In: On the Move to Meaningful Internet Systems 2005: OTM Workshops, 999–1008 pp.

Laurini, R., 2001. Information Systems for Urban Planning: A Hypermedia Cooperative Approach. Taylor and Francis.

Laurini, R., Thompson, D., 1992. Fundamentals of Spatial Information Systems.

Laurini, R., Paolino, L., Sebillo, M., Tortora, G., Vitiello, G., 2004. Dealing with geographic continuous fields: the way to a visual GIS environment. In: Proceedings of the Working Conference on Advanced Visual Interfaces. ACM, Gallipoli, Italy, 336–343 pp.

Laval University, 2011. Perceptory Web Site. http://sirs.scg.ulaval.ca/perceptory/english/enewindex2.asp.

Lbath, A., Pinet, F., 2000. The Development and Customization of GIS-Based Applications and Web-Based GIS Applications with the CASE Tool AIGLE. 8th ACM International Symposium on Advances in Geographic Information Systems.

Lbath, A., 1997. A Generic Graphical User Interface for Customization of GIS Applications. Joint European Conference on Geographical Information, Vienna, Austria.

Lbath, A., 2002. OMEGA: Object Modeling for End-User Geographic Applications: A Visual UML Based Methods for GIS. IEEE International Symposium on Signal Processing and Information Technology, Marrakech, Marco.

Le Ber, F., Napoli, A., Metzger, J.L., Lardon, S., 2003. Modeling and comparing farm maps using graphs and case-based reasoning. Journal of Universal Computer Science 9 (9), 1073–1095.

Lisboa Filho, J., Cirano, I., 1999. Specifying analysis patterns for geographic databases on the basis of a conceptual framework. In: Proceedings of the 7th ACM International Symposium on Advances in Geographic Information Systems. ACM, Kansas City, Missouri, United States.

Lisboa Filho, J., Cirano, I., 2008. Modeling with a UML Profile. Encyclopedia of GIS, 691–700 pp.

Lisboa Filho, J., Cirano, I., Beard, K., 16–19 November, 1998. Applying Analysis Patterns in the GIS Domain, the 10th Colloquium of the Spatial Information Research Centre. University of Otago, New Zealand, 181–188 pp.

Lisboa Filho, J., Sampaio, G.B., Silva, E.O., Gazola, A., 2007. Design and Implementation of the Valid Time for Spatio-Temporal Databases. International Conference on Enterprise Information Systems, Madeira, Portugal, 569–573 pp.

Lisboa Filho, J., Sampaio, G.B., Nalon, F.R., Borges, K., 2010. A UML Profile For Conceptual Modeling in GIS Domain. CAiSE 2010 Workshop, Hammamet, Tunisia, 18–31 pp. DE@CAiSE'10.

Lujan-Mora, S., Trujillo, J., Song, I.-Y., 2006. A UML profile for multidimensional modeling in data warehouses. Data & Knowledge Engineering 59 (3), 725–769.

Malinowski, E., Zimanyi, E., 2008. Advanced Data Warehouse Design: From Conventional to Spatial and Temporal Applications. Springer.

Miralles, A., 2006. Ingénierie des modèles pour les applications environnementales. PhD Thesis, University of Montpellier 2, France, 322 p.

Miralles, A., Libourel, T., 2008. Spatial database modeling with enriched model driven architecture. In: Shekhar,, S., Xion,, H. (Eds.), Encyclopedia of Geographical Information Sciences. Springer, 700–705 pp.

Miralles, A., Libourel, T., Papajorgji, P.J., Pardalos, P.M., 2009a. Application of a Model Transformation Paradigm in Agriculture: a Simple Environmental System Case Study. In: Advances in Modelling Agricultural Systems. Springer. 37–54.

Miralles, A., Libourel, T., Papajorgji, P.J., Pardalos, P.M., 2009b. A New Methodology to Automate the Transformation of GIS Models in an Iterative Development Process. In: Advances in Modelling Agricultural Systems. Springer. 19–36.

Miralles, A., Pinet, F., Bédard, Y., 2010. Describing spatio-temporal phenomena for environmental system development: an overview of today's needs and solutions. International Journal of Agricultural and Environmental Systems 1 (2).

Moglia, M., Perez, P., Burn, S., 2010. Modelling an urban water system on the edge of chaos. Environmental Modelling & Software 25 (12), 1528–1538.

Mozgeris, G., 2009. The continuous field view of representing forest geographically: from cartographic representation towards improved management planning. Sapiens 2 (2).

Muzy, A., Innocenti, E., Aiello, A., Santucci, J.-F.o., Santoni, P.-A., Hill, D.R.C., 2005. Modelling and simulation of ecological propagation processes: application to fire spread. Environmental Modelling & Software 20 (7), 827–842.

OGC, 2011. The OGC's Role in Geosciences and the Environment. http://www.opengeospatial.org/domain/geosciences_and_environment.

OMG, 2009. Unified Modeling Language (OMG UML), Infrastructure Version 2.2, Technical Report.

OMG, 2011. Catalog of UML Profile Specifications. http://www.omg.org/technology/documents/profile_catalog.htm.

Pantazis, D.N., 1995. CONGOO formalism basic concepts and three conversion examples. In: Proc First Joint European Conference and Exhibition on Geographical Information, Eurogi, The Hague, The Netherlands, 223–226 pp.

Pantazis, D., 1997. CONGOO: A Conceptual Formalism for Geographic Database Design. In: Geographic Information Research. 348–367.

Pantazis, D., Cornélis, B., 1997. Designing and implementing a GIS in an international context. Transactions in GIS 1 (4), 301–320.

Papajorgji, P., Pardalos, P.M., 2006. Software Engineering Techniques Applied to Agricultural Systems an Object-Oriented and UML Approach. Springer.

Papajorgji, P., Pinet, F., Miralles, A., Jallas, E., Pardalos, P.M., 2010. Modeling: a central activity for flexible information systems development in agriculture and environment. International Journal of Agricultural and Environmental Information Systems 1 (1), 1–25.

Parent, C., Spaccapietra, S., Zimanyi, E., Donini, P., Plazanet, C., Vangenot, C., Rognon, N., Pouliot, J., Crausaz, P.A., 1997. MADS: un modele conceptuel pour des applications spatio-temporelles. Revue Internationale de Géomatique 7 (3–4), 317–352.

Parent, C., Spaccapietra, S., Zimanyi, E., Donini, P., Plazanet, C., Vangenot, C., July 11–15, 1998. Modeling Spatial Data in the MADS Conceptual Model. The International Symposium on Spatial Data Handling, SDH 98, Vancouver, Canada.

Parent, C., Spaccapietra, S., Zimanyi, E., November 2–6, 1999. Spatio-temporal conceptual models: data structures + space + time. In: Proceedings of the 7th ACM Symposium on Advances in Geographic Information Systems, Kansas City, USA, 26–33 pp.

Parent, C., Spaccapietra, S., Zimanyi, E., 2006a. Conceptual Modeling for Traditional and Spatio-temporal Applications. Springer.

Parent, C., Spaccapietra, S., Zimanyi, E., 2006b. The MurMur project: modeling and querying multi-representation spatio-temporal databases. Information Systems 31 (8), 733–769.

Pasquasy, F., Laplanche, F., Sainte, J.-C., Donnay, J.-P., 2005. MECOSIG adapted to the design of distributed GIS. In: Meersman, R., Tari, Z., Herrero, P. (Eds.), On the Move to Meaningful Internet Systems 2005: OTM Workshops. Springer Berlin, Heidelberg, 1117–1126 pp.

Percivall, G., 2010. The application of open standards to enhance the interoperability of geoscience information. International Journal of Digital Earth 3, Supplement 1, 14–30.

Pinet, F., Lbath, A., 24–26 April 2003. Object-oriented modelling of communicating GIS-based applications. In: 6th AGILE European Conference on Geographic Information Science, Lyon, 743–750 pp.

Pinet, F., Schneider, M., 2010. Precise design of environmental data warehouses. Operational Research 10 (3), 349–369.

Pinet, F., Kang, M.A., Vigier, F., 2005. Spatial constraint modelling with a GIS extension of UML and OCL: application to agricultural information systems. Lecture Notes in Computer Science 3511, 160–178.

Pinet, F., Duboisset, M., Soulignac, V., 2007. Using UML and OCL to maintain the consistency of spatial data in environmental information systems. Environmental Modelling & Software 22 (8), 1217–1220.

Pinet, F., Duboisset, M., Demuth, B., Schneider, M., Soulignac, V., Barnabe, F., 2009. Constraints Modeling in Agricultural Databases. In: Advances in Modeling Agricultural Systems. Springer.

Pinet, F., Miralles, A., Bimonte, S., Vernier, F., Carluer, N., Gouy, V., Bernard, S., 2010. The use of UML to design agricultural data warehouses. In: International Conference on Agricultural Engineering, AGENG.

Price, R., Tryfona, N., Jensen, C., 1999. A Conceptual Modeling Language for Spatiotemporal Applications, Technical Report.

Proulx, M.J., Larrivée, S., Bédard, Y., 2002. Représentation multiple et généralisation avec UML et l'outil Perceptory, Généralisation et Représentation multiple. Hermes, 113–129 pp.

Raffaetà, A., Ceccarelli, T., Centeno, D., Giannotti, F., Massolo, A., Parent, C., Renso, C., Spaccapietra, S., Turini, F., 2008. An application of advanced spatio-temporal formalisms to behavioural ecology. GeoInformatica 12 (1), 37–72.

Rocha, L.V.d., Edelweiss, N., Lochpe, C., 2001. GeoFrame-T: a temporal conceptual framework for data modeling. In: Proceedings of the 9th ACM International Symposium on Advances in Geographic Information Systems. ACM, Atlanta, Georgia, USA.

Rumbaugh, J., Balaha, M., Premerlani, W., Eddy, F., Lorensen, W., 1991. Object-Oriented Modeling and Design. Prentice-Hall.

Saveliev, A.A., Mukharamova, S.S., Chizhikova, N.A., Budgey, R., Zuur, A.F., 2007. Spatially continuous data analysis and modelling. In: Zuur, A.F., Leno, E.N., Smith, G.M. (Eds.), Analysing Ecological Data. Springer.

Schneider, M., 1999. Uncertainty management for spatial data in databases: fuzzy spatial data types. In: Güting, R., Papadias, D., Lochovsky, F. (Eds.), Advances in Spatial Databases. Springer Berlin, Heidelberg, 330–351 pp.

Shashi, S., Mark, C., Brajesh, G., Duen-Ren, L., Shyamsundar, S., 1997. Data models in geographic information systems. Commun. ACM 40 (4), 103–111.

Shu, H., Spaccapietra, S., Parent, C., Quesada Sedas, D., March 19–20 2003. Uncertainty of geographic information and its support in MADS. In: The 2nd International Symposium on Spatial Data Quality. Hong Kong, China.

Sözer, A., Yazici, A., Oguztüzün, H., Tas, O., 2008. Modeling and querying fuzzy spatiotemporal databases. Information Sciences 178 (19), 3665–3682.

Spaccapietra, S., Parent, C., Zimányi, E., 2007. Spatio-temporal and Multi-representation Modeling: a Contribution to Active Conceptual Modeling. In: Active Conceptual Modeling of Learning, 194–205 pp.

Stempliuc, S.M., Lisboa Filho, J., Andrade, V., Borges, K., 2009. Extending the UML-GeoFrame Data Model for Conceptual Modeling of Network Applications. International Conference on Enterprise Information Systems, Milão, Italy, 164–170 pp.

Tryfona, N., Jensen, C.S., 1999. Conceptual data modeling for spatiotemporal applications. GeoInformatica 3 (3), 245–268.

Tryfona, N., Pfoser, D., Hadzilacos, T., 1997. Modeling Behavior of Geographic Objects: An Experience with the Object Modeling Technique. In: Advanced Information Systems Engineering, 347–359 pp.

Tryfona, N., Anderson, S., Mogensen, S.R., Jensen, C., 1999. A methodology and a tool for spatiotemporal database design. In: The 7th Hellenic Conference on Informatics.

Tveite, H., 2001. Structural modelling for geographical information systems using icons. In: The 8th Scandinavian Research Conference on Geographical Information Science, Norway, 185–201 pp.

UFV, 2011. ArgoCASEGeo Web Page. http://www.dpi.ufv.br/projetos/argocasegeo/indexENG.htm.

Victor de Freitas, S., Lisboa Filho, J., Vilela, V., Andrade, V., 2005. Improving productivity and quality of GIS databases design using an analysis pattern catalog. In: Proceedings of the 2nd Asia-Pacific Conference on Conceptual Modelling, Vol. 43. Australian Computer Society, Inc., Newcastle, New South Wales, Australia.

Wang, K., Fierbinteanu, C., Maekawa, M., 2003. A Conceptual Framework for Spatiotemporal Data Modeling. In: Database and Expert Systems Applications, 57–66 pp.

Yazici, A., Zhu, Q., Sun, N., 2001. Semantic data modeling of spatiotemporal database applications. International Journal of Intelligent Systems 16 (7), 881–904.

Zhong, Z.N., Jing, N., Chen, L., Wu, Q.Y., 2004. Representing topological relationships among heterogeneous geometry-collection features. Journal of Computer Science and Technology 19 (3), 280–289.

Zimanyi, E., Minout, M., 2005. Preserving semantics when transforming conceptual spatio-temporal schemas. In: Meersman, R., Tari, Z., Herrero, P. (Eds.), On the Move to Meaningful Internet Systems 2005: OTM 2005 Workshops. Springer Berlin, Heidelberg, pp. 1037–1046.