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Spatial Conflict Resolution in a Multi-Agent Process by the Use of a Snake Model

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ABSTRACT In automatic map compilation, both the scale reduction and the geometric transformation of map features may give rise to spatial conflicts. Several generalization approaches have been established to resolve this problem, mainly for the displacement operator. This paper proposes one such approach that is based on the snake model and multiple agents. It focuses on the resolution of various spatial conflicts that emerge when generalizing the rural areas of medium density. In this approach, the map features are converted into map agent, object agent, group agent, and conflicting agent, and the spatial relationships between these features are managed by an auxiliary relationship agent. Each agent is assigned with tasks accordingly, and all agents collaborate with each other to complete the generalization. The snake-based algorithm is applied in the conflicting agent when it identifies a certain configuration. The experimental results indicate that the approach proposed in this paper can obtain good results.

INDEX TERMS Conflict resolution, cartographic displacement, map generalization, multi-agent process.

I. INTRODUCTION

Cartographic generalization is the process of generalizing and abstracting according to the map purpose, scale variation and theme of the map data. Its automation has long been a core issue in automated map generation and multi-scale spatial representation. With the development of automated map generalization, there has been a huge accumulation of algorithms and models in this field [1]. How to complete the complicated task of overall generalization by combining these achievements is currently a research hotspot. Agent technology in the field of artificial intelligence offers a good approach to achieve this goal because it is autonomous, interactive, and its reasoning and decision capabilities enable better simulation of a human's way of thinking, which leads to the autonomous implementation of the generalization tasks when accorded with rules of generalization.

Some scholars have introduced agent technology into the automatic generalization field and developed many multi-agent-based generalization models, including two models applicable to the generalization of different types of landscapes: the AGENT model and CartACom model. The AGENT model proposed by Ruas [2] is well adapted for the generalization of dense, well-structured urban spaces. For rural zones, the CartACom model developed by Duchêne [3] has been successfully applied to the generalization of low-density, heterogeneous data. However, in some rural zones of medium density, CartACom will encounter over-constrained situations, as the density is such that some contextual elimination is necessary. Hence, it is necessary to develop a new model that is dedicated to the generalization of such zones.

One difficulty in the generalization of such zones is how to resolve spatial conflicts among objects. This is because spatial conflicts that emerge in generalization are usually complicated: they may occur between a small number of local spatial objects or between multiple spatial objects of different feature types; in some scenarios, the issue of spatial conflicts cannot be thoroughly resolved merely by the application of a displacement algorithm or graphic generalization. Although multiple displacement algorithms and models have been developed by scholars around the world for the resolution of spatial conflicts, a complete solution is not yet available.

This article presents a combined approach to resolve spatial conflicts that emerge in the generalization of rural zones of medium density. In this approach, we integrate a snake-based procedure for displacement as well as the graphic generalization of map objects into a multi-agent process. The approach is capable of considering multiple types of map features simultaneously. As the feature types of rural maps are mainly buildings and roads, this article takes them as its major research objects.

The proposed approach first converts map features into map agent, object agent, group agent, and conflicting agent, and the spatial relationships between these features are managed by an auxiliary relationship agent. Each agent is assigned tasks accordingly, and all agents collaborate with each other to complete the generalization. The group agent plays a leading role in resolving spatial conflict. According to its built-in rules, it repeatedly goes through a perception-reasoning-decision-action cycle until its goals are satisfied. In this recursive process, conflicting agents are created dynamically, and then appropriate actions are executed according to the types of conflicts. The execution of the action implies the triggering of a certain algorithm, which mainly refers to the snake-based displacement in this article.

This article is structured as follows. After the introduction (section 1), section 2 sketches out the state of the art for the agent-based approaches and displacement algorithms in generalization. Section 3 presents in detail the principles of the snake model and key issues in its application. Section 4 describes the framework of a multi-agent process and how to build the snake model into this framework to resolve spatial conflict. Section 5 conducts an experiment with real data to verify the effectiveness of the approach and discusses the experimental results. Section 6 presents the conclusion of this article.

II. RELATED WORK

The related work section will briefly review the current use of the agent-based approaches in cartographic generalization and displacement algorithms.

A. CURRENT USE OF THE AGENT-BASED APPROACHES

In the late 1990s, interest arose in modeling the generalization process by a multi-agent paradigm. The core idea is that map objects are modeled as agents or active and autonomous entities that select and apply proper generalization actions to themselves in order to satisfy their goals. Some scholars have tried to make use of multi-agent systems for generalization of particular map themes, such as road network generalization [4], polygon generalization [5], [6], urban structure generalization [7] and isobath generalization [8]–[10]. Other scholars have focused on developing models for particular landscapes.

Among the many agent-based generalization models, the most representative one is the AGENT model, which was first proposed by Ruas [11], [12] and then enriched by the European AGENT project [13], [14]. The model divided agents into three levels (micro, meso, and macro), and each level of agents has its own constraints to meet. The hierarchical organization of agents makes this model highly suitable for the generalization of urban blocks. For rural areas where no obvious hierarchy exists, Duchêne [3] proposed another approach called CartACom, which only considers the micro agents. The model focused on modeling relational constraints shared by two micro agents and allowed transversal interactions between agents. Later, a prototype generalization system was developed that included the two complementary models [15]. Gaffuri [16] proposed a GAEL model that addresses the particular relations between background fields (such as relief and land use) and the foreground themes (such as buildings, roads or rivers).

The three models each generated very encouraging results. However, they all have limitations that prevent them from being the solution to a complete generalization. One promising approach is to seek the possible synergies between them. For example, Duchêne and Gaffuri [17] compared the three models and explored three complementary scenarios for their combined use. After that, the first scenario was further studied and extended to include other existing generalization models (Least Squares, Elastic Beams, etc.), resulting in a new model called CollaGen [18]–[20]. In this scenario, the map space is partitioned spatially and/or thematically, and different models are applied to corresponding space. Recently, Maudet *et al.* [21] proposed a DIOGEN model, which explores another scenario. The model considers management of agent levels and interactions between levels. In the foreseeable future, the orchestration of several existing models in generalization will remain an important research task.

B. DISPLACEMENT ALGORITHM REVIEW

In map generalization, the displacement operator is mainly applied to resolve spatial conflicts. Over decades, considerable research efforts have been directed toward the development of automated displacement methods. Technically, these approaches can be distinguished into two types, namely, sequential and global approaches.

In a sequential approach, map objects in conflict are handled one by one. After analyzing the conflict situation and calculating possible displacement vectors, appropriate objects are chosen to execute the displacement in a particular order. Examples include a road displacement algorithm, which emphasized the importance of junctions [22]; a proportional radial algorithm for point cluster displacement [23]; a translation algorithm that makes use of a constrained Delaunay triangulation to detect and resolve proximity conflicts [24]; and a complex approach using the control strategy based on constraints analysis and evaluation [25]. Generally, geometric approaches are sophisticated to implement, and secondary conflicts may occur repeatedly, which lead to poor algorithm convergence.

Due to the limitations of sequential approaches, the interest in automated displacement research has been focused on the introduction of optimization techniques to provide a holistic treatment for displacement. In contrast to sequential methods, a global method aims at taking multiple map objects into account and resolving all conflicts simultaneously.

One class of global methods is conducted using combinatorial optimization techniques, such as gradient descent [26], simulated annealing [26], [27], tabu search [28], and genetic algorithm [29], [30]. In these methods, the displacement space of each map object in spatial conflict is first discretized into a finite trial position. Then, a set of possible configurations can be obtained by means of placing conflicting objects in different positions. Finally, an acceptable solution can be found from these configurations using heuristic search algorithms. One drawback of these approaches is the complexity of the search, which may increase dramatically when the number of map objects and/or the trial positions increase.

Another class of global methods is based on continuous optimization techniques. They are more complicated and more reasonable than the combinatorial approaches. By introducing various models developed in physics or engineering fields, the problem of displacement is modeled as the process of finding the optimal solution to a global equation system. Examples of such approaches are as follows. Højholt [31] presented a finite element method (FEM) from structural mechanics, which models the map as an elastic rubber sheet. The least squares adjustment method [32]–[35] converted all displacement constraints into equations and resolved the conflicts in a mathematical way. The spring model [36] and the snake model [37] achieved displacement by seeking an equilibrium of different forces. Bader [38] systematically summarized the principle of the energy minimization displacement algorithm and proposed an elastic beam method based on the snake model. The snake model and elastic beam model were originally used for the displacement of linear features. Recently, several algorithms were developed to use these two models to handle building displacement [39]–[41]. Ai *et al.* [42] developed a displacement algorithm based on vector fields from the physics discipline. This algorithm performs the displacement in a holistic way, although it does not use optimization techniques.

III. THE SNAKE MODEL

The snake model was first proposed by Kass *et al.* [43] and applied in the field of computer vision. After being introduced by Burghardt and Meier [37] into the field of cartographic generalization and applied in the displacement of linear objects, the snake model has been widely used in generalization. The snake model is not only applicable to the displacement of linear features but also capable of building displacement by constructing the connection lines between buildings. In addition, the snake model has the advantages of small displacement propagation and good maintenance of geometric characteristics. Therefore, this article uses the snake model as the major algorithm for displacement in resolving conflict.

A. THE PRINCIPLE OF THE SNAKE MODEL

A snake is an energy minimizing spline consisting of internal energy and external energy. In displacement algorithms based on the snake model, the description of energy is represented by the most basic displacement magnitude. Specifically, internal energy is described by the change to the geometry of linear features after displacement, while external energy is described by the spatial conflicts between neighboring linear features. The optimal shape and location of a curve after displacement is calculated under the principle of minimum energy.

Formula (1) is for the calculation of displacement magnitude:

$$s \mapsto d(s) = (x(s) - x_0(s), y(s) - y_0(s))^T, \quad 0 \leq s \leq l \tag{1}$$

where l represents the length of the line, x_0(s) and $y_0(s)$ represent the original coordinates of l before displacement, $x(s)$ and $y(s)$ represent the coordinates of l after displacement, and $d(s)$ represents the displacement magnitude.

Formula (2) is for the calculation of total energy:

$$E(d) = \int_l (E_{int} + E_{ext}) ds \tag{2}$$

where $E\,(d)$ represents total energy, E_{int} represents internal energy, and E_{ext} represents external energy.

Formula (3) is for the calculation of internal energy:

$$E_{int} = \frac{1}{2}(\alpha(s)|d'(s)|^2 + \beta(s)|d''(s)|^2) \tag{3}$$

where $d'\,(s)$ and $d''\,(s)$ are the first-order and the second-order derivative of the displacement magnitude $d(s)$ on s, respectively, and they reflect the degree of deformation caused by displacement; the parameters $\alpha\,(s)$ and $\beta\,(s)$ decide the elasticity and stiffness of the snake model, respectively, and they reflect the properties of the model and play a role in controlling the effect of displacement, both of which are collectively referred to as geometric parameters. External energy is produced from conflicting map symbols and is in direct proportion to the severity of conflict. External energy resolves the conflict by stimulating displacement and deformation of the line.

The principle of the snake model is to keep the total energy value of internal and external energy to the minimum. Therefore, the displacement magnitude of each point on the curve when $E\,(d)$ takes its minimum value needs be determined. The matrix equation of $\boldsymbol{K}^{\mathbf{e}}\boldsymbol{D}^{\mathbf{e}}=\boldsymbol{F}^{\mathbf{e}}$, as shown at the bottom of the next page, is finally obtained with the Euler equation, finite element method and a series of transformation. In this matrix equation, $\boldsymbol{K}^{\mathbf{e}}$ represents the element stiffness matrix of the segment, $\boldsymbol{F}^{\mathbf{e}}$ represents the force matrix of the segment element, and $\boldsymbol{D}^{\mathbf{e}}$ represents the displacement magnitude and change to the first-order derivative of the starting and finishing points of the segment under the effect of the force matrix $\boldsymbol{F}^{\mathbf{e}}$.

In these matrices, h represents the length of the segment between two points; x_0 and x_1 are the coordinates of two end points of the segment in the direction of x; accordingly, $d(x_0)$ and $d(x_1)$ represent the displacement magnitude of two end points in the direction of x, while $d'\,(x_0)$ and $d'\,(x_1)$ represent the first-order derivative of two end points in the direction of x; and $f\,(x_0)$ and $f\,(x_1)$ represent the component of force on two end points in the direction of x.

The snake algorithm decomposes the displacement into the directions of x and y and determines the real displacement magnitude by combining the displacement magnitudes in the directions of x and y. After achieving the element stiffness matrix of each segment, all element stiffness matrices are combined according to their order of connection into a global stiffness matrix $\boldsymbol{K}$. $\boldsymbol{K}$ is a sparse singular matrix and its inverse matrix cannot be obtained. To obtain the solution of the matrix equation, boundary conditions need be added to the global stiffness matrix to convert $\boldsymbol{K}$ into a regular matrix which is solvable.

Because the situation in most conflict zones is complicated and there exist many objects in conflict, it is usually impossible to thoroughly resolve all conflicts with a single operation. Instead, conflicts need be resolved with an iterative method. The equation to resolve spatial conflicts with the iterative method by the snake algorithm is as below:

$$(1+\gamma K)d^{t}=d^{t-1}+\gamma\mu f^{t-1} \tag{4}$$

In this equation, $\boldsymbol{K}$ represents the global stiffness matrix; $\mathbf{1}$ represents the identity matrix; t represents the number of iterations; d^{t} and d^{t-1} are the displacement vectors for the t iteration and the $t-1$ iteration, respectively; f^{t-1} is the force vector of each point in the $t-1$ iteration. γ is the iteration step, which is related to the positional accuracy of the object's displacement. The smaller γ, the smaller displacement magnitude in each iteration. μ is to enlarge the force so that external energy would be enlarged, thus resolving the conflict faster by enabling external energy to lead the movement of internal energy.

B. TYPES OF SPATIAL CONFLICTS

In map generalization, spatial conflicts have a variety of types, among which the most common one is proximity conflict. Proximity conflict refers to conflict arising from the fact that the distance between map objects is closer than the required visual separation. Topological conflict is the upgraded version of proximity conflict and refers to the inconsistency of the object's topological relations before and after generalization. In this article, topological conflict mainly refers to the phenomenon in that objects that were separate from each other before generalization become overlapped or intersected after generalization. This type of conflict may be caused by various reasons. As illustrated in Fig. 1(a) and Fig. 1(b), building enlargement may cause topological conflict between buildings or between buildings and neighboring roads; as illustrated in Fig. 1(c) and Fig. 1(d), graphic simplification and displacement of a road may also cause topological conflict between the road and its neighboring buildings.

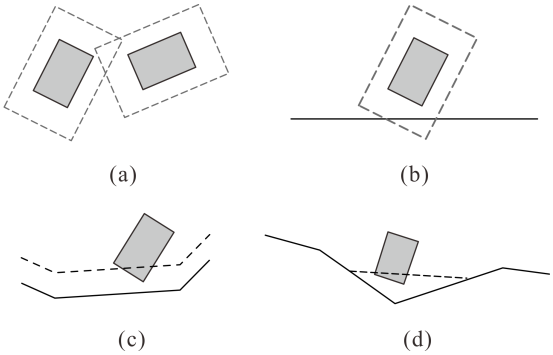

FIGURE 1. **Four types of topological conflicts.**

Based on the above definition of proximity conflict and topological conflict and in combination with the feature types of spatial objects involved in conflict, five types of conflicts are defined as below:

BBP-conflict: the proximity conflicts between a pair of buildings;

BLP-conflict: the proximity conflicts between a building and a road;

LLP-conflict: the proximity conflicts between a pair of roads;

$$K^{e}=\begin{bmatrix}\dfrac{6(\alpha h^{2}+10\beta)}{5h^{3}} & \dfrac{\alpha h^{2}+60\beta}{10h^{2}} & -\dfrac{6(\alpha h^{2}+10\beta)}{5h^{3}} & \dfrac{\alpha h^{2}+60\beta}{10h^{2}}\\ \cdots & \dfrac{2(\alpha h^{2}+30\beta)}{15h} & -\dfrac{\alpha h^{2}+60\beta}{10h^{2}} & -\dfrac{\alpha h^{2}-60\beta}{30h}\\ \cdots & \cdots & \dfrac{6(\alpha h^{2}+10\beta)}{5h^{3}} & -\dfrac{\alpha h^{2}+60\beta}{10h^{2}}\\ \cdots & \cdots & \cdots & \dfrac{2(\alpha h^{2}+30\beta)}{15h}\end{bmatrix}$$

$$D^{e}=\begin{bmatrix}d(x_0)\\ d'(x_0)\\ d(x_1)\\ d'(x_1)\end{bmatrix}\quad F^{e}=\begin{bmatrix}\dfrac{1}{2}hf(x_0)\\ \dfrac{1}{12}h^{2}f(x_0)\\ \dfrac{1}{2}hf(x_1)\\ -\dfrac{1}{12}h^{2}f(x_1)\end{bmatrix}$$

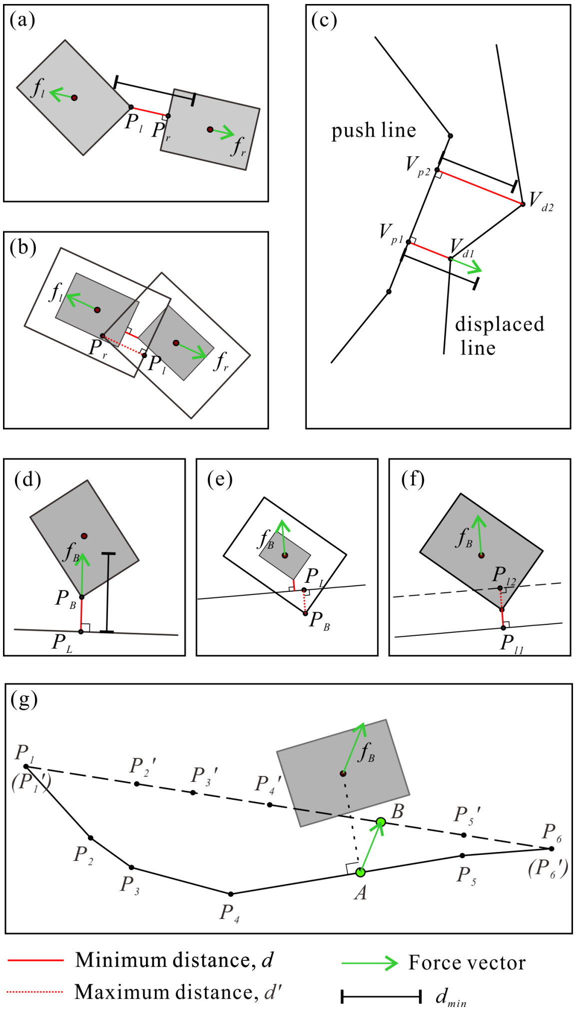

FIGURE 2. Seven force models for proximity and topological conflicts.

BBT-conflict: the topological conflicts between a pair of buildings;

BLT-conflict: the topological conflicts between a building and a road.

C. CALCULATION OF INITIAL DISPLACEMENT VECTORS

In displacement of objects with the snake model, different types of spatial conflicts have different initial displacement vectors. An initial displacement vector is the initial force vector of a conflict object. Seven types of force models have been defined for these five types of conflicts to calculate their initial displacement vectors (Fig. 2), among which (a), (c) and (d) are the force models designed for proximity conflicts, and (b), (e), (f) and (g) are those for topological conflicts.

1) INITIAL DISPLACEMENT VECTORS OF PROXIMITY CONFLICTS

To avoid conflict on maps, the distance between neighboring objects shall be more than the minimum distance threshold, d_{min}. The value of d_{min} can be determined with Formula (5) as below:

$$d_{\min} = d_c + (s_1 + s_2)/2 \tag{5}$$

where d_c is the minimum separation distance between objects required to ensure readability on the maps (e.g., 0.2 mm), and s_1 and s_2 are symbol widths of the two neighboring objects. Where the distance between a pair of neighboring objects is smaller than the threshold value, a conflict exists, and the severity of such a conflict can be evaluated with Formula (6) as below:

$$s_p = d_{\min} - d \tag{6}$$

where d represents the minimum distance between a pair of features.

For a BBP-conflict (Fig. 2(a)), the push forces that act on the left and right buildings are calculated as follows:

$$\overrightarrow{f_l} = \frac{1}{2} s_p \frac{\overrightarrow{P_r P_l}}{|P_r P_l|} \tag{7}$$

$$\overrightarrow{f_r} = \frac{1}{2} s_p \frac{\overrightarrow{P_l P_r}}{|P_l P_r|} \tag{8}$$

For a LLP-conflict, a vertex-line force model is adopted to calculate the initial displacement vector. Specifically, the minimum distance of each vertex on the displaced line (except for the end points) to the push line is to be calculated. Where the minimum distance of a vertex is smaller than d_{min}, this vertex bears force. Otherwise, this vertex bears no force. As illustrated in Fig. 2(c), the forces that V_{d1} and V_{d2} bear are $s_p \frac{\overrightarrow{V_{p1} V_{d1}}}{|V_{p1} V_{d1}|}$ and $\mathbf{0}$, respectively.

For a BLP-conflict, the road stays still, which means the force is $\mathbf{0}$. The conflict is resolved by displacing the building. As illustrated in Fig. 2(d), the formula for the calculation of the force on the building is as below:

$$\overrightarrow{f_B} = s_p \frac{\overrightarrow{P_L P_B}}{|P_L P_B|} \tag{9}$$

2) INITIAL DISPLACEMENT VECTORS OF TOPOLOGICAL CONFLICTS

According to the above description of a topological conflict, the severity of a topological conflict can be evaluated with the formula as below:

$$s_t = d' + d \tag{10}$$

where d' is the maximum distance between two objects in the overlapped zone; d is the minimum distance between original objects. It is discovered that a proximity conflict may still exist even after a topological conflict has been resolved.

For a BBT-conflict (Fig. 2(b)), the push forces that act on the left and right buildings are calculated as follows:

$$\overrightarrow{f_l} = \frac{1}{2} s_t \frac{\overrightarrow{P_l P_r}}{|P_l P_r|} \tag{11}$$

$$\overrightarrow{f_r} = \frac{1}{2} s_t \frac{\overrightarrow{P_r P_l}}{|P_r P_l|} \tag{12}$$

For a BLT-conflict, the initial displacement vector of objects involved in the conflict varies according to the different causes of conflicts. In the occurrence of the type of topological conflict in Fig. 1(b), the calculation of the initial displacement vector is illustrated in Fig. 2(e) and the formula for the force on the building is as below:

$$\overrightarrow{f_B} = s_t \frac{\overrightarrow{P_B P_L}}{|P_B P_L|} \tag{13}$$

In the occurrence of the type of spatial conflict in Fig. 1(c), the calculation of the initial displacement vector is illustrated in Fig. 2(f) and the formula for the force on the building is as below:

$$\overrightarrow{f_B} = s_t \frac{\overrightarrow{P_{l1} P_{l2}}}{|P_{l1} P_{l2}|} \tag{14}$$

In the occurrence of the type of topological conflict in Fig. 1(d), the calculation of the initial displacement vector is illustrated in Fig. 2(f). The graphic simplification of a line is viewed as displacement of points on the line and as illustrated in Fig. 2(f), the point of P_2' can be viewed as the point of P_2 after displacement when the solid line has been simplified into a dotted line. The initial displacement vector of the building is $\overrightarrow{AB}$, in which the point of B is the corresponding point of Aafter simplification of the line and can be calculated with the equal-proportion distance method. First, the curve lengths from A respectively to the end points of P_1 and P_6 are calculated on the curve segment of $P_1P_2P_3P_4P_5P_6$; then, the position of B on the linear segment of $P_1'P_6'$ is calculated according to the ratio of the two curve lengths.

D. STRUCTURE LINE OF DISPLACMENT

As roads have linear characteristics naturally, the snake algorithm can be applied to them directly. Unlike the road feature, buildings are discretely distributed on a map. When applying the snake algorithm to building displacement, a structure line is created to serve as a snake. When establishing structure lines, buildings can be treated as rigid objects that cannot be deformed and they are denoted with their centers of gravity. The method to construct the structure line is illustrated below by taking some roads and their neighboring buildings as an example.

A spatial conflict like that illustrated in Fig. 2(e) or Fig. 2(g) may arise after enlargement of the building or graphic simplification of the road, and the shortest distance line, such as the red linear segment in Fig. 3, needs be drawn between the center of the building and the original road (the black solid line in Fig. 3). For a spatial conflict, such as that illustrated in Fig. 2(d), the shortest distance line is drawn between the center of the building and the generalized road like the blue linear segment in Fig. 3. Similarly, when a road needs to be displaced, it is necessary to determine whether new conflicts may arise between the road and its neighboring buildings. Where new conflict may arise as in Fig. 2(f), a similar blue linear segment need be drawn as in Fig. 3.

As building groups in rural areas are generally distributed (or arranged) along the roads, disruption to this spatial characteristic by displacement would go against relevant cartographic rules. This problem can be handled collaboratively in the process of displacement, and MST (Minimum Spanning Tree) is a good method to express such spatial characteristics. An MST graph with distance between each pair of buildings as weight is utilized as structure lines of displacement to maintain the linear distribution or arrangement so far as possible as illustrated in Fig. 3.

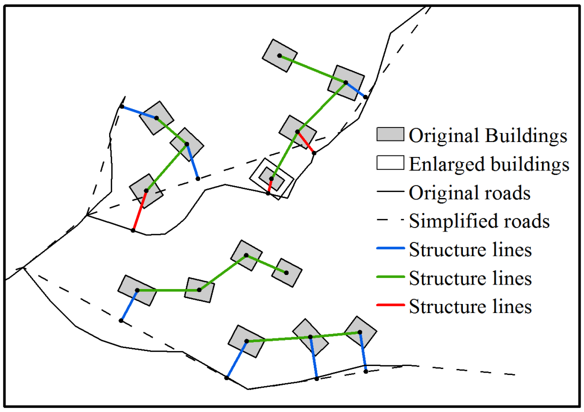

FIGURE 3. Structure lines of building displacement.

Where there is spatial conflict only between buildings, MST itself can serve as the structure line. Where there is conflict between buildings and their neighboring roads, MST together with the straight lines that link buildings and their adjacent roads constitutes the structure line. The snake algorithm is applied to the structure line to achieve building displacement. Some points on the structure line stay still when displacement is performed, e.g., the points inserted into a road to connect the road with buildings. These points are added in the snake equation as boundary conditions.

IV. THE COMBINED APPROACH

This section first introduces the classification of agents in the combined approach as well as the mechanism of the transmission and response of information between different agents. As the group agent is the main agent to resolve spatial conflict, the internal reasoning mechanism of the group agent is then described in detail.

A. CLASSIFICATION OF AGENTS

In cartographic generalization with agent technology, it is usually necessary to divide map space into different levels of agents, and each agent has its own goal and implements corresponding generalization tasks to achieve such goal. This part describes the classification of agents (Fig. 4) and the goals of each agent in our approach.

1) MAP AGENT (MA)

The map agent includes all map objects involved in generalization. The map agent is responsible for the initialization of each sub-level agent as well as the decomposition and assignment of generalization tasks.

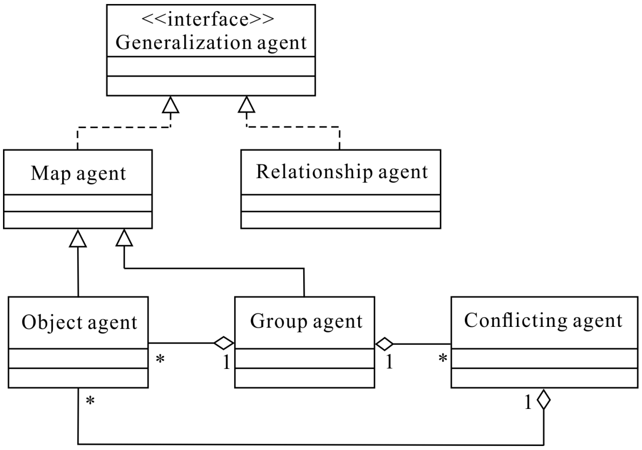

FIGURE 4. Classification of Agents.

2) OBJECT AGENT (OA)

Object agent refers to a single map object of a certain type of map feature and has two categories, i.e., road object agent (ROA) and building object agent (BOA). The object agent is equivalent to a micro agent in the AGENT model. The object agent has two functions. One is to generalize the object itself, specifically the simplification of ROA and the enlargement of BOA in this article; the other is to implement generalization actions like elimination and displacement as required by the group agent.

3) GROUP AGENT (GA)

Group agent refers to a set consisting of object agents interacting with each other. The GA stores the references of these object agents instead of their physical entities, which means the geometry transformation of these object agents arising from self-generalization would be reflected in the GA. The objective of the GA is to resolve spatial conflict and can be classified into multiple levels as needed. Where object agents contained in the GA are the same type of features, this GA is homogeneous; otherwise, this GA is heterogeneous.

4) CONFLICTING AGENT (CA)

A conflicting agent is a special type of group agent and consists of object agents among which there exists conflict currently or there exists no conflict currently but may give rise to conflict in the process of generalization. The CA is dynamically constructed in the process of generalization according to the characteristics of the specific conflict. The CA only reacts to external requirements and then resolves the conflict with the appropriate algorithm.

5) RELATIONSHIP AGENT (RA)

The relationship agent is responsible for the construction and dynamic update of the spatial relationship of all object agents as well as the provision of spatial relationship query service and conflict detection service for the implementation of generalization tasks. The RA stores the spatial relationship between objects but contains no map data. The RA detects the proximity and topological relationship between objects with methods, such as constrained Delaunay triangulation and buffers, and stores the detected relationship in the spatial relationship table, as illustrated in Table 1. The row of *Neighboring or Not* has two effective values, 0 and 1. Zero represents two objects are not neighboring, while 1 represents two objects are neighboring. The rows of *Topological Relationship* also have two effective values: 0 if two objects deviate from each other and 1 otherwise. The initial topological relationship remains unchanged once it has been determined and is compared with the current topological relationship to determine whether topological conflict has arisen.

TABLE 1. Spatial relationship table.

Object1		Object2		Neighboring or Not	Topological Relationship	
type	ID	type	ID		Initial	Current

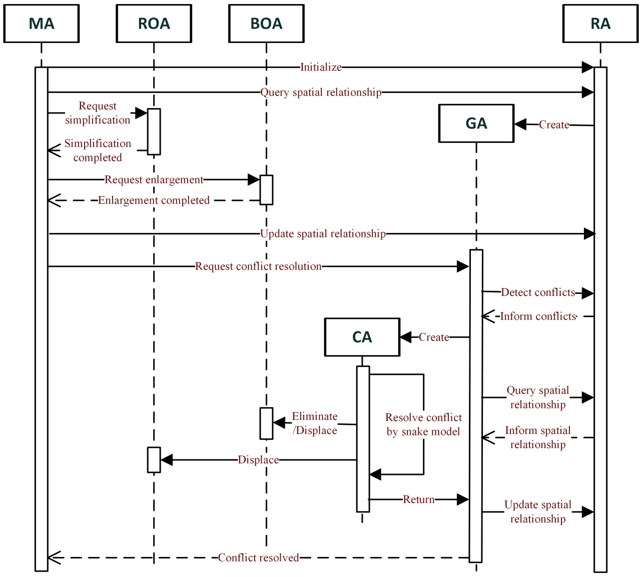

FIGURE 5. Diagram of interaction between agents.

B. INTERACTION BETWEEN AGENTS

The resolution of spatial conflict requires the agents to collaborate with each other. Fig. 5 illustrates the mechanism of the transmission and response of information between different agents in the process of generalization.

After being activated, the MA will convert the road data and building data in the map into ROAs and BOAs, respectively, and then inform the RA to construct the initial spatial relationship between all objects of these two types of map features and store it in its internal spatial relationship table.

After that, the MA creates group agents with a process of first clustering and then dividing, the major steps of which are as below. First, create a buffer zone for each object agent

TABLE 2. Reasoning rules to solve spatial conflict.

	IF	THEN
Rules to detect conflict	GA activated Displacement of ROAs completed Displacement of BOAs completed	Determine existence and type of conflict
Sequence rules to resolve conflict	Co-existence of topological and proximity conflict	Resolve topological conflict first
	Co-existence of BBT-conflicts and BLT-conflicts	Resolve BBT-conflict first
	Existence of proximity conflict	Resolve LLP-conflict first, then BLP-conflict and BBP-conflict finally
	Conflict can be resolved either by displacement or elimination	Select displacement
	Existence of conflict between road object and building object	Resolve conflict by displacement of building object

TABLE 3. Rules to process topological conflict.

Type of Conflict	Condition	Actions
BBT-conflict	Involving more than two buildings	Iterative elimination
	Involving two buildings	Construction of CA; direct displacement Local elimination
BLT-conflict	Cannot be resolved by displacement	Local elimination
	No other object within displacement propagation range	Construction of CA; direct displacement
	Existence of other object(s) within displacement propagation range	Construction of CA; implementation of collaborative displacement based on snake model

by drawing a circle with the maximum displacement distance allowed in a map (0.5 mm) as the radius. The object agents whose buffer zones overlap with each other collectively constitute an initial group agent. For homogeneous group agents, the step of construction is finished so far. For heterogeneous group agents, implement iterative division among the buildings with roads contained in the agent until no building is separated by a road. The roads used in division belong to both sub-group agents that are created through division at the same time.

The GA remains in a waiting status temporarily after its construction. At this point, the MA will require each object agent to implement self-generalization, mainly the simplification operation on roads and enlargement operation on buildings. Both of these two generalization operations may lead to changes to the topological relationship between objects. Therefore, the RA will be informed to update the current topological relationship in its relationship table after the completion of such operations.

The GA is activated to resolve spatial conflict after graphic generalization of all objects. In this process, the RA is utilized to detect spatial conflict, and the CA is constructed dynamically as needed. The appropriate method is selected according to the conflict type and the number of objects affected by displacement. When resolving the conflict, the CA may request displacement of the involved ROAs or elimination or displacement of the involved BOAs. The CA will be destroyed after resolution of the conflict, at which time the spatial relationship table in the RA will need to be updated. For a very conflicted GA, this process as described may require multiple iterations in order to resolve the conflict finally and thoroughly.

C. INTERNAL REASONING OF THE GA

Once it has been activated, the GA will determine by itself the action to take to resolve conflict according to the specific situations of the conflict, i.e., resolving different types of spatial conflicts in a map by collaborating different operators and algorithms under specific rules. Table 2, Table 3 and Table 4 display a set of rules to follow to resolve spatial conflicts. The GA is driven by these rules to make decisions on what action to take.

TABLE 4. Rules to process proximity conflict.

Type of Conflict	Condition	Actions
LLP-conflict		Construct CA; implement road displacement based on snake model
BLP-conflict	Existence of other objects within displacement propagation space	Construct CA; implement collaborative displacement based on snake model
	Non-existence of any other objects within displacement propagation space	Construct CA; displace directly
BBP-conflict	Existence of displacement propagation	Construct CA; implement building displacement based on snake model displacement
	Non-existence of displacement propagation	Construct CA; direct displacement

D. RULES TO PROCESS TOPOLOGICAL CONFLICT

The typical operations used to resolve topological conflict are the displacement and local elimination of buildings, and the former is preferred where possible. According to the rules to process conflict in Table 2, the type of conflict that need be resolved first at this stage is BBT-conflict and then BLT-conflict. The specific rules are displayed in Table 3.

When starting to resolve topological conflict, a building may have topological conflict with more than one building around it. In this situation, the buildings in conflict only have limited space for displacement. Therefore, an action of iterative elimination is taken first to release space. In this action, elimination is computed step-by-step. At each step, an elimination cost of each building is computed. This cost function is the sum of overlapped areas between a building and its neighboring buildings, which is detected through overlay analysis. At each step, the building with the highest value of cost function is eliminated, and then the cost of contiguous buildings is updated. Iterations are repeated until each building has a topological conflict with no more than one building.

After iterative elimination, implement displacement directly according to the initial displacement vector in Fig. 2(b) for any pair of building agents between which there still exists topological conflict. After displacement, determine whether there exists conflict between this pair of building agents and any other buildings agents. Where secondary conflict arises, eliminate the building with higher secondary conflict. After the process as above, the topological conflict between buildings are resolved thoroughly.

For a BLT-conflict, pre-elimination needs to be implemented before displacement. Specifically, it is analyzed in advance whether this conflict can be finally resolved through displacement of the involved BOA. If not, the BOA is eliminated. The standard to determine pre-elimination is to calculate the minimum displacement distance of the BOA needed to resolve the conflict and then compare it with the maximum displacement distance of map objects (0.5 mm) allowed. If it exceeds the allowed maximum displacement distance of map objects, implement elimination, as such conflict cannot be resolved by displacement. Otherwise, construct a CA and select the displacement method according to whether there exists any other object within its displacement propagation range. The value of the minimum displacement distance needed can be set with Formula (15):

$$D = d' + d_{\min} \tag{15}$$

where d' is the maximum distance between two objects within the overlapped areas, and d_{min} has the same definition as in Formula (5).

E. RULES TO PROCESS PROXIMITY CONFLICT

In the collaborative generalization of different features, the generalization sequence of different geographic features varies, making it a necessity to determine the feature that plays a controlling role and to generalize such feature in priority. In the specific generalization background dealt with in this article, roads, as the controlling feature, constrain the generalization of buildings to a great extent. Based on this, two sequence rules are set to process conflict (Table 2). The first rule is that in the co-existence of three types of proximity conflicts, the sequence is to resolve the LLP conflict first, then the BLP conflict and finally the BBP conflict. The second rule is to keep roads still when resolving the BLP conflict as much as possible and resolve the conflict by displacement of buildings.

Displacement in map generalization is not as simple as merely separating conflicting objects. Displacement is an operation in connection with the spatial context, and displacement of one map object may affect its neighboring objects. It may lead to a secondary conflict with neighboring objects or disruption to spatial relations with neighboring objects, which is referred to as displacement propagation. Considering displacement propagation, a strategy commonly adopted when resolving spatial conflict with a snake algorithm is to construct structure lines for the conflicted objects and the affected objects. These lines are a kind of propagation path of displacement with which the displacement of map objects is integrated into a linear network.

As illustrated in Table 3 and Table 4, a key step to select the actions of displacement when resolving the three types of proximity conflicts (BLT-conflict, BLP-conflict and BBP-conflict) is to determine whether there exists any other object within the displacement propagation range of the conflict. Generally, it is difficult to decide what size of range is adequate because this is connected with various factors, among which the most significant one is how severe the initial conflict is. The more severe the initial conflict is, the greater the initial displacement vector of the involved building is. In this situation, a greater extent of displacement propagation is needed to absorb possible mutation.

Therefore, the building in an initial conflict would be taken as a source of displacement propagation. Whether a neighboring building will be affected by displacement can be judged according to its distance to the source building. The distance threshold z is set, which is k times the sum of the initial displacement magnitude of the source building and d_{min}. For a neighboring building, if its distance to the source building is less than the threshold, this building is considered as affected by displacement propagation. Where buildings other than the source building are affected by displacement, a displacement propagation path will be constructed for these buildings, and the snake algorithm will be implemented.

F. BEHAVIOR OF THE CA

After construction of the CA, the most appropriate action to be taken on its internal objects is selected according to the rules provided in Table 4. These actions are imposed by the group agent and can be direct displacement or optimized displacement based on the snake model.

The overall process of iterative displacement within the CA of the snake algorithm is as below:

```
Input: the initial state of the map objects in CA, $\boldsymbol{P}(0)$.
  Construct structure lines of displacement;
  Set up algorithm parameters;
  Compute global stiffness matrix $\boldsymbol{K}$;
  Initialize the iterative time, $t \leftarrow 1$, and set $\boldsymbol{d}^{t-1} = \boldsymbol{0}$;
  Repeat
    Detect conflict and compute force vector, $\boldsymbol{f}^{t-1}$;
    Compute displacement vector $\boldsymbol{d}^{t}$ according to
      equation (4);
    Update coordinates of the displaced buildings;
    $t \leftarrow t+1$;
  Until conflicts are resolved or $t>80$.
Output: the resultant state of the map objects, $\boldsymbol{P}(t)$.
```

When resolving proximity conflict merely by displacement, the results may be unsatisfactory due to the overly high density of buildings. Where the conflict is not resolved after a single displacement, it means currently there is no adequate space for displacement. The displacement will be set invalidated and all objects will restore their initial status before displacement. The GA will then be informed to implement contextual elimination of building agents to release space and detect conflict once again.

Contextual elimination is implemented based on local congestion. The congestion value of a building is determined by evaluating its severity of conflict, i.e., the sum of all displacement magnitudes required by its neighboring buildings. Elimination is implemented first within internal buildings that do not adjoin the roads. Buildings that adjoin the roads are eliminated only in the absence of internal buildings. Elimination implemented according to this strategy can maintain buildings that adjoin the roads as much as possible, which conforms to cartographic sense. In addition, only one building is eliminated each time to avoid dramatic changes on the map.

Generally, conflict can be resolved pursuant to the above process. An exception is that a non-iterative snake model is needed for BLT conflicts. For a building in this type of conflict, as it is pushed by a road that intersects with itself, the algorithm cannot calculate the real displacement magnitude internally. Therefore, the displacement magnitude of such a building can be predefined in the snake model [44]. In this way, the topological conflict can be resolved with a single displacement, and there is no need for iteration.

Moreover, an internal constraint of position accuracy is installed in the BOAs to prevent buildings from moving too far away from their initial positions. After implementation of effective displacement, the involved BOAs are informed to conduct self-evaluation, which is mainly to judge whether such displacement operation violates the constraint of position accuracy. BOAs that violate such constraint will be eliminated.

V. EXPERIMENT AND DISCUSSION

A. EXPERIMENTAL RESULTS

To validate the approach, one sub-zone of the rural map in Fig. 6 was selected to carry out experiments. It was extracted from the topographic dataset of Caidian District in Wuhan City, China. The original scale of the topographic map was 1:10,000, and the target scale was 1: 25,000. The experiment dataset contains a total of 101 buildings and 21 roads. On this map, there are two levels of roads, i.e., the motor road and the foot path. The symbol width of the former was set to 0.2 mm, while the latter was 0.15 mm. The outline width of buildings was set to 0.1 mm. The proposed approach was programmed using C# and ArcGIS Engine, and the tests were implemented on a PC with Windows 7 OS and Intel®Core$^{\mathrm{TM}}$i5-4460 CPU (3.20 GHz).

In the experiment, simplification is realized with the Douglas-Peucher algorithm [44], and the simplification tolerance can be set as needed. This article sets such tolerance to 0.5 mm. Enlargement can be achieved by simple

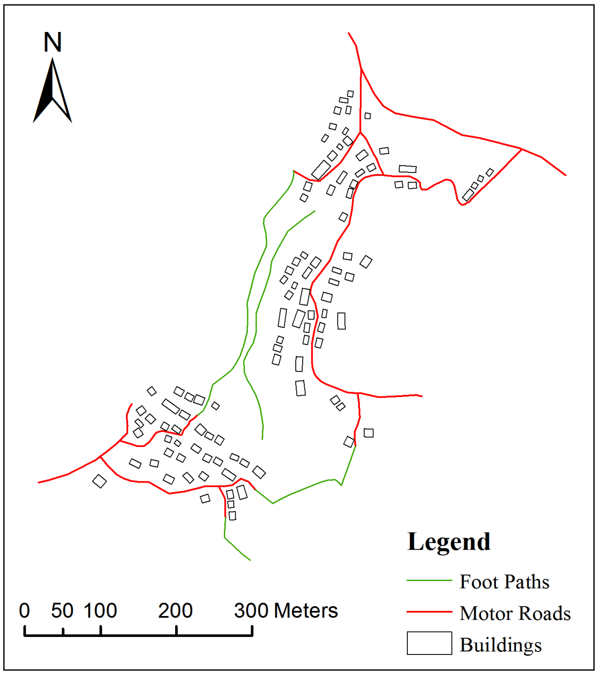

FIGURE 6. Raw experimental data (1:10, 000).

geometric scaling using the buildings' centers of gravity as the anchor points. According to the National Administration of Surveying [45], the size required by the final scale is 0.7 mm × 0.5 mm. The k used to determine the displacement propagation range is set to 1.5 by experiment.

In addition, some parameters of the snake model need be determined before the experiment. α and β are two important geometric parameters in the snake model. In the process of displacement, the greater these two parameters are, the less the deformation of linear features will be. Roads are consecutive features naturally, and their deformability should be smaller than that of the MST connecting the buildings' centers of gravity. In this experiment, α and β of roads are determined by human-computer interaction, and a relatively small value is set for α and β of structure lines between buildings and between buildings and roads. It was discovered by experimentation that when α and β of such connecting lines are approximately 1/100 of α and β of roads, the effect of displacement is ideal. γ, μ and t are iterative parameters and are set to 0.1, 1 and 80, respectively, all of which are empirical values.

The result of the experiment is illustrated in Fig. 7.

B. EVALUATION OF RESULT

In the above analysis, the focus of our approach is on conflict resolution. Seen from this angle, our approach is quite effective. First, all conflicts on the map have been resolved after generalization. Second, the characteristic of buildings being distributed along the road is also well maintained. By comparison between Fig. 7(a) and Fig. 7(b), the map after generalization is more legible.

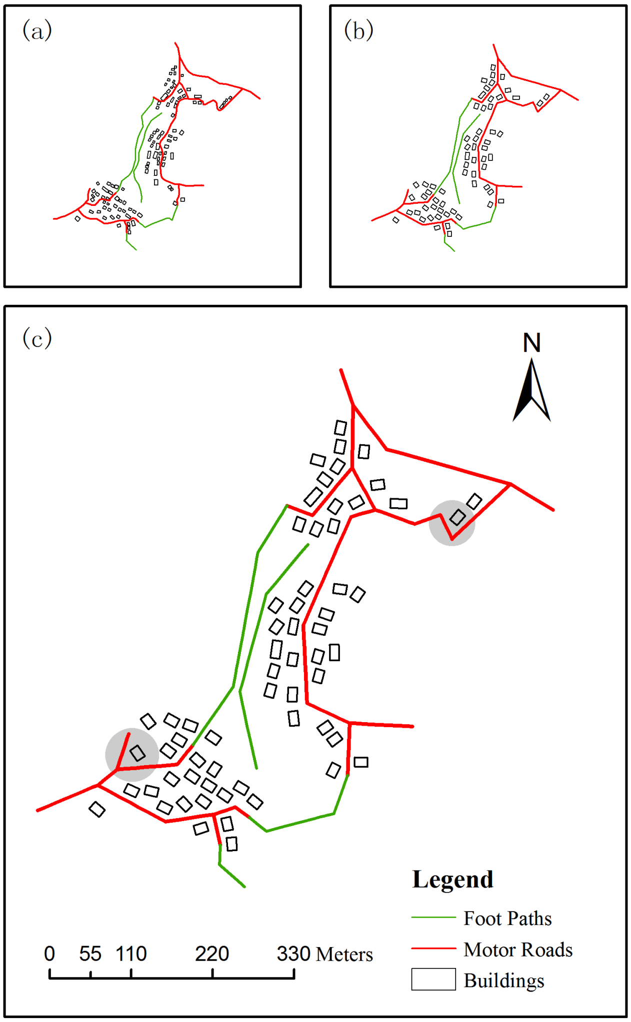

FIGURE 7. Comparison diagram (a) raw data at 1: 25,000; (b) result of generalization at 1:25,000, and; (c) result of generalization at 1:10,000.

TABLE 5. Statistical information about the displacement magnitudes.

Displacement Magnitude of Building Vertex (mm)			Displacement Magnitude of Road Vertex (mm)		
MAX	MIN	AVG	MAX	MIN	AVG
0.62	0.00	0.21	0.47	0.00	0.11

The statistical information of displacement magnitudes in experiment is displayed in Table 5. According to the National Administration of Surveying [46], for displacement of map features caused by scale reduction or overlapping after symbolization, the displacement magnitude should not exceed 0.5 mm, or 1 mm at the most in special situations. In the experiment, all displacement magnitudes of all road vertices are kept within 0.5 mm; the number of buildings whose displacement magnitudes exceed 0.5 mm is two, which are separately located in the round gray zones in Fig. 7(c). It can be found that both of these buildings are located at the road intersections. In cartography, such buildings are deemed important and should be preserved. In this situation, it is reasonable enough to give some relaxation to the positional accuracy constraint. The displacement magnitudes of all buildings other than these two are smaller than 0.5 mm, while their average displacement magnitude is 0.21 mm, all meeting relevant requirements.

In addition to displacement, the other generalization operation applied in the experiment to resolve conflict is elimination of buildings. In regular cartographic generalization, elimination is usually performed prior to invoking other operators. Therefore, the number of objects to be eliminated can be predefined, and it is easy to control the level of elimination. In the approach proposed in this article, elimination is implemented dynamically in the process of generalization according to the need to resolve conflict. Therefore, it is necessary to evaluate whether the level of elimination is reasonable enough. Töpfer's radical law [37] can be applied:

$$N_t = N_s\sqrt{M_s/M_t} \tag{16}$$

where N_t is the number of buildings in the target map, N_s is the number of buildings in the source map, M_s is the denominator of the source scale, and M_t is the denominator of the target scale. According to the radical law, there should remain 64 buildings on the map after generalization. In this article's experiment, the number of buildings that remain on the map after generalization is 62 which is quite close to 64. Therefore, it is concluded that the level of elimination is acceptable.

As illustrated in Fig. 7, the relative size order of buildings after generalization has been slightly disturbed. This is because building enlargement is implemented only on buildings smaller than the threshold size, which makes the final buildings have nearly equal size. In areas where the size distribution of buildings is highly heterogeneous, it is necessary to consider constraints of relative sizes between buildings. In other words, buildings already large enough should also have their size enlarged (like using a decay function) to preserve the heterogeneity of the building sizes.

VI. CONCLUSIONS AND FUTURE WORK

In this article, we presented an approach for spatial conflict resolution with multiple agents. The snake algorithm for displacement is built into the multi-agent process as a particular action. This approach is capable of considering multiple types of map features and collaborating the graphic generalization with the displacement and elimination of map objects to process multiple types of spatial conflicts with increased efficiency. The obtained results can be considered as globally correct from a cartographic point of view.

In this article, the displacement operator is mainly implemented by the snake model. However, the snake model does not apply to all data in generalization. In the framework proposed in this article, how to integrate more algorithms and processes that have been independently studied by scholars would be a future direction of research.

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