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DIOGEN, a multi-level oriented model for cartographic generalization

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ABSTRACT

Among approaches for automated generalization of vector data, we focus on the multi-agent paradigm: cartographic objects are modeled as agents (autonomous objects) that apply generalization algorithms to themselves to satisfy cartographic constraints. Several agent levels are considered, for example, individual agents, such as a building, and agents representing a group of agents, such as an urban block composed of the surrounding roads and contained buildings. Several multi-agent models were proposed to automate the orchestration of map generalization processes. Existing multi-agent generalization models have different approaches to manage the relations between agent levels. In this paper, we unify existing models, adapting a multi-level simulation model, to simplify interactions between agents in different levels. We propose the DIOGEN model, in which the principle of interactions between agents of different levels is adapted to constraint-driven cartographic generalization. DIOGEN unifies three existing multi-agent generalization models (AGENT, CartACom and GAEL), combine their behaviors and take advantage of their skills. Our proposal is evaluated on different use cases: instances of topographic mapping, and mapping of hiking routes over topographic data as an example of thematic mapping.

RÉSUMÉ

Nous nous intéressons aux approches dédiées à la généralisation automatique basées sur le paradigme multi-agents: les objets cartographiques sont modélisés comme des agents (objets autonomes) qui s'appliquent des algorithmes de généralisation pour satisfaire des contraintes cartographiques. Plusieurs niveaux d'agents sont considérés, par exemple des agents individuels, comme un bâtiment, et des agents représentant un groupe d'agents, comme un îlot urbain composé des routes qui l'entourent et des bâtiments qu'il contient. Plusieurs modèles multi-agents ont été proposés pour automatiser l'orchestration d'un processus de généralisation. Les modèles existants gèrent différemment les relations entre les niveaux d'agents. Dans cet article, nous travaillons sur l'unification des modèles existants. Nous simplifions les interactions entre agents des différents niveaux en adaptant un modèle agent récemment défini pour la

KEYWORDS

Cartographic generalization; multi-agent systems; multi-level modeling; interactions; constraint solving problems; topographic mapping; hiking route maps

simulation, et qui met l'accent sur la modélisation du multi-niveau. La modélisation des interactions entre niveaux issue de ce modèle est adaptée au cas de la généralisation cartographique guidée par des contraintes. Le modèle résultant s'appelle DIOGEN. Il unifie trois modèles de généralisation existants (AGENT, CartACom et GAEL), permettant de combiner leurs comportements et leurs capacités. Notre proposition est évaluée sur des cas concrets de cartographie topographique, ainsi que sur de la cartographie conjointe d'itinéraires de randonnée et de données topographiques qui constitue un exemple de cartographie thématique.

1. Introduction

Cartographic generalization is a process that transforms a geographic vector dataset to display a legible map, answering a given user need, at a given smaller scale. This process notably uses simplification and caricature (International Cartographic Association, 1973). To automate generalization, individual algorithms have first been designed to simplify or caricature map objects, and several approaches exist to model a generalization process (Harrie & Weibel, 2007). The agent-oriented approach consists in modeling each geographic object as an agent (i.e. an autonomous entity, cf. e.g. Weiss, 1999), able to generalize itself while considering its direct environment and the nearby elements. These agents select and invoke algorithms to satisfy a set of constraints that describe the expected characteristics of the map objects, as initially proposed by Beard (1990): a building should not be too small, road and building symbols should not overlap, etc. – see, for example, Burghardt, Schmid, and Stöter (2007) for a taxonomy of generalization constraints. Several agent-based generalization models have been proposed in the literature (Baeijs, Demazeau, & Alvares, 1996; Barrault et al., 2001; Duchêne 2003; Gaffuri, 2007; Jabeur, 2006; Ruas, 1998; Sabo, Bédard, Moulin, & Bernier, 2008).

Following the proposal of Ruas and Plazanet (1996) and then Ruas (1998, 2000), in most agent-based generalization models different levels of agents are considered, for example, an agent can represent a single map object, a group of objects, a part of an object or a vertex of an object's geometry. Depending on the considered model, agents interact in different ways with agents of the same level and/or of other levels. Scenarios to use several agent-based generalization models together have been proposed in Duchêne and Gaffuri (2008). One of them, where the models are orchestrated on different parts of the map, was implemented by Touya and Duchêne (2011). This paper explores another scenario, where models are merged by mixing together the atomic behaviors of the agents. The purpose of the DIOGEN model presented in this paper is to formalize the modeling of levels and the interactions between agents at different levels. This proposal is inspired from a model initially designed for agent-based simulation, called PADAWAN (Picault & Mathieu, 2011). Our aim is twofold: first, to make agent-based generalization models easier to understand, parameterize and maintain; second, to foster their interoperability by expressing their behaviors in a common formalism. A preliminary study (Maudet, Touya, Duchêne, & Picault, 2013) identified cases where multi-level interactions enabled by existing agent generalization models would gain to be combined or extended. A first agent generalization model, the AGENT model (Barrault et al., 2001; Ruas, 1998), was

also ported to the PADAWAN paradigm as a first experiment. In this paper, we present the whole model, called DIOGEN, resulting from the porting of two more models, CartACom (Duchêne, 2003; Duchêne, Ruas, & Cambier, 2012) and GAEL (Gaffuri, 2007; Gaffuri, Duchêne, & Ruas, 2008), and how this model was used on real generalization use cases. Section 2 presents the agent-based models on which our new model DIOGEN is based: it briefly describes the three existing generalization models AGENT, GAEL and CartACom and how they manage agent levels and interactions between levels. The section also introduces the principles of the PADAWAN model. In Section 3, we describe the principles of the DIOGEN model and how the three existing multi-agent generalization models are ported to the DIOGEN formalism. In Section 4, we present some proofs of concepts for DIOGEN, on several use cases, showing how agent behaviors stemming from the three existing generalization models are combined and how new agent behaviors are introduced. Finally, Section 5 concludes and draws some perspectives for further work.

2. Agent-based models on which DIOGEN is based

2.1. Agent, CartACom and GAEL: three agent-based generalization models

The three agent-based generalization models on which DIOGEN is based share a common basis: each geographic object present on the map is modeled as an agent, that is, an autonomous computational entity. Its behavior consists in executing series of perception–deliberation–action cycles. The perception stage consists in assessing its internal state and/or its neighborhood, through the evaluation of generalization constraints – internal and shared with the neighbors. The deliberation stage uses generalization procedural knowledge (Beard, 1990) to decide what generalization action should be tried next. The chosen action is then applied (action stage), then confirmed or backtracked after evaluation, and a new cycle begins. The specificities of these models are described hereafter.

2.1.1. Agent

In the AGENT model (Barrault et al., 2001; Ruas, 1998), several levels of agents are considered, especially *micro* agents representing individual objects, and *meso* agents representing groups composed of *micro* or *meso* agents, which can thus be nested (e.g. a city composed of blocks composed of buildings). An agent cannot be part of several *mesos*, which results in a tree-like hierarchical structure. Interactions are hierarchical: a *meso* agent can activate its components or give them orders (Ruas, 2000). This model was successfully applied to hierarchically structured data like urban zones of topographical maps.

2.1.2. CartACom

CartACom (Duchêne et al., 2012) is dedicated to cases where no obvious hierarchy exists. It enables to handle constraints shared by two agents (e.g. proximity) without using an upper (*meso*) level. Instead, interactions are transversal: each agent perceives its neighbors and constraints shared with them (called *relational constraints*), and communicate with these neighbors to inform them about its actions and ask them to act. CartACom agents act as AGENT agents regarding their own non-relational constraints, but cannot be included in any *meso* agent.

CartACom was tested and validated on rural areas of topographical maps, where it is difficult to define hierarchies of agents.

2.1.3. GAEL

GAEL (Gaffuri, 2007; Gaffuri et al., 2008) aims at making geographical objects *locally deformable*, notably to preserve relations with another object that has just been generalized (e.g. enable the terrain to smoothly absorb the displacement of a river segment so that it keeps in a thalweg). Compared to AGENT and CartACom, two levels of agents are added: *deformable* agents and *point* agents – the points composing the geometry of a deformable agent. An additional intermediate level is also considered, called *submicro* objects, not modeled as agents. These are groups of points (a segment, an angle composed of two adjacent segments, a triangle of a triangulation, etc.) that carry length or orientation constraints to preserve the shape of the deformable agent. Point agents act to find a balance between physical forces computed from these constraints.

2.2. PADAWAN, a multi-level paradigm

PADAWAN (Picault & Mathieu, 2011) is a multi-agent model used for multi-level simulation. This model depicts different levels in a formalized way, using the notion of environment. In PADAWAN, an environment is an entity where agents may be located. An environment may be encapsulated by an agent, thus allowing a non-tree-like structure between agents at different levels, which is the reason why we propose to adapt it to multi-level map generalization. Inside each environment, agents may interact in a specific way, the interactions of agents being expressed using an interaction matrix, specific to each environment. An interaction matrix, concept from the interaction-oriented design of agent simulations model (Kubera, Mathieu, & Picault, 2010) on which PADAWAN is based, is a double entry table expressing how an agent type may interact with other agent types using *interactions*. *Interactions* are formalized as the expression of the trigger allowing the interaction (for instance, in an animal simulation, the hunger of an animal may be a trigger of an 'eat' interaction), the preconditions to the execution of the interaction (an animal needs to have access to food in order to execute the 'eat' interaction) and the description of the sequence of actions when executed (when an animal eats, the food disappears and the level of starvation of the animal decreases).

To adapt this model to the specificities of agent-oriented automated generalization, we needed to add some concepts. This results in a new model, DIOGEN, described in the following section.

3. DIOGEN

The DIOGEN model, for 'Distributed Interaction Oriented GENERALisation', uses the principles of PADAWAN to reproduce the existing behaviors stemming from the three agent-oriented generalization models presented above. It includes the main elements of these models, as the algorithms and constraints. If some elements are easily integrated in the PADAWAN formalism, others require specific adaptations.

3.1. Agents, environments and interactions

In generalization models, agents are entities drawn from geographical objects. Hierarchical relations are based on the relation between a meso and its components, or a deformable object and its submicro objects. Agents from generalization models are still represented as agents in DIOGEN. Submicro objects from GAEL are represented as agents too. A meso agent is now modeled as an agent to encapsulate an environment in which its components are included. The submicro agents are located inside an environment encapsulated by the deformable agent.

Actions, based on algorithms that agents may execute, are used as the basis for interactions in DIOGEN. Different situations are identified:

- Actions involving only one agent, which are the standard action in the AGENT model (e.g. geometric simplification (Lang, 1969)), are described as reflexive interactions of the agent (i.e. with itself).
- Actions asked to an agent by another agent in CartACom (e.g. displacement of a building after another building or a road asked for it) are represented as interactions between the two kinds of agents.
- The point agent displacement are described as interactions between this point agent and relevant submicro agents: each submicro agent, motivated by a constraint to satisfy, interacts with the point to let it move.
- Actions of a meso agent on a set of its components are described as interactions between the host (the agent encapsulating the environment), and some agents inside the environment.

3.2. Constraints

In AGENT, CartACom and GAEL, an unsatisfied constraint requires the execution of an action.

In order to include this in DIOGEN, we associate the constraint satisfaction to the precondition notion from PADAWAN. Thus, DIOGEN introduces the notion of *opinion* of constraints. Each constraint carried by an agent may express its opinion on the execution of an interaction, which may be one of the following four:

- *indifferent*: the default opinion, used when knowledge does not exist about the impact of the execution of the action on the agent; for example, a minimum size constraint for buildings is indifferent to simplification algorithms;
- *favorable*: when a constraint is unsatisfied, and existing generalization knowledge assumes that the action may have a good impact on the constraint satisfaction; for example, a minimum size constraint for buildings is favorable to enlarging algorithms;
- *unfavorable*: when existing generalization knowledge expects the action execution to have a negative impact on the constraint satisfaction;
- *opposed*: when knowledge in generalization allows to consider that the constraint satisfaction will decrease, with irreversible modifications; for example, a concavity preservation constraint for concave buildings is opposite to a 'simplify by a rectangle' action that makes the building convex.

In DIOGEN, an agent that is assessing the opportunity to trigger a given interaction synthesizes the opinions of its constraints about this interaction in order to get a conclusion about the interaction. The interaction may be

- feasible: if at least one constraint is favorable, and no other is opposite or unfavorable;
- feasible but risky: if at least one constraint is favorable, at least one is unfavorable and none is opposite;
- not feasible: if no constraint is favorable, or at least one is opposite.

The summarized opinions of constraints are not sufficient to choose which interaction has to be executed in priority. To sort the interactions, we use the notion of trigger from PADAWAN, with the evaluation of a heuristic, taking into account the importance of the constraint, its unsatisfaction and its priority. A more complete description of these principles is available in Maudet, Touya, Duchêne, and Picault (2014).

4. Application cases

In order to validate and give a set of interactions to DIOGEN, we adapt several actions and constraints from AGENT, CartACom and GAEL as interactions inside DIOGEN. Specific configurations of interaction matrices were used in order to reproduce successfully the results obtained in previous models.

This validation done, we used DIOGEN on new generalization cases described in this section.

DIOGEN was implemented on the Geoxygene platform, within the Cartagen library (Renard, Gaffuri, & Duchêne, 2010). All the application cases were validated on this platform. All unique mechanisms from PADAWAN, such as interactions, matrices and environments, and from DIOGEN, such as opinions, have been implemented. Elements from previous generalization models, such as constraints, were partially reused.

4.1. Parallelization of buildings to roads inside urban blocks

In CartACom, an action allows the rotation of a building in order to make it parallel to the road when it is initially approximately parallel. This is possible thanks to a shared constraint between a building and a neighboring road, which requires them to become parallel. Including such an interaction in an urban zone managed by the AGENT model, where agents are subject to collective interactions only, would not be straightforward. However, DIOGEN enables this by creating an interaction matrix containing both interactions from AGENT (reflexive and host-to-agent interactions) and CartACom (agent-to-agent interactions), as described in Maudet et al. (2014) and illustrated in Figure 1. This shows that mixing behaviors stemming from previously separated models (AGENT and CartACom) is made possible by DIOGEN.

4.2. Displacement of dead-end with its neighborhood

The presence of dead-end roads inside urban blocks often causes legibility issues as the road symbol width increases. Simply moving the road is not a good solution, because buildings close to a dead-end road may have a relative position to this dead-end to preserve. In this case, DIOGEN enables the creation of an environment for each dead-end

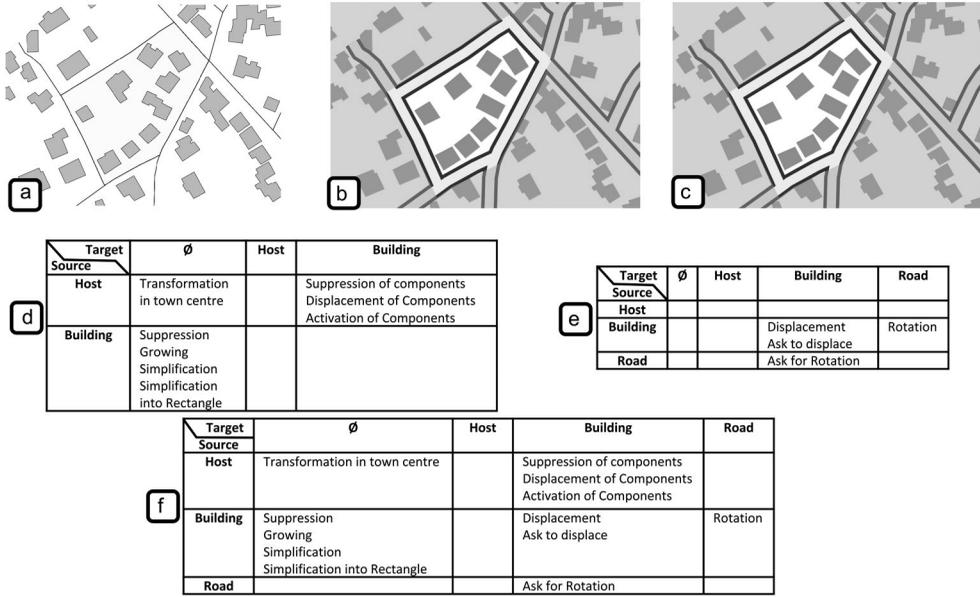


Figure 1. Example of rotation of a building inside an urban block. (a) shows the initial situation and (b) the application of DIOGEN without rotation interaction. (c) shows the generalization using DIOGEN with rotation interaction. (d) shows the interaction matrix used to reproduce AGENT behavior. This matrix is used to obtain results shown in (b). (e) shows the interaction matrix used to reproduce CartACom behavior. (f) shows the interaction matrix using behaviors from both (d) and (e) matrices. It is used to obtain results shown in (c).

containing all the close building agents. This neighborhood agent gets interactions and constraints, allowing gliding on the road where the dead-end is connected, in order to give space to buildings. Figure 2 shows an example of displacement, with the relation between agents and an interaction matrix.

4.3. Generalization of adjacent buildings

Sometimes, adjacent buildings are symbolized in two different ways in order to show the difference of category between the buildings (for instance, a church and a town hall). In order to generalize these building, it is needed to maintain the limit between them, even when the global geometry of the aggregated shape is modified.

By using DIOGEN, we propose a solution for this generalization problem. All points of the buildings are modeled as agents. The segments of the buildings are modeled as agents too, and as environments. Point agents are located inside the segments environment where they belong. During a simplification process applied on the aggregated geometry of two buildings, each point suppressed is added to the new segment, at a position proportional to the two suppressed segments. Left part of Figure 3 explains the evolution of the situation of a suppressed point.

When the simplification process is over, the boundary between the two buildings is used to separate them. The extreme points of this boundary are identified inside the new shape thanks to the preservation of their position inside the segment environments.



Source \ Target	∅	Building	Dead-end Neighborhood
Urban Block as Host	Transform into town center block	Remove Displace Activate	Activate
Building	Enlarge Turn Simplify Replace by a rectangle		
Dead-end Neighborhood	Slide to left Slide to right		

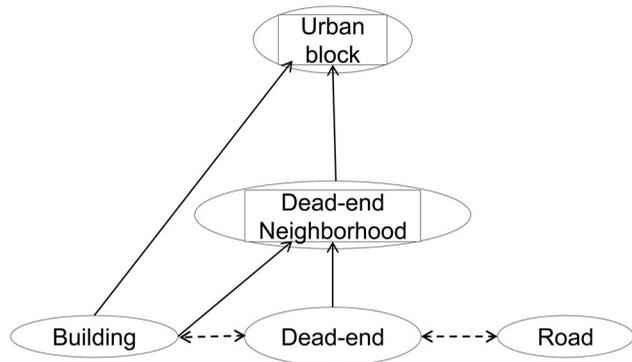


Figure 2. Example of dead-end road gliding with its neighborhood in order to liberate room between it and the southernmost other dead-end. Top left: initial situation. Bottom left: the buildings were enlarged and partially suppressed, and dead-ends glided. Top right: the interaction matrix for the urban block environment. Bottom right: schemas of relations between agent type (plain arrows mean 'situated in').

4.4. Hiking route maps

Including thematic information on top of a topographic map requires an adaptation of the generalization process (Duchêne 2014). A multi-level approach is relevant to address thematic data, because they often use topographical data to refer their positions. For instance, the case of hiking route maps is interesting, because routes are carried by roads and path. When we want to symbolize each route with an independent symbol, such as a bus map, generalization problems occur. First, the choice of the position on the road symbol: which side, and in what order. Second, the addition of symbols creates new constraints on map, with objects in proximity of the roads carrying routes. With DIOGEN, we propose first solutions to solve this kind of map generalization.

First, the positions of the routes on the carrying roads have to be optimally set to minimize the intersections between different routes. In order to solve this problem, we use a Constraint-Oriented Problem (COP)-based approach, described in Teulade-Denantes, Maudet, and Duchêne (2015). This approach gives a first position for routes, but this position may be changed, because this COP approach does not consider the other features of the map that lie around the routes and may be hidden by route symbols. DIOGEN is used afterwards to solve this kind of conflicts between roads carrying routes and another feature.

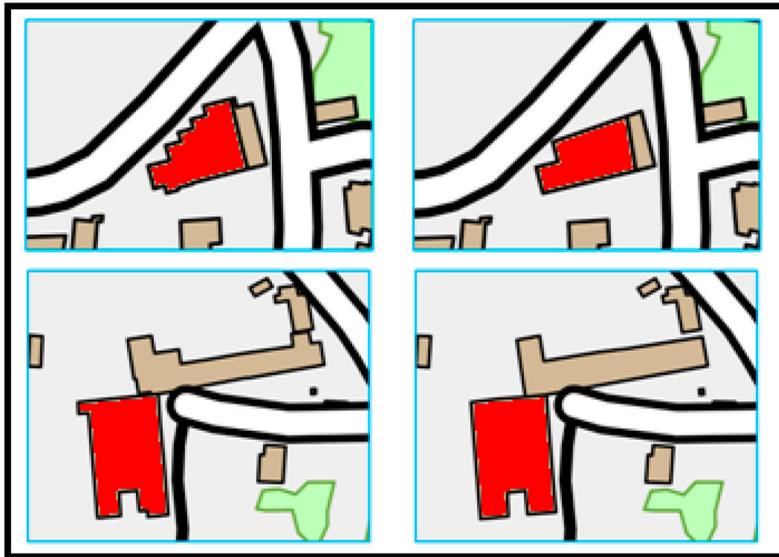
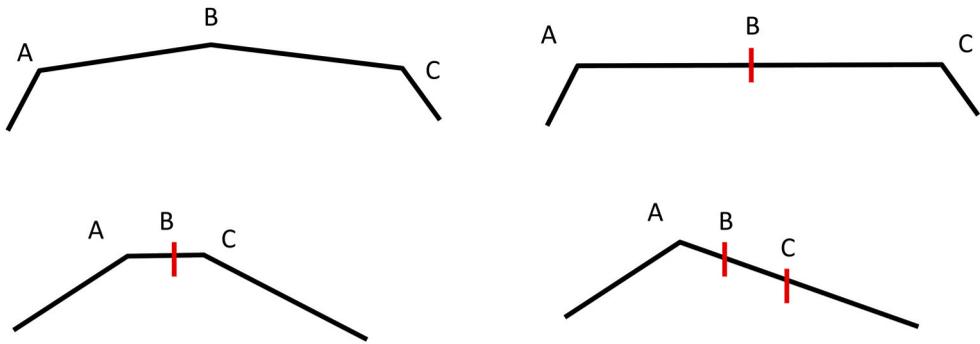


Figure 3. Upper part: on top left, point B, as a vertex, is suppressed in the top right figure, but remains as a point agent located in the environment of segment AC. On bottom left, point C, as a vertex, is suppressed. On bottom right, point B is displaced on the new segment. Bottom part: application of DIOGEN on adjacent buildings. On the left, before generalization, on the right, after the generalization.

4.4.1. Interactions between routes and small objects

When small objects are overlapped by roads carrying routes, the displacements of these objects might be handled by DIOGEN. We introduce an environment representing the road neighborhood. Each building of the road neighborhood gets a relative position, using a coordinate system relative to this environment. When a route changes from one side to another, the buildings are moved in order to preserve their position with respect to the road. [Figure 4](#) shows the organization of agent types for this case.

4.4.2. Interactions between routes and deformable objects

When the road carrying routes is close to a large deformable object, such as a river section, a lake or a coastline, it may only interact with the close part, without interacting with other parts. In order to solve this problem, DIOGEN adds the river points that are near the road

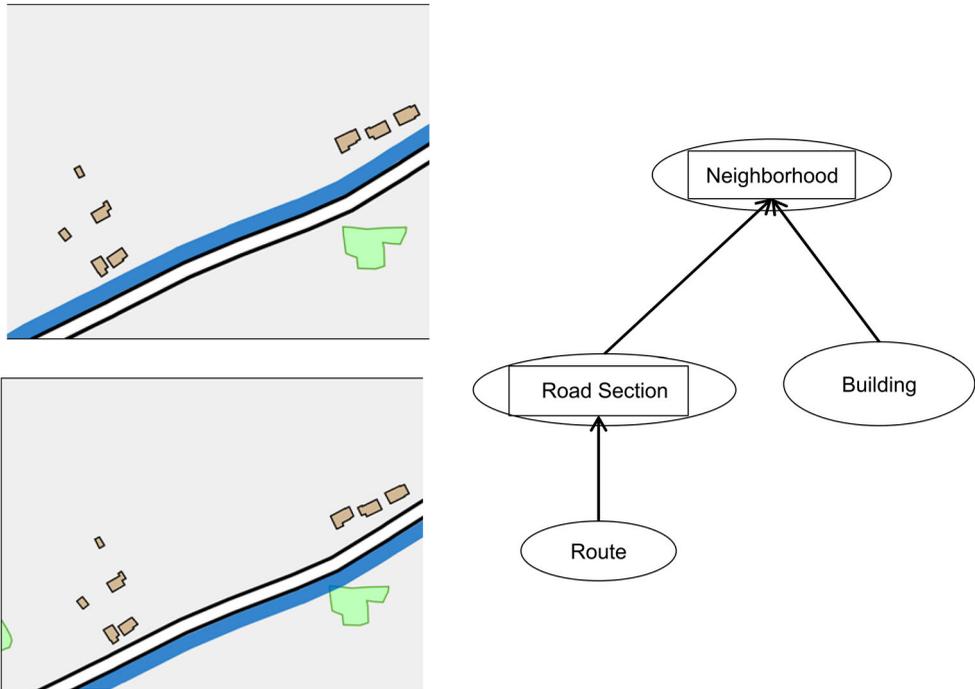


Figure 4. On the left is the instance of displacement: when the route needs to change position, nearby buildings need to move too, in order to preserve their relative position inside the neighborhood of the road. On the right is the organization of agents for this case of buildings displacement.

section inside the neighborhood environment. But these point agents are also part of the deformable object environment, and share relations with other submicro agents inside this environment (i.e. the river line). These point agents have to move using constraints from both environments. The displacement of DIOGEN point agents follows the same principles as in the GAEL model. [Figure 5](#) shows an example of displacement and deformation, and the organization of the agent for this issue. This choice contradicts some good cartographic practice, implying the deformation of the road instead of the deformation of the river (Muller, Lagrange, & Weibel, 1995) because distorting a river might move it out of its bed displayed by the contour lines. But the smoothness of river lines makes them better choices to absorb a local distortion, and the submicro level also allows the joint distortion of the contour lines to preserve the river bed relation (Gaffuri, 2007).

5. Conclusions and perspectives

This paper presented the DIOGEN model and its application on specific generalization cases. The presented examples are proofs of concept that show DIOGEN capacities to unify existing multi-agent generalization models, and to handle different multi-level interactions occurring in map generalization, particularly when thematic data are attached to a topographic map.

However, we now need a demonstration that DIOGEN is viable in a realistic environment where a map is completely generalized. As DIOGEN focuses on multi-level relations, we think that continuing to work on maps with multi-level elements is a good example.

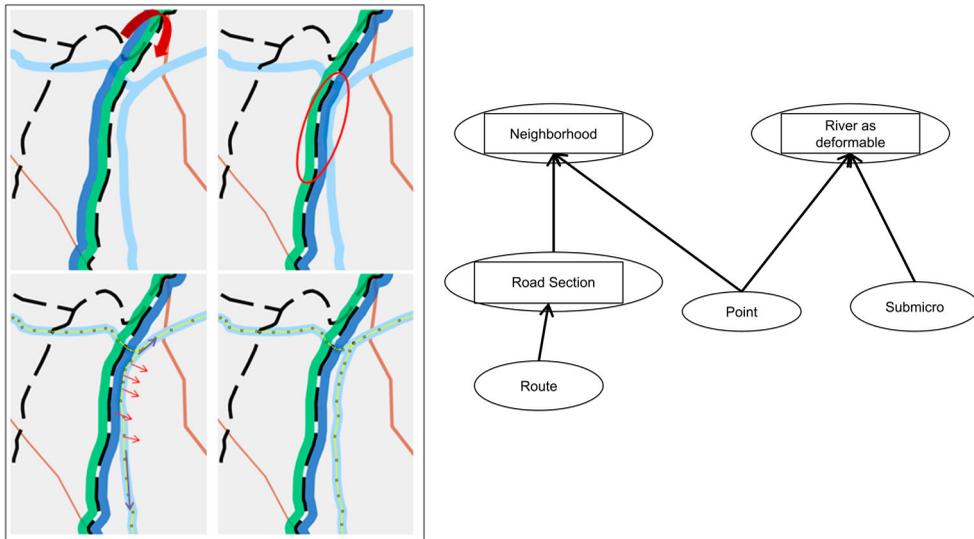


Figure 5. Deformation of a river section. When we want to move a route symbol to the other side of the road, a part of the river is overlapped by the route symbol. This decreases the satisfaction of the constraint shared by the road carrying routes and the points of the river section. Overlapped points decide to move, taking into consideration submicro objects inside the river section, in order to preserve the global shape.

For instance, introducing a relation between points of interest and a specific location on a route may produce new hierarchical relations. The creation of new environments (in DIOGEN terms) to describe these relations will be the first step in order to automate the generalization of such mash-up maps. The second step will be to describe additional constraints (e.g. consistent positioning with the salient feature of the route, like bend) and interactions (e.g. moving the point of interest).

The main issue will be to orchestrate the multiple multi-level interactions between all agents of the map. We guess that techniques such as multiple criteria decision, vote theory and group behavior will be required to scale a DIOGEN process. The use case of hiking maps will be used to go into the orchestration in depth.

Disclosure statement

No potential conflict of interest was reported by the authors.

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