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A Collaborative Displacement Approach for Spatial Conflicts in Urban Building Map Generalization

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ABSTRACT Spatial conflicts can remain unresolved during map generalization if only displacement is used, especially for urban building maps. To solve all possible spatial conflicts during urban building map generalization, we propose a collaborative displacement method, combining aggregation, elimination, and constrained reshape. After applying an improved vector field-based displacement for solution of initial conflicts, two types of sequential conflicts are detected and evaluated to identify additional displacement solutions based on a trial and error strategy. If no displacement solution is available, aggregation, elimination, or constrained reshape are selected and applied for the unsolved sequential conflicts based on cartographic rules. For a more reasonable generalization result, an improved constrained reshape approach is also introduced for buildings in conflicts along roads. Two data sets with scales of 1:5000 and 1:25 000 for urban building map were selected to validate this approach. The results indicate that it is reasonable and feasible to solve all defined spatial conflicts in urban building map generalization using our proposed method.

INDEX TERMS Map generalization, collaborative displacement, conflicts resolution, constrained reshape, urban buildings.

I. INTRODUCTION

Cartographic generalization adaptively processes data depending on map scale or theme [1], with the goal of satisfying two requirements: visually legible and good representation of reality [2]. These cartographic requirements can be developed into constraints in a map generalization process, creating map generalization as a constraint satisfaction problem [3], [4]. Any map object that cannot meet defined constraints is considered in spatial conflict; therefore, generalization also aims to solve spatial conflicts based on constraints.

As important man-made features in topographic maps, urban buildings have become the subject of intense research in map generalization [5]. After a reduction in scale or geometric transformation, spatial conflicts may arise, in which map objects overlap or become too dense to be clearly distinguished [6]. Displacement is an effective resolution procedure for these spatial conflicts, because this operation does not significantly reduce the information content in map [7]. However, after a displacement of buildings in initial conflicts, sequential conflicts may arise. Thus, a well-designed displacement method should consider solutions to sequential conflicts, known as displacement propagation [6].

To solve all possible spatial conflicts in a global view, some methods aim to achieve satisfactory results meeting all defined constraints at one time, such as a least squares adjustment [8], [9] or finite element [10], [11] approach. Other methods, considering a local view, resolve these conflicts step by step using search strategies, including the Tabu Search [12], simulated annealing approach [7], and genetic algorithms [13]–[15]. To reduce the large potential search space, some methods with domain knowledge (cartographical rules) have also been introduced [6].

Even applying these techniques, spatial conflicts can remain unsolved if the generalization is only conducted based on displacement for given capacity of map space [5]. In addition to displacement, aggregation, elimination, or constrained reshape are also required to provide solutions [7], [16]. Some scholars also show that it is effective to solve all possible spatial conflicts using several generalization operators collaboratively driven by cartographical rules [17]–[19].

Motivated by these prior works, and with the goal of solving all possible spatial conflicts while generalizing urban building maps, we proposed a collaborative displacement method combining aggregation, elimination, and constrained reshape. An improved vector field based displacement is first adopted to solve initial conflicts. Then two types of sequential conflicts are detected and evaluated to determine if a solution can be achieved with additional displacement. If not, elimination, aggregation, and constrained reshape are applied for the unsolved sequential conflicts according to cartographical rules. An improved constrained reshaped approach is also introduced for buildings in conflicts along roads.

II. RELATED WORK

A. CONSTRAINTS FOR DISPLACEMENT

In building displacement, many constraints have been developed for different purposes. For example, according to Mackaness [20], map objects must be moved within a minimum distance threshold to conserve spatial integrity. Local spatial relationship and patterns also need to be maintained. In contrast, Harrie [8] concentrated on whether or not map objects can be displaced. If buildings are assumed to be rigid bodies, three types of constraints can be summarized:

- Legible constraints (C1). After displacement, buildings should be distinguishable, and no legible conflicts are detected, which means buildings must be separated by a certain distance, e.g., 0.2 mm [6].
- Positional accuracy constraints (C2). A building cannot be moved a long distance to avoid spatial conflicts; the distance needs to be limited, e.g., 0.5 mm [21].
- Constraints for building groups (C3). Groups of buildings have a range of constraints. For example, maintenance of global spatial relationship between buildings, such as building density; maintenance of relative relationship between buildings, such as building patterns [5].

Buildings can be considered in spatial conflicts when they do not meet these three types of constraints in displacement. However, cartographic constraints often have conflicting requirements that need to be optimized, i.e., constraints should be fulfilled as much as possible [2]. Among the three types of constraints, constraints C1 and constraints C2 must be satisfied, while constraints C3 need to be satisfied as much as possible in a generalization process [22].

B. DISPLACEMENT APPROACHES

Displacement approaches for map objects can be generally classified into two types: local and global view approaches. In local view approaches, some optimal approaches are also introduced.

With a local view, buildings are displaced one by one or one group by one group to decrease spatial conflicts step by step. A representative approach may be the equation system proposed by Lichtner [23] to compute displacement vector, which is perpendicular to objects. Ruas [6] developed a sophisticated approach for building displacement, wherein buildings are displaced one by one with cartographical rules considering different scenarios. Fei [16] divided buildings into four types according to relationships between buildings and roads; different displacement approaches are then separately applied to different types of buildings. To solve conflicts between buildings and roads, Wu *et al.* [24] proposed a multi-level displacement method, in which buildings are displaced group by group according to the adjacent degree between buildings and roads. Different displacement principles are then applied considering building density. However, these methods may fail in dense areas, and the relative relationship between buildings is not well maintained [14]. In an attempt to maintain relative relationships between buildings, Li *et al.* [25] also introduced a displacement method based on geometric similarity considering distance, angle, and area constraints. A minimum spanning tree (MST) is first built to structure the buildings, then they are displaced one by one along the MST according to rules generated from the geometric similarity constraints. The drawback of this method is that it is based on the premise of reducing the building area. Developments in computer science have also led to the introduction of optimal algorithms originating from artificial intelligence. Ware *et al.* [7] used simulated annealing for building displacement based on trial positions in a predefined order. The continuous displacement range of each object is divided into discrete candidate positions in the algorithm, and a fitness function is determined according to cartographic constraints. Based on the same concept, Wilson *et al.* [13] applied a genetic algorithm to resolve spatial conflicts. Later, Sun *et al.* [14] proposed an immune genetic algorithm considering Gestalt rules. However, in optimal algorithms, it is hard to define a "good position", and often different results are obtained after every algorithm application [26].

With a global view, researchers have tried to achieve satisfactory results by resolving all defined conflicts at one time. Mackaness [20] presented a radial displacement approach, wherein clusters for displacement are first detected, and then the clusters' central points are computed. Displacement of each building is obtained according to a distance decay function. Later, based on energy minimization, Snake algorithms were first introduced for linear objects displacement based on a spring model [10]. Based on Snake algorithm research, Bader *et al.* [27] proposed a Beams algorithm. By constructing an enhanced MST structured skeleton of buildings, the method converts building displacement into a linear objects displacement problem. Also based on the Snake algorithm, Sun *et al.* [28] proposed an approach for building displacement based on topological structures, and Liu *et al.* [21] proposed an improved Beams algorithm with a proximity graph to structure building skeletons. In these approaches, parameters for displacement are difficult to determine, and may perform poorly in high density areas [29]. Based on a least squares adjustment approach, Harrie [8] described the geometry and topology constraints for displacement as a series of linear functions, where the solution to the linear function set represents the result after displacement.

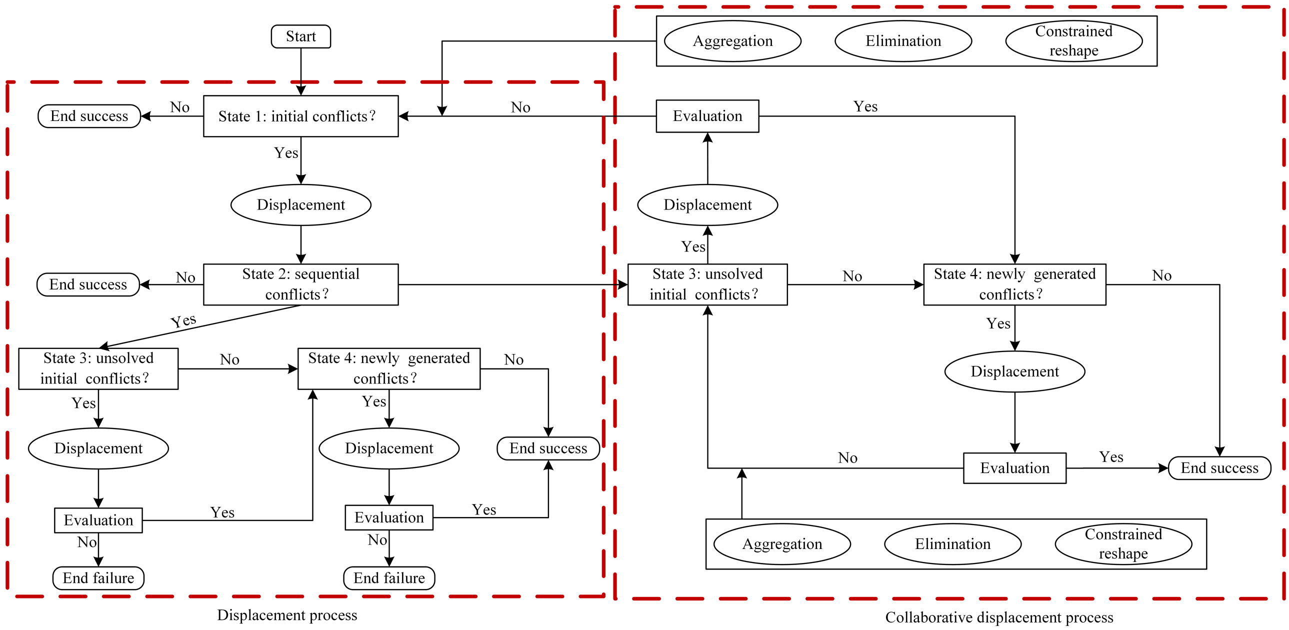

FIGURE 1. General framework for the collaborative displacement process.

However, it is hard to describe different constraints as united linear functions in this approach, solutions to the linear function set are not always obtained. Based on continuous deformation, Højholt [11] divided map space using constrained Delaunay triangulation (CDT), where different stiffness and boundary conditions are allocated to triangles according to defined constraints. Then a finite element method (FEM) is applied to maintain relative relationship between buildings, and resolve the conflict propagation problem. However, the approach encounters problems with large deformations. Ai *et al.* [5] proposed a vector field based approach for building displacement, where the displacement vector field is built based on CDT. Thus, displacement is then conducted based on the vector field, in which direction and magnitude of the displacement force are computed based on an iso-line model. It proves to be effective in maintenance of spatial relationship between buildings, but may also fail in dense areas.

III. METHODOLOGY

A. GENERAL FRAMEWORK

The objective of generalizing urban building maps is to solve initial conflicts while maintaining building integrity using tools, such as elimination, aggregation, and displacement. Displacement is an effective resolution procedure for spatial conflicts in which map objects are overlapped or are too dense to be clearly distinguished [7]. As described in section II.B, applying a well-designed displacement method can avoid sequential conflicts effectively, but does not preclude their generation, and additional displacements may be needed, as shown on the left of Figure 1.

Continuously resolving sequential conflicts with additional displacements remains a problem. For scenarios where additional displacements cannot resolve the conflict, an unreasonable generalization results may be obtained. Thus, an evaluation needs to be applied. For sequential conflicts that cannot be solved with additional displacements, then other generalization operators need to be applied, such as elimination, aggregation, or constrained reshape. A classical approach to conduct an evaluation is by means of trial and error, which has been introduced into map generalization field [4]. After a displacement of buildings in sequential conflicts, constraints described in section II.A can be developed into rules for evaluating the displacement result.

As indicated in Figure 1, after the displacement of initial conflicts (state 1), two types of sequential conflicts (state 2) may generate: unsolved initial conflicts (state 3) and newly generated conflicts (state 4). If any sequential conflicts are detected after the initial displacement, types of sequential conflicts need to be identified first. For any detected unsolved initial conflicts, an additional displacement is applied to them first. After all unsolved initial conflicts are solved, displacement is then applied to the newly generated conflicts. An evaluation is conducted separately for the two types of sequential conflicts after every additional displacement. If unsolved initial conflicts are evaluated as unsolvable with additional displacement, then return to initial conflicts (state 1) for collaboration; similarly, if newly generated conflicts are evaluated as unsolvable with an additional displacement, then return to newly generated conflicts (state 4) for collaboration.

This procedure results in a group of defined unsolved sequential conflicts. Which one needs to be solved first? A sequence should be constructed. And cartographic rules need to be applied to the other collaborative generalization operators. For example, buildings similar in orientation are appropriate for solving by aggregation, but not eliminate one of them [30]. These cartographical rules can be summarized in a rule table to guide the generalization operator application.

With above understanding taken into account, a collaborative displacement process is designed, shown on the right of Figure 1. After applying the selected displacement method, an evaluation determines if the generated sequential conflicts can be solved by additional displacements: if yes, an additional displacement is conducted; and if no, other generalization operators are applied with the given cartographical rules. This process continues until no defined conflicts are detected.

B. DISPLACEMENT FOR INITIAL CONFLICTS

A vector field based displacement method is adopted for solving initial conflicts, which has proven effective in resolving multiple conflicts while minimizing sequential conflict generation and preserving spatial relationship between buildings using displacement [5]. The general concept is that buildings in conflicts are the force source, which push away from each other. Next, the forces are propagated to their nearest neighbors with decreasing magnitude; then to further neighbors until the force magnitude reduces to zero. A vector field is built to model the degree of adjacency. Thus, displacement is propagated and decayed along the built vector field.

To build a vector field, a proximity graph needs to be built first to model the proximity relationship. A proximity graph is built based on a Delaunay triangulation skeleton to partition the buildings [31]. Thus, buildings connected by an edge in the proximity graph may influence each other in the displacement process, Figure 2(a) and Figure 2(b). However, some buildings connected by edges in the proximity graph are not in close proximity, and may not influence each other directly in the displacement process [25]. For buildings that may be forced to displace by roads, if the distance between building and roads is more than twice the width of a road symbol, then the building may not be forced to displace directly by roads; for buildings that may be forced to displace by another building, if the distance between two buildings is more than four times the positional accuracy threshold, then the building may not be forced to displace directly by another building [21]. Thus, these longer edges in the proximity graph may need to be deleted first, e.g., edges colored red and symbolized with heavy lines in Figure 2(b), and a pruned proximity graph is then obtained, Figure 2(c). Furthermore, some building patterns are important and need to be preserved during displacement. If buildings in a pattern have no conflicts with each other, then they can be considered as a group, e.g., buildings connected by edges colored cyan and symbolized with heavy lines in Figure 2(d), which results in an adjusted proximity graph.

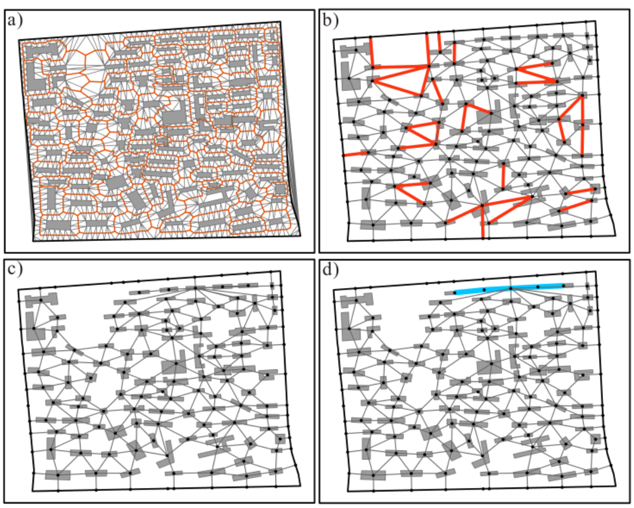

FIGURE 2. Establishment of proximity relationship between buildings and roads. (a): Delaunay triangulation skeleton to partition the buildings [31]; (b): Proximity graph built based on Delaunay triangulation skeleton; (c): Pruned proximity graph after deleting some longer edges (edges colored red and symbolized with heavy lines in Figure 2(b)); (d): Adjusting proximity graph with consideration of building pattern (buildings connected by edges colored cyan and symbolized with heavy lines).

The vector field is built based on the pruned and adjusted proximity graph after detecting multiple sources of conflicts. After roads are symbolized, buildings are forced to displace by roads inwards. Thus, buildings along roads are in the force source that are pushed away by roads. Next, the forces are propagated to their nearest neighbors (first adjacent degree); then, to further neighbors (second adjacent degree, third adjacent degree, etc.), a vector field driven by roads can then be built, Figure 3(a). If the distance between two buildings is too short, which violates constraint C1. It may also force two buildings to displace apart, a vector field driven by conflicts between buildings can also be built, Figure 3(b).

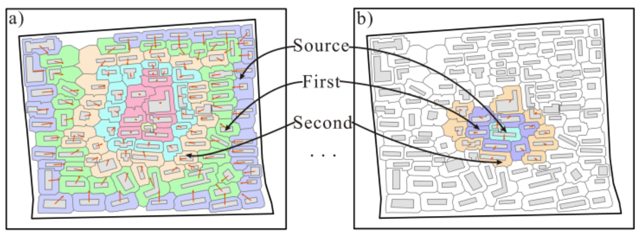

FIGURE 3. Establishment of vector field. (a): A vector field built driven by roads. (b): A vector field built driven by conflicts between buildings.

The direction and magnitude of each building can then be computed based on the built vector fields. In a built vector field, the force direction of a building is determined by the buildings that directly push it to displace, while the magnitude is determined by the degree of adjacency between the building and buildings in conflicts. Suppose the degree of adjacency of a building is B_{adj} in one built vector field, the initial force is f_i, and its force in the built vector field can be computed as equation (1).

$$f_B = f_i - \frac{f_i \times B_{adj}}{k} \quad (B_{adj} \leq k, k \neq 0) \tag{1}$$

Where $k \in \{1, 2 \ldots, \max\{B_{adj}\}\}$ is the parameter controlling the propagation depth and decay speed of the force. The initial force f_i depends on the severity of the detected conflicts. For a vector field driven by roads, the initial force can be half the width of road symbols; for a vector field driven by conflicts between buildings, the initial force can be the distance required to resolve conflicts in the conflicting center.

As directed by positional accuracy constraint (C2), building displacements need to be limited in a certain distance. Thus, an attractive force needs to be introduced to satisfy the positional accuracy constraints in the displacement process [21]. If displacing a building violates constraint C2, an attractive force is then added, as shown in equation (2).

$$f_a = \max[0, (\left|\overrightarrow{OO_1}\right| - d_{max})] \times \frac{\overrightarrow{O_1O}}{\left|\overrightarrow{O_1O}\right|} \tag{2}$$

where O is the original position of the building's centroid, O_1 is the new position of the building's centroid after displacement, and d_{max} is the positional accuracy threshold.

C. EVALUATION ON DISPLACEMENT FOR SEQUENTIAL CONFLICTS

1) TYPES OF SEQUENTIAL CONFLICTS

After a vector field based displacement is applied, some sequential conflicts violating constraint C1 may be generated. According to their relationship between initial conflicts, the sequential conflicts can be divided into two types.

- Unsolved initial conflicts (Type 1 sequential conflicts).

These are the initial conflicts that are not solved by the first vector field based displacement. For example, if a building is in conflicts with two or more roads, then it may be forced to displace in opposing directions, which is an unsolved initial conflict, Figure 4(a); a building in conflicts with two or more buildings leads to a similar result, Figure 4(b).

- Newly generated conflicts (Type 2 sequential conflicts).

These are the new conflicts generated after applying the vector field based displacement. For example, two buildings close to each other are forced to displace by a road, which results in a new conflict, Figure 4(c).

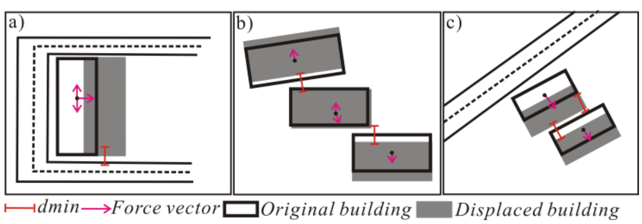

FIGURE 4. Types of sequential conflicts. (a), (b): Unsolved initial conflicts (Type 1 sequential conflicts); (c): Newly generated conflicts (Type 2 sequential conflicts).

Application of a vector based displacement aims to solve initial conflicts. Thus, if any Type 1 sequential conflicts are detected after displacement, they need to be solved first. Thus, an additional displacement is first applied for all buildings in Type 1 sequential conflicts. After all Type 1 sequential conflicts are solved, then an additional displacement is applied for all buildings in Type 2 sequential conflicts.

2) EVALUATING THE DISPLACEMENT FOR SEQUENTIAL CONFLICTS

Evaluation is conducted separately for the two types of sequential conflicts based on a trial and error strategy. First, displacement is conducted for buildings in two types of sequential conflicts one after another. Second, the displacement result is evaluated to determine if the sequential conflicts can be solved with additional displacement. If not, the unsolved sequential conflicts of specific type need to be identified.

After the initial steps, all buildings have been displaced to solve initial conflicts or have generated sequential conflicts. Thus, only buildings in sequential conflicts are considered for additional displacement [5]. If a building is in a sequential conflict with roads, the force applied to the building for additional displacement is computed as equation (3), and shown in Figure 5(a) and Figure 5(c).

$$f_r = \begin{cases} \dfrac{\overrightarrow{P_RP_B}}{\left|\overrightarrow{P_RP_B}\right|} \times \left(d_{min} + 0.5 \times (r1 + r2) + \left|\overrightarrow{P_RP_B}\right|\right) \\ \qquad \times (\text{Intersect ed} = \mathit{true}) \\ \dfrac{\overrightarrow{P_RP_B}}{\left|\overrightarrow{P_RP_B}\right|} \times \left(d_{min} + 0.5 \times (r1 + r2) - \left|\overrightarrow{P_RP_B}\right|\right) \\ \qquad \times (\text{Intersect ed} = \mathit{false}) \end{cases} \tag{3}$$

If two buildings are in a sequential conflict, the force applied to one building for additional displacement is computed as equation (4), Figure 5(b) and Figure 5(d).

$$fl = \begin{cases} 0.5 \times \dfrac{\overrightarrow{P_rP_l}}{|\overrightarrow{P_rP_l}|} \times \left(d_{min} + r2 + |\overrightarrow{P_rP_l}|\right)(\text{Intersect ed} = \mathit{true}) \\ 0.5 \times \dfrac{\overrightarrow{P_rP_l}}{|\overrightarrow{P_rP_l}|} \times \left(d_{min} + r2 - |\overrightarrow{P_rP_l}|\right)(\text{Intersect ed} = \mathit{false}) \end{cases} \tag{4}$$

Where r_1 is the width of road symbol, r_2 is the outline width of building symbol, d_{min} is the minimum distance threshold between two map objects, and Intersected $=$ *true* denotes that the two objects in conflict intersect with each other. As described in section III.B, an attractive force is also added in this displacement process to satisfy the positional accuracy constraint (C2).

After an additional displacement to solve sequential conflicts, the constraints summarized for building displacement in section II.A can be used for evaluation, in which constraints C1 and C2 must be satisfied, and constraint C3 should be satisfied as much as possible [22]. A vector field based displacement method is built to preserve the spatial relationships and important building patterns, which can meet the C3 constraint to some extents. Additionally, an attractive force has been added to limit the displacement distance for a building, which satisfies constraint C2. Thus, constraint C1 is the primary concern in our evaluation.

After additional displacements of all buildings in Type 1 sequential conflicts, if any Type 1 sequential conflicts are

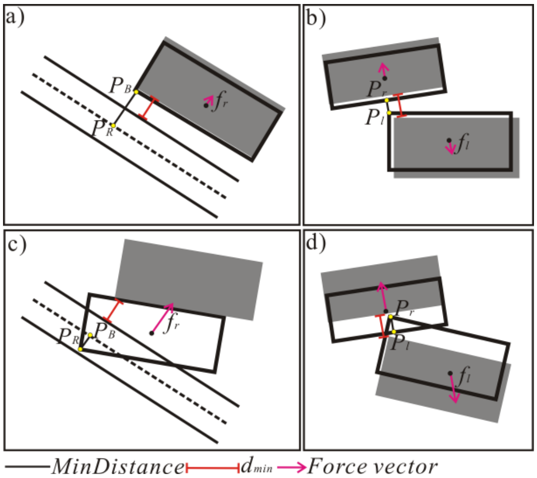

FIGURE 5. Force computation for buildings in sequential conflicts in additional displacement. (a): Force computation for buildings in sequential conflicts with roads, in which building doesn't intersect with roads; (b): Force computation for buildings in sequential conflicts with buildings, in which buildings don't intersect with each other; (c): Force computation for buildings in sequential conflicts with roads, in which building intersects with roads; (d): Force computation for buildings in sequential conflicts with buildings, in which buildings intersect with each other.

detected violating constraint C1. Then, the Type 1 sequential conflicts are evaluated as unsolvable with an additional displacement. The sequential conflicts in Type 1 sequential conflicts that violate constraint C1 after an additional displacement are defined as unsolved sequential conflicts. After all Type 1 sequential conflicts are solved, additional displacements of all buildings in Type 2 sequential conflicts are performed; if any buildings after a displacement violate constraint C1, then the Type 2 sequential conflicts are evaluated as unsolvable with an additional displacement. The sequential conflicts in Type 2 sequential conflicts that generate additional conflicts after additional displacements are defined as unsolved sequential conflicts.

D. RULE-DRIVEN COLLABORATION

When one type of sequential conflict is evaluated as unsolvable with additional displacement, a group of defined unsolved sequential conflicts may be obtained. However, only one unsolved sequential conflict is selected for collaboration each time. To identify the appropriate conflict to first apply the collaboration, some cartographical rules need to be considered.

1) SEQUENCE

The general idea for identifying the one defined unsolved sequential conflict for collaboration is to determine the unsolved sequential conflict that needs to be solved first in a displacement process.

Two types of sequential conflicts have been defined in section III.C. If Type 1 sequential conflicts are evaluated as unsolvable with additional displacement, then initial conflicts cannot be solved by displacement. If Type 2 sequential conflicts are evaluated as unsolvable with additional displacement, the newly generated conflicts cannot be solved by displacement. The purpose of generalization is to solve initial conflicts. Thus, if an unsolved sequential conflict is of Type 1, it needs to be solved first returning to initial conflicts state (state 1 in Figure 1) for collaboration; while solving an unsolved sequential conflict of Type 2 returns to the newly generated conflicts state (state 4 in Figure 1) for collaboration.

In building map generalization, conflicts between buildings and roads need to be solved in prior to the conflicts between buildings [6]. Thus, for the same type of sequential conflicts, an unsolved sequential conflict between buildings and roads needs to be solved first. Furthermore, the severity of conflicts also differs. The severity of conflicts can be defined with equation (5).

$$Sc = \begin{cases} d_{min} + MinDistance & (\text{Intersect ed} = true) \\ \max\left[0, d_{min} - MinDistance\right] & (\text{Intersect ed} = false) \end{cases} \tag{5}$$

where d_{min} is the minimum distance threshold between two map objects, and *MinDistance* is the minimum distance between two map objects, as shown in Figure 5. Buildings in more serious conflict, with longer displacement distances to avoid conflict, may need to be solved first. Thus, if two sequential conflicts are detected unsolved, the more serious conflict needs to be solved first. If one type of sequential conflicts is evaluated as unsolvable with additional displacement, a search sequence to find the target unsolved sequential conflict for collaboration is implemented, as shown in Table 1.

2) COLLABORATION

Many cartographical rules are involved in applying the aggregation, elimination, and constrained reshape while solving a spatial conflict, for example, it may be more proper for two buildings with the similar orientation to be aggregated, but not eliminate one of them [30]. These cartographical rules can be considered as production presentation rules that can be represented in a form such as P → Q or IF P THEN Q. P is the premise of the production, which gives the production of the use of the prerequisite; Q is a set of conclusions or operations, which indicates that if the current P is satisfied, then the conclusion or operations in Q can be launched [32]. For collaboration in sequential conflicts, the production follows the rules provided in Table 2.

The premise of generalization (P) involves two kinds of information: map objects for generalization and conditions of generalization. If target unsolved sequential conflict is of Type 1, then return to the initial conflicts state (state 1 in Figure 1) for collaboration; if the target unsolved sequential conflict is of Type 2, then return to newly generated conflicts state (state 4 in Figure 1) for collaboration. Map objects in these conflicts can be individual buildings or two-building groups. Individual buildings are buildings in conflicts with roads; two-building groups are two buildings in a conflict.

The generalization conditions are derived from cartographical rules. Although many cartographical rules can be

TABLE 1. Sequence to find the target unsolved sequential conflict for collaboration.

```
Input: unsolved sequential conflicts (UConflicts)
Output: target conflict (TConflict) for collaboration
If UConflicts are Type 1 sequential conflicts
  Set TConflict←UConflicts[0]
  For each sequential conflict (NConflict) except UConflicts[0] in UConflicts
    If TConflict is a conflict between roads and buildings
      If NConflict is a conflict between roads and buildings
        If NConflict is more serious than TConflict
          TConflict←NConflict
    Else
        If NConflict is a conflict between roads and buildings
          TConflict←NConflict
        Else
          If NConflict is more serious than TConflict
            TConflict←NConflict
Else if UConflicts are Type 2 sequential conflicts
  Set TConflict←UConflicts[0]
  For each sequential conflict (NConflict) except UConflicts[0] in UConflicts
    If TConflict is a conflict between roads and buildings
      If NConflict is a conflict between roads and buildings
        If NConflict is more serious than TConflict
          TConflict←NConflict
    Else
        If NConflict is a conflict between roads and buildings
          TConflict←NConflict
        Else
          If NConflict is more serious than TConflict
            TConflict←NConflict
```

TABLE 2. Rules for conflicts in collaborative displacement in backus normal form (BNF).

Generalization for conflicts:: <premise of generalization> (P)→<result of generalization > (Q)
Premise of generalization (P):: <map objects for generalization> | <conditions of generalization>
Result of generalization (Q):: <aggregation> | <elimination> | <constrained reshape>

summarized, the importance of buildings according to their area and similarity between two buildings in orientation are primarily considered in our approach. Furthermore, buildings in a pattern acts as one building in our collaborative process. Thus, whether the building is a pattern also needs to be considered. Importance determines which building need to be eliminated first, while similarity determines if two buildings are appropriate for aggregation. Importance is defined as follows: buildings with larger area are more important [15]. A building with smaller area is eliminated before eliminating its larger counterpart. Similarity in orientation of buildings is defined by whether they have a parallel or perpendicular relationship [33].

$$
\begin{aligned}
&ParallelRelation \\
&\quad = \{\beta(a,b) \,|\, \beta(a,b) \leq \delta \cup 180 - \beta(a,b) \leq \delta\} \qquad (6)
\end{aligned}
$$

$$
\begin{aligned}
&PerpendicularRelation \\
&\quad = \{\beta(a,b) \,|\, |\beta(a,b) - 90| \leq \delta\} \qquad (7)
\end{aligned}
$$

Where $\beta(a, b)$ is the angle between orientation of the smallest minimum bounding orientation of two buildings, δ is the threshold, and $\delta = 30$ in our approach. If orientation of two buildings are in either *ParallelRelation* or *PerpendicularRelation*, they are defined as similar in orientation. With the given premise of generalization (P), the result of generalization (Q) is application of aggregation, elimination or constrained reshaped. The detailed rules are given in Table 3.

For individual building in a conflict between roads for collaboration, constrained reshape is always applied. If the building is a building pattern, then break up the pattern. Buildings in patterns conflicting with roads are then constrained reshaped. For a two-building group for collaboration, if the two buildings are both not building patterns, the similarity in orientation is considered first; if two buildings are similar in orientation, then aggregation is applied; else, eliminate the building with smaller area. If one building is a pattern, then we may eliminate the other one. If two buildings are all patterns, then we break up the pattern with fewer buildings or less area, converting into an occasion in which one building is a pattern.

E. IMPROVED CONSTRAINED RESHAPE APPROACH

After reducing the map scale, map space is limited for symbolizing all objects. Sometimes to indicate the existence of a map object in limited map space, reshape or collapse is needed according to its surrounding environment [16]. In urban building maps, some buildings in serious spatial conflicts with roads may not be solvable with displacement alone, and constrained reshape is also needed. To indicate the existence of a building in limited map space, the shape of the building and relationship between buildings and roads in this scenario becomes less important. Because building map generalization need to maintain the area rate after generalization, little change in the area of reshaped buildings is required. Fei [16] introduced a constrained reshape method to reshape building away from roads, Figure 6(a). This method can also be conducted by reducing the size of building in an equal proportion, Figure 6(b). But sometimes, constrained reshape the building fitting along roads to avoid a huge decrease in area of the reshaped building is also required, usually 30% [25], Figure 6(c). Based on this, we improved the constrained reshape method by reshaping buildings fitting along roads, described as follows.

1) POSSIBLE SURROUNDING ENVIRONMENTS

The constrained reshape of a building along roads needs to be conducted according to its surrounding environment, which

TABLE 3. Detailed rules in IF-THEN forms for target sequential conflicts. Here, B_{Num} denotes the building number in a sequential conflict, Ob_i ***denotes the orientation of a building.***

IF				THEN
B_{Num}	$Pattern \in$ sequential conflicts		$Ob_1 \cong Ob_2$	Generalization operators
1	True			Break up the pattern
	False			Constrained reshape
2	True	One building is a pattern		Eliminate the one doesn't belong to a pattern
		Two buildings are patterns		Break up one pattern
	False		True	Aggregation
			False	Eliminate the smaller one

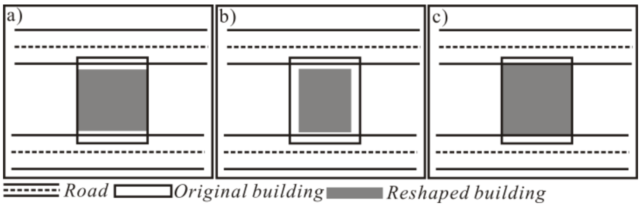

FIGURE 6. Constrained reshape of a building. (a): Constrained reshape building away from roads; (b): Constrained reshape building by reducing size in an equal proportion; (c): Constrained reshape building fitting along roads.

refers to the relationship between reshaped buildings and conflicted roads. After fitting buildings along roads, the white spaces are divided into two types, Figure 7:

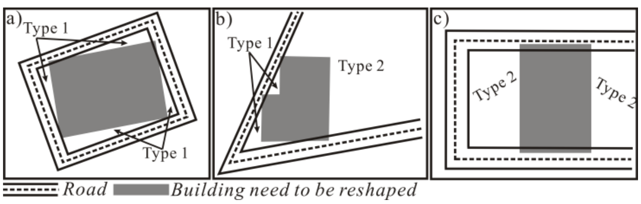

FIGURE 7. Types of surrounding environment of reshaped buildings. (a): Only Type 1 white spaces are generated after fitting building along roads (Environment 1); (b): Type 1 and Type 2 white spaces are all generated after fitting building along roads (Environment 2); (c): Only Type 2 white spaces are generated after fitting building along roads (Environment 3).

- Type 1 white spaces: spaces that are enclosed by conflicted roads and reshaped buildings;
- Type 2 white spaces: spaces that are not enclosed by conflicted roads and reshaped buildings.

Type 1 white spaces, generated from conflicts between roads and reshaped buildings, have small or relatively small areas compared to the reshaped building. Thus, they need to be aggregated with the reshaped buildings. According to the definition of white spaces, the environments surrounding reshaped buildings can also be defined:

- Environment 1: only Type 1 white spaces are generated after fitting building along roads, Figure 7(a);
- Environment 2: Type 1 and Type 2 white spaces are both generated after fitting building along roads, Figure 7(b);
- Environment 3: only Type 2 white spaces are generated after fitting building along roads, Figure 7(c).

2) CONSTRAINED RESHAPE OPERATORS

Three main operators are needed while reshaping buildings fitting along roads. First, these buildings need to be fitted along roads. Second, if any Type 1 white spaces are generated, they need to be aggregated with the reshaped buildings. Finally, after an aggregation of Type 1 white spaces, which may lead a large increase in area of the reshaped building, an area reduction may be needed. Among the three operators, aggregation of two adjacent areas can be easily implemented.

a: FITTING BUILDINGS ALONG ROADS

Buildings fit is conducted by projecting the vertexes of buildings to the roads. These vertexes can be classified into two types, Figure 8(a):

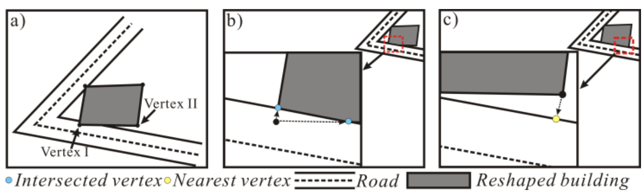

FIGURE 8. Fit building along roads. (a): Original building and types of vertexes; (b): Projection of the first type of vertexes to roads; (c): Projection of the second type of vertexes to roads.

- Vertex I: vertexes that are on road symbols, distance to roads symbols is 0. Projection of the first type of vertexes (Projection I): find the intersection between road symbols and reshaped building; intersected vertexes are then considered as new vertexes of the reshaped building, Figure 8(b);
- Vertex II: vertexes that are not on road symbols, but distance to road symbols is less than the minimum distance threshold. Projection of second type of vertexes (Project II): find the nearest vertex on road symbols to the projected

vertex, which is considered the new vertex of the reshaped building, Figure 8(c).

Then every vertex of a reshaped building is processed as follows:

$$VertexAction\begin{cases}Project\ I & if\ D_n = 0\\ Project\ \Pi & if\ 0 < D_n < d_{min}\\ NoAction & else\end{cases} \tag{8}$$

where D_n denotes the distance between a vertex and road symbols, and d_{min} refers to the minimum distance threshold.

b: AREA REDUCTION

Constrained reshape should promise a little change in area of a reshaped building; however, areas may increase for reshaped buildings after an aggregation with Type 1 white spaces. In this case, area reduction needs to be conducted by adjusting the edges of the reshaped building. Two types of reshaped building edges are generated after aggregation with Type 1 white spaces, Figure 9(a):

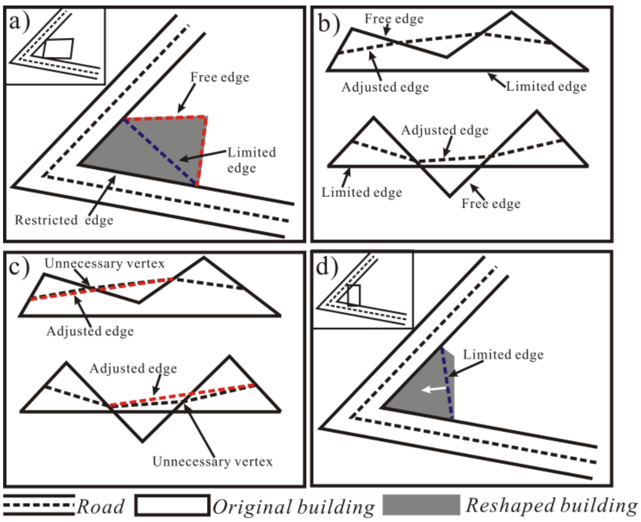

FIGURE 9. **Area reduction of reshaped building. (a): Free edges and restricted edges; (b): Adjustment of free edges; (c): Elimination of unnecessary vertexes; (d): Adjustment of restricted edges.**

- Restricted edges: edges of the reshaped building that are on road symbols;
- Free edges: edges of the reshaped building that are not on road symbols.

Edges that are not on road symbols may have a higher priority for adjustment than those on road symbols. Thus, free edges are adjusted first for area reduction.

Adjustment of free edges is conducted as follows: free edges sometimes group together, for example, the dashed red line in Figure 9(a). Thus, the group of edges needs to be adjusted together. Although different groups of free edges may be generated, they are adjusted in order of their total length. Limitation of the adjustment of the group of edges is to transform these free edges into one edge connected by the first and last vertex, e.g., the dashed blue line in Figure 9(a). Thus, the free edges are transformed to approach the limited edge. In the case that a connection between the first and last vertex leads to a reduction in building area, referring to the curve approximation method in mathematical, interpolate the midpoint of every free edge to approach the limited edge, Figure 9(b). This process may leave vertexes unnecessary for describing the shape of the reshaped building. Thus, a line simplification (Point_Remove method in ArcEngine 10.2, which can be embedded into program) about the free edge is conducted. However, sometimes a connection between the first and last vertex may lead to an increase in the building area. In this case, after all free edges that lead to reduction in area of building are adjusted, then the first and last vertex are connected directly.

Adjustment of restricted edges is conducted as follows: adjusting the free edges may not be enough to recover the reshaped building area. Then, the restricted edges need to be adjusted by moving the limited edge to its perpendicular and area-decreasing orientation (arrow colored white) along these restricted edges, Figure 9(d). An area-decreasing orientation can be detected by moving opposing orientations in trials.

3) CONSTRAINED RESHAPE PROCESS

According to the surrounding environment definition for reshaped buildings and given reshape operators, the constrained reshape process is provided in Table 4. For Environment 1, after fitting buildings along roads and aggregation for Type 1 white spaces with the reshaped building, the process will create a block; for Environment 2, the aggregation for Type 1 white spaces with the reshaped building may lead to an increase in building area, so an area reduction is conducted; for Environment 3, only fitting buildings along roads is needed. The results of the constrained reshape for buildings in these three types of environments are shown in Figure 10.

TABLE 4. **Constrained reshape process according to types of surrounding environment of reshaped buildings.**

Environment Types	Operators
Environment 1	Fit building along roads; aggregate Type 1 white spaces
Environment 2	Fit building along roads; aggregate Type 1 white spaces; area reduction
Environment 3	Fit building along road

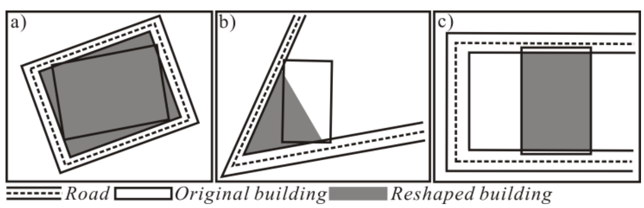

FIGURE 10. **Results of constrained reshape. (a): Reshape building in Environment 1; (b): Reshape building in Environment 2; (c): Reshape building in Environment 3.**

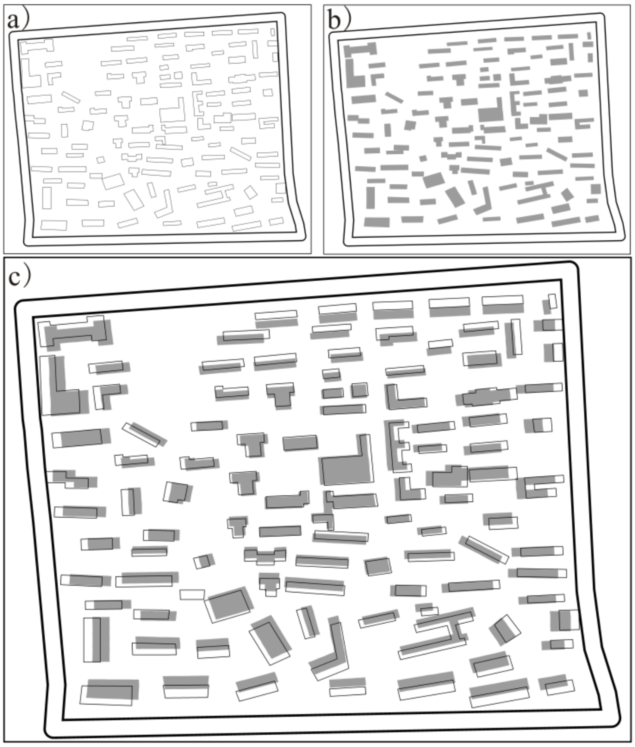

FIGURE 11. Generalization results of Dataset A (1 : 5, 000). (a): Raw data; (b): Generalization result based on the collaborative displacement; (c): A comparison about the raw data and generalization result based on collaborative displacement.

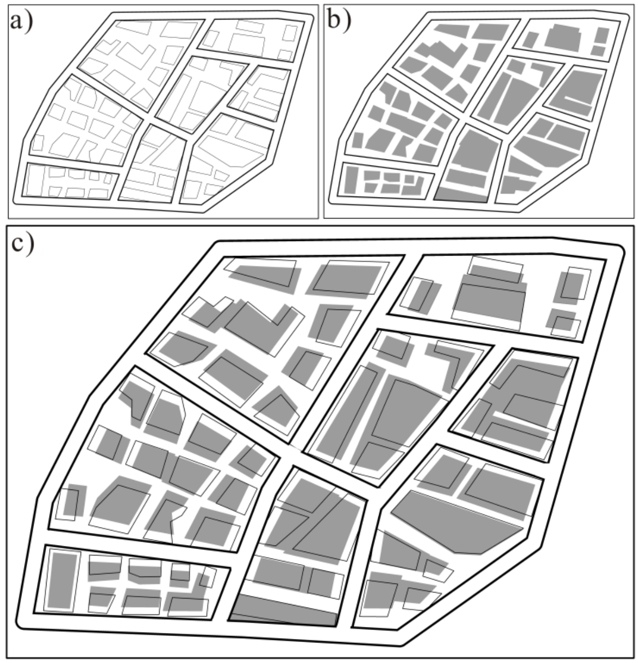

FIGURE 12. Generalization results of Dataset B (1 : 25, 000). (a): Raw data; (b): Generalization result based on the collaborative displacement; (c): A comparison about the raw data and generalization result based on collaborative displacement.

IV. EXPERIMENTS

A. RESULTS AND COMPARISIONS

To validate the feasibility and adaptability of our approach, two topographic data sets from urban building maps at different scales (Dataset A, 1: 5,000 and Dataset B, 1: 25,000) were selected for experiments. The width of the road symbol in Dataset A is set to 0.8 mm; the symbol width for roads in Dataset B is set to 1 mm. For both data sets, the outline width of buildings is set to 0.05 mm, minimum distance threshold is set to 0.2 mm, and positional accuracy threshold is set to 0.5 mm. Building aggregation is conducted using the 'Aggregate polygons' Tool in ArcEngine 10.2 with a 'preserve orthogonal shape' option, which can be embedded in the program. Figure 11 and Figure 12 are the results of our collaborative displacement, in which all defined conflicts are solved after applying our method.

To evaluate the results of our proposed collaborating displacement method, generalization based only on vector field based displacement is applied to Dataset A and Dataset B for comparison; the results are shown in Figure 13(a) and Figure 13(b). In comparisons of Figure 11 and Figure 13(a), and Figure 12 and Figure 13(b), generalization only conducted based on vector field based displacement results in unsolved conflicts. For example, in Dataset A, conflict A and conflict D remain unsolved after applying the vector field based displacement, while they can be solved by an additional displacement in our collaborative displacement method. Conflicts C and E are Type 1 unsolved conflicts, in which conflict C can be solved by aggregating the two buildings and conflict E can be solved by eliminating the smaller area building using our collaborative displacement method. Conflict B is a Type 2 unsolved conflict, which can be solved by aggregation in our collaborative displacement method. Similar comparisons are made in Dataset B. Conflict F is a Type 2 unsolved conflict, solvable with aggregation, and conflict G is a Type 1 unsolved conflict, solvable with constrained reshape using our collaborative displacement method.

B. DISCUSSION

The experimental results indicate that our proposed method is effective in solving defined conflicts in urban building maps. However, the method has some limitations. First, the 'Aggregate polygons' tool with a 'preserve orthogonal shape' option in ArcEngine 10.2 is adopted for building aggregation in our method, which may sometimes fail. In this circumstance, 'Aggregate polygons' tool without a 'preserve orthogonal shape' option is adopted, which is not always reasonable in practices. Second, the generalization process involves different operators and algorithms, and more generalization operators may be needed, such as typification and simplification. In our method, buildings in patterns are considered as a group for generalization, and occasionally patterns are broken up in a way that distorts the patterns. Therefore, it may be better to apply typification. Furthermore, after aggregation, buildings may need additional simplification. Displacement methods have been designed for different scenarios, and it may be better to apply an alternate displacement method with

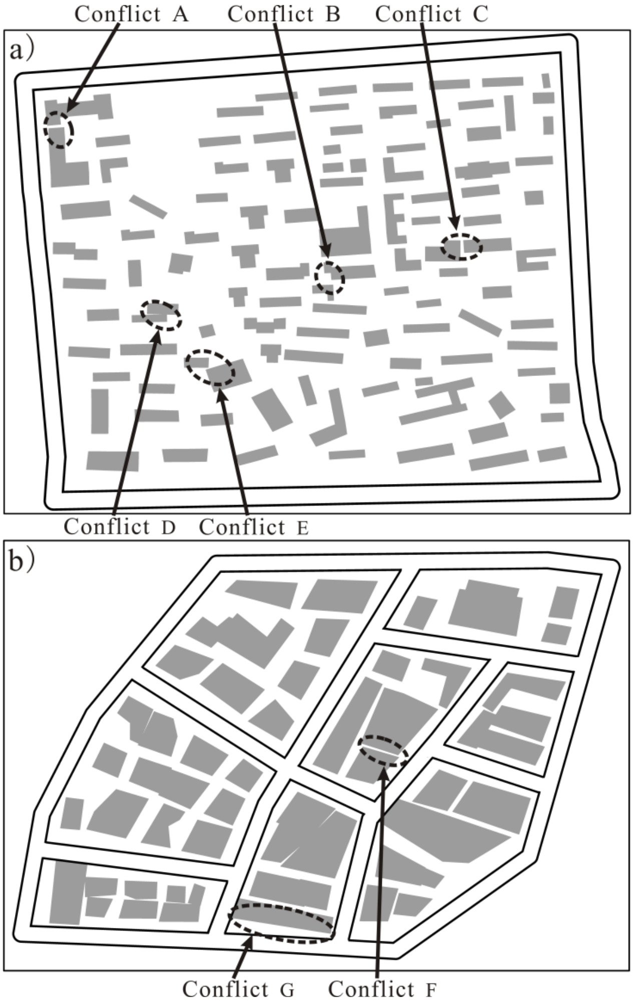

FIGURE 13. Generalization results only based on vector field displacement. (a): Generalization result of Dataset A; (b): Generalization result of Dataset B.

knowledge of the buildings, such as building density, while only a vector field based displacement is considered in our approach. Third, only spatial characteristics about building are considered in our method, but with enhancements in geographic information content, attribute information about buildings need also be taken into consideration. For example, it may be more reasonable for two buildings to be aggregated with the same types. Finally, more cartographical rules may need to be considered in our collaboration. For example, buildings along roads or with large area may be more important and cannot be easily eliminated. However, in our approach, only the importance of buildings according to their area and similarity between two buildings in orientation are considered.

V. CONCLUSION

To solve all possible sequential conflicts in generalizing urban building maps, this study proposes a collaborative displacement method. In our method, an improved vector field based displacement method is adopted for initial conflicts. Then, two types of sequential conflicts are evaluated to determine if an additional displacement will solve the conflict. Aggregation, elimination, and constrained reshape are then applied for these unsolved sequential conflicts based on cartographical rules. We also introduce an improved constrained reshape method for buildings in conflicts along roads. Based on two experimental dataset, our method is both reasonable and feasible for providing solutions to all defined conflicts. This method can also be extended to other spatial conflict problems, such as road network generalization.

Future works will focus on additional generalization operators or algorithms to achieve more optimized results, such as typification for building patterns or specialized displacement methods for different scenarios. More detailed cartographical rules for applying different generalization operators or algorithms for spatial conflicts can be added to our cartographical rule table. Finally, more information on the context of conflicts needs to be taken into consideration.

REFERENCES

[1] N. Regnauld, "Contextual building typification in automated map generalization," *Algorithmica*, vol. 30, no. 2, pp. 312–333, 2001.

[2] X. Zhang, J. Stoter, T. Ai, M. J. Kraak, and M. Molenaar, "Automated evaluation of building alignments in generalized maps," *Int. J. Geograph. Inf. Sci.*, vol. 27, no. 8, pp. 1550–1571, 2013.

[3] M. K. Beard, "Constraints on rule formation," in *Map Generalization: Making Rules for Knowledge Representation*, B. P. Buttenfield and R. B. McMaster, Eds. London, U.K.: Longman, 1991, pp. 121–135.

[4] P. Taillandier and J. Gaffuri, "Improving map generalisation with new pruning heuristics," *Int. J. Geograph. Inf. Sci.*, vol. 26, no. 7, pp. 1309–1323, 2012.

[5] T. Ai, X. Zhang, Q. Zhou, and M. Yang, "A vector field model to handle the displacement of multiple conflicts in building generalization," *Int. J. Geograph. Inf. Sci.*, vol. 29, no. 8, pp. 1310–1331, 2015.

[6] A. Ruas, "A method for building displacement in automated map generalisation," *Int. J. Geograph. Inf. Sci.*, vol. 12, no. 8, pp. 789–803, 1998.

[7] J. M. Ware, C. B. Jones, and N. Thomas, "Automated map generalization with multiple operators: A simulated annealing approach," *Int. J. Geograph. Inf. Sci.*, vol. 17, no. 8, pp. 743–769, 2003.

[8] L. E. Harrie, "The constraint method for solving spatial conflicts in cartographic generalization," *Cartogr. Geograph. Inf. Sci.*, vol. 26, no. 1, pp. 55–69, 1999.

[9] M. Sester, "Generalization based on least squares adjustment," *Int. Arch. Photogram. Remote Sens.*, vol. 33, Part B4, pp. 931–938, Jul. 2000.

[10] D. Burghardt and S. Meier, "Cartographic displacement using the snakes concept," in *Semantic Modeling for the Acquisition of Topographic Information from Images and Maps: SMATI*. Basel, Switzerland: Birkhäuser, 1997, pp. 114–120.

[11] P. Højholt, "Solving space conflicts in map generalization: Using a finite element method," *Cartogr. Geograph. Inf. Sci.*, vol. 27, no. 1, pp. 65–74, 2000.

[12] J. M. Ware *et al.*, "A tabu search approach to automated map generalisation," in *Proc. 10th ACM Int. Symp. Adv. Geograph. Inf. Syst.*, McLean, VA, USA, 2002, pp. 101–106.

[13] I. D. Wilson, J. M. Ware, and J. A. Ware, "A genetic algorithm approach to cartographic map generalisation," *Comput. Ind.*, vol. 52, no. 3, pp. 291–304, 2003.

[14] Y. Sun, Q. Guo, Y. Liu, X. Ma, and J. Weng, "An immune genetic algorithm to buildings displacement in cartographic generalization," *Trans. GIS*, vol. 20, no. 4, pp. 585–612, 2016.

[15] L. Wang, Q. Guo, Y. Liu, Y. Sun, and Z. Wei, "Contextual building selection based on a genetic algorithm in map generalization," *ISPRS Int. Geo-Inf.*, vol. 6, no. 9, p. 271, 2017.

[16] L. Fei, "A method of automated cartographic displacement: On the relationship between streets and buildings," Ph.D. dissertation, Fachrichtung Vermessungswesen, Univ. Hannover, Hannover, Germany, 2002.

[17] C. Duchêne, A. Ruas, and C. Cambier, "The CartACom model: Transforming cartographic features into communicating agents for cartographic generalisation," *Int. J. Geograph. Inf. Sci.*, vol. 26, no. 9, pp. 1533–1562, 2012.

[18] J. Renard and C. Duchêne, "Urban structure generalization in multi-agent process by use of reactional agents," *Trans. GIS*, vol. 18, no. 2, pp. 201–218, 2014.

[19] L. Wang, Q. Guo, Z. Wei, and Y. Liu, "Spatial conflict resolution in a multi-agent process by the use of a snake model," *IEEE Access*, vol. 5, pp. 24249–24261, 2017.

[20] W. A. Mackaness, "An algorithm for conflict identification and feature displacement in automated map generalization," *Cartogr. Geograph. Inf. Sci.*, vol. 21, no. 4, pp. 219–232, 1994.

[21] Y. Liu, Q. Guo, Y. Sun, and X. Ma, "A combined approach to cartographic displacement for buildings based on skeleton and improved elastic beam algorithm," *PLoS ONE*, vol. 9, no. 12, p. e113953, 2014.

[22] S. Steiniger, P. Taillandier, and R. Weibel, "Utilising urban context recognition and machine learning to improve the generalisation of buildings," *Int. J. Geograph. Inf. Sci.*, vol. 24, no. 2, pp. 253–282, 2010.

[23] W. Lichtner, "Computer assisted processes of cartographic generalization in topographic maps," *Geo-Process.*, vol. 1, no. 2, pp. 183–199, 1979.

[24] X. Wu, Q. Du, and Z. Xu, "Disposal of spatial conflict between roads and buildings based on the multilevel displacement principles," *Acta Geodaetica Cartograph. Sinica*, vol. 39, no. 6, pp. 649–654, 2010.

[25] Z. Li, C. Yang, B. Wei, X. Zhou, L. He, and R. Xin, "A displacement algorithm based on geometry similarity for spatial conflicts between roads and buildings," *Acta Geodaetica Cartograph. Sinica*, vol. 45, no. 6, pp. 747–755, 2016.

[26] Q. Zhou, T. Ai, and X. Zhang, "A displacement field model to resolve multiple spatial conflicts," *Acta Geodaetica Cartograph. Sinica*, vol. 42, no. 4, pp. 615–620, 2013.

[27] M. Bader, M. Barrault, and R. Weibel, "Building displacement over a ductile truss," *Int. J. Geograph. Inf. Sci.*, vol. 19, no. 8, pp. 915–936, 2015.

[28] Y. Sun, Q. Guo, Y. Liu, X. Lv, and N. Yang, "Building displacement based on the topological structure," *Cartograph. J.*, vol. 53, no. 3, pp. 230–241, 2016.

[29] Y. Liu, "Research and improvement of cartographic displacement algorithms based on energy minimization principles," Ph.D. dissertation, Wuhan Univ., Hubei, China, 2015.

[30] H. Yan, R. Weibel, and B. Yang, "A multi-parameter approach to automated building grouping and generalization," *Geoinformatica*, vol. 12, no. 1, pp. 73–89, 2008.

[31] T. Ai and X. Zhang, "The aggregation of urban building clusters based on the skeleton partitioning of gap space," in *The European Information Society* (Lecture Notes in Geoinformation and Cartography). Berlin, Germany: Springer, 2007, pp. 153–170.

[32] F. Wu *et al.*, *Intelligent Processing of Spatial Information for Automatic Map Generalization*. Beijing, China: Science Press, 2008.

[33] S. Du, M. Shu, and C.-C. Feng, "Representation and discovery of building patterns: A three-level relational approach," *Int. J. Geograph. Inf. Sci.*, vol. 30, no. 6, pp. 1161–1186, 2016.

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