Automated building generalization based on urban morphology and Gestalt theory

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Abstract. Building generalization is a difficult operation due to the complexity of the spatial distribution of buildings and for reasons of spatial recognition. In this study, building generalization is decomposed into two steps, i.e. building grouping and generalization execution. The neighbourhood model in urban morphology provides global constraints for guiding the global partitioning of building sets on the whole map by means of roads and rivers, by which enclaves, blocks, superblocks or neighbourhoods are formed; whereas the local constraints from Gestalt principles provide criteria for the further grouping of enclaves, blocks, superblocks and/or neighbourhoods. In the grouping process, graph theory, Delaunay triangulation and the Voronoi diagram are employed as supporting techniques. After grouping, some useful information, such as the sum of the building’s area, the mean separation and the standard deviation of the separation of buildings, is attached to each group. By means of the attached information, an appropriate operation is selected to generalize the corresponding groups. Indeed, the methodology described brings together a number of well-developed theories/techniques, including graph theory, Delaunay triangulation, and the Voronoi diagram, urban morphology and Gestalt theory, in such a way that multiscale products can be derived.

1. Introduction

Automated map generalization has been a hot issue in the GIS and cartography communities since the 1960s. In the past two decades, a great deal of effort has gone into developing geometric algorithms (operators) and, as a result, many algorithms (operators) for specific map features have been developed. (In the context of this paper, a generalization operator refers to an algorithm, transformation model, or procedure to realize a generalization operation e.g. aggregation. However, in some other studies, the term ‘operator’ is used to mean the generalization operation.) They include algorithms for point feature generalization (Van Kreveld 1995, Yukio 1997, Ai and Liu 2002), linear feature
generalization (Douglas and Peucker 1973, Li and Openshaw 1992, Wang and Müller 1992, De Berg et al., 1995) and areal feature generalization (Monmonier 1983, Zhang and Tulip 1990, Müller and Wang 1992, Schylberg 1992a, b, 1993, Beines 1993, Su and Li 1995, Li and Su 1996, Su and Li 1997, 1997a, b, Bader and Weibel 1997, Barrault 2001, Ruas 2001, Galanda and Weibel 2002). It is understandable that an algorithm (operator) is concerned about how to achieve a generalization operation (referred to as an operator in some studies), e.g. combination of areal features or the simplification of a line. Algorithms (operators) are designed for geometric transformations only. If an algorithm (operator) could realize a particular generalization operation well, it is a good algorithm for this particular operation. The question that arises is when does one use such an algorithm (operator) (McMaster and Shea 1989)? That is, the scene needs to be set based on some geographical attributes and spatial configurations. Alternatively, constraints need to be formed for the use of the generalization algorithms (operators). Here, constraints refer to the guidelines for the generalization of specific features, which determine the use of appropriate generalization algorithms (operators). A constraint could be local if it is for a single object or global if for a set of objects. Also, depending on their nature, constraints could be topological, metric or geographical.

In recent years, research on the ‘constraints’ of map generalization has been emphasized (Ruas and Plazanet 1996, Sester 2000, Harrie 2002). It is noticeable that most of the constraints are for individual objects. However, ‘defining constraints on groups of objects is more difficult, and often requires the preservation of object patterns, which is particularly difficult’ (Harrie 2002). Such a remark is particularly true for the development of constraints for building features, and the discussion in this paper is confined to this topic.

In the development of constraints for the generalization of building features, Regnauld (1996, 2001) carried out some interesting research. He detected and organized building relations using the Minimum Spanning Tree (MST) and used a graph of proximity on the building set, which was analysed and segmented with respect to various criteria taken from Gestalt theory. Such analysis provides some essential geographical information, such as the average size of buildings, shape of the group and density, attached to each group of buildings. Christophe and Ruas (2002) detected building alignments using straight-line templates. Building alignments are identified from the templates. The alignments are then characterized by a set of parameters such as proximity and similarity, and only those perceptually regular buildings are retained. Rainsford and Mackness (2002) have also used the template matching technique for building grouping. Boffet and Serra (2001) identified spatial structures within urban blocks for the characterization of towns. Anders and Sester (2000) put forward a parameter-free cluster detection method used in spatial databases. Ware and Jones (1998) introduced simulated annealing to handle the displacement of buildings while preserving the alignment. The common drawback of such processes lies in the heavy computation involved (Boffet and Serra 2001). There is also a lack of global constraints to guide the use of an appropriate algorithm to generalize individual groups of buildings after the grouping has been made. The objective of the present paper is to describe an integrated methodology for the fully automated generalization of buildings. The contents include (1) the automated grouping of buildings, (2) the automated
selection of a generalization operation and (3) the automated execution of the generalization process.

The paper is organized as follows. After the introduction (Section 1) is a general discussion of the operations and constraints used in building generalization (Section 2). Section 3 focuses on the global constraints from urban morphology in grouping buildings. Section 4 discusses in detail the local constraints based on Gestalt principles. The building grouping process is presented in Section 5, and the process of building generalization is discussed in Section 6. Section 7 presents an approach to evaluating the results of the generalization. An example to illustrate the method is given in Section 8. Finally, some conclusions are presented in Section 9.

2. Building generalization: operations and constraints

Researchers have tried various theories (e.g. Gestalt theory) and methodologies (e.g. cluster detection and spatial structure analysis) for the generalization of buildings. Indeed, significant achievements have already been made in this area (Lichner 1979, Regnauld 2001). The present paper contributes to advancing this area in the following two aspects:

- By offering a theoretically sound methodology for grouping.
- By devising a set of rules for determining which generalization operation should be employed for a given case.

2.1. Analysis of possible operations for building generalization

In a digital environment, the generalization process has been decomposed into many operations (McMaster and Shea 1992), such as simplification, aggregation, combinations, collapse, etc. In particular, considering building features only, the following seem to form a subset of operations, i.e. aggregation, collapse, displacement, exaggeration, selective omission, simplification and typification. The meanings of these operations are derived from the work by McMaster and Shea, with occasional modifications. Table 1 illustrates such operations.

<table>
<thead>
<tr>
<th>Operators</th>
<th>Original</th>
<th>Simply reduced</th>
<th>Generalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregation</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Collapse</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>Displacement</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>Exaggeration</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>Elimination</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
<tr>
<td>Simplification</td>
<td><img src="image16.png" alt="Image" /></td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td>Typification</td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
<td><img src="image21.png" alt="Image" /></td>
</tr>
</tbody>
</table>
• Aggregation: to combine buildings separated by space.
• Collapse: to make the feature represented by a symbol with a lower dimension, e.g. to represent a city as a point feature on small-scale maps.
• Displacement: to move the building to a slightly different position, normally to solve the problem of conflict.
• Exaggeration: to enlarge a building with small size for representation at a smaller scale maps on which it should be too small to be represented.
• Selective omission (or elimination): to eliminate small and unimportant buildings.
• Simplification: to make the shape simpler.
• Typification: to represent buildings with a typical distribution pattern, e.g. to represent groups of buildings aligned in rows (e.g. five rows) using fewer (e.g. three) rows.

Displacement and exaggeration can in fact be considered as a post-generalization process at the stage of graphic presentation (Li and Su 1995). Collapse means to represent an area feature using a line (e.g. river) or a point (e.g. a city) (Su et al. 1998). This happens only when the change in scale is very dramatic and the target scale is very small. A discussion of collapse is beyond the scope of this study. Therefore, building groupings will only be related to such generalization operations as aggregation, simplification, elimination, and typification. (In this study, no differentiation is made between amalgamation and aggregation because the procedures for both operations are virtually the same.)

2.2. Two types of constraints for building grouping: global and local

In the cognitive interpretation of visual signals, two steps are involved, i.e. a preattentive phase and an attentive phase. In the former, an unconscious attempt is made quickly to extract information from an image through a global search operation that involves active grouping. The latter is a local phase, in which attention is paid to specific features of the visual landscape that have been identified as being different during the preattentive phase. That is, the global searching for groupings and locally focused identification are involved.

It is understandable that the visual information processing in map recognition is also similar. It can be imagined that in the generalization of building features, cartographers must also have followed such a two-step process. In other words, there is a group of global constraints and a group of local constraints for the grouping and then the generalization of buildings. After the constraints have been formed, the generalization operations can then be carried out. Finally, a quality assessment is made of the generalized map, and of the individual groups and neighbourhood. This strategy will be the one followed in this study.

3. Global constraints based on urban morphology

As discussed previously, there is a need for two types of constraints in the generalization of buildings, i.e. global and local. This section is devoted to the formation of global constraints.
3.1. Basic ideas in urban morphology

Urban morphology, dealing with the structure and/or pattern of a city, is a well-established discipline. Therefore, some of the principles used in urban morphology may be adopted for grouping buildings for the purpose of map generalization.

Urban morphology is about the hierarchical structure of a city. Indeed, in a classic neighbourhood model (Patricios 2002) in urban morphology, a city is, in essence, a hierarchical one comprising four levels, i.e.

- Enclave.
- Block.
- Superblock.
- Neighbourhood.

Figure 1 shows four such levels in a hierarchy. The fundamental component is an enclave of 20 or so houses. Three or four of these enclaves are lined together to form a block. The enclaves within the block are separated from one another by a pedestrian pathway. The blocks are arranged around the sides of a central parkway in such a manner as to enclose the open green spaces. The clustered blocks, together with the central parkway, comprise a superblock. Several adjacent superblocks together form a neighbourhood bounded by major roads or natural features. Each neighbourhood is a fundamental unit of the city.

The roads in the neighbourhood are arranged hierarchically. Major traffic roads border each neighbourhood; distributor roads surround each superblock; cul-de-sacs provide access to individual property lots.

It has become natural to think that such a hierarchical partitioning of a city can be used for the hierarchical representation of urban features, such as buildings and roads, on maps at different scales. The four levels of the hierarchy must correspond to a change in scale. Of course, if the change in scale is too great, then the whole

![Figure 1. Hierarchical structure of cities (after Patricios 2002). (a) Enclave, (b) block, (c) superblock and (d) neighbourhood.](image-url)
city may become a point. But at such a change in scale, not much needs to be done in terms of generalization. Indeed, this neighbourhood model provides a macro view for the generalization of buildings with a limited range of change in scale, and can be used to form global constraints.

3.2. Global constraints based on urban morphology

The neighbourhood model plays two roles in the formation of global constraints for building grouping and generalization:

- Neighbourhood model is used for global partitioning. In this step, an analysis of the whole map area is made. The features analysed are mainly roads and rivers, but not the buildings themselves. The axes of the roads and rivers are first extracted. The topological polygons of these crossed lines are then constructed. Each polygon stands for a partitioned global group of buildings. The resultant groups correspond to enclaves, blocks, superblocks or neighbourhoods due to different reductions in scale. Figure 2 is an example of global partitioning using the neighbourhood model. The extraction of medial-axes from streets is not a very sophisticated process, nor is the construction of topological polygons using crossed lines (Gold 1991, Klein and Meimer 1993, Christensen 1999). Therefore, no details will be given here.

![Figure 2](image_url)

**Figure 2.** Global partitioning using the neighbourhood model. (a) Street map of a city and (b) global partition based on the topological polygons formed by the street axes.
What should be accentuated is that roads (and rivers if any) have a higher priority than buildings in the process of automated map generalization, as in the case of manual generalization. In other words, only after roads are generalized can the global partitioning of buildings in the same area be calculated correctly. In the following study, the building alignment is restricted to buildings within one street block.

- After generalization, the topological polygons created based on the neighbourhood model are used as criteria to check if the relations among buildings and linear features (rivers and roads) have been well preserved, by which the harmony of the whole map can be ensured.

4. Local constraints based on Gestalt principles

After the global partitioning step, building sets in blocks, superblocks or neighbourhoods are not well arranged. Whether or not the buildings can easily be generalized is still uncertain, as the configurations and the relations among a group of buildings are still unknown. At this stage, it is not easy to determine which operation (e.g. aggregation) should be employed to generalize a specific group. Therefore, it is necessary to detect, analyse and group the global groups.

This step consists of two procedures: forming fundamental groups and the reunion of the fundamental groups. Gestalt principles are the theoretical basis for these procedures.

4.1. Gestalt principles

It has been noted that Gestalt principles have been applied for the recognition of spatial distribution patterns for many years (Weibel 1996), in both digital and manual generalization. In any case, from the point of view of perception, one conclusion from the research results remains unquestionable (Rock, 1996):

Grouping is not a simple, early process that works only on properties of image-based representations. Rather, it is a much more sophisticated process, one that incorporates the results of pictorial depth perception, occlusion, and amodal completion, as well as stereoscopic depth perception and lightness constancy.

Wertheimer (1923) took the initial step of identifying a number of important factors that have come to be known as the ‘Gestalt law of grouping’, although ‘principle of grouping’ is perhaps a more appropriate description. These principles are proximity, similarity, closure, continuity and common fate. To this list, two more factors have recently been added, i.e. common region (Palmer 1992) and element connectedness (Palmer and Rock 1994). For the detection of building alignments, the factor of common orientation plays an important role and we will also add it to the list. The definitions of these factors are as follows:

- Proximity: closeness.
- Similarity, i.e. the factor of likeness. If rows of stimuli with constituents of different sorts are given, there is a tendency towards the form in which the like ones appear grouped together.
- Common fate: the factor of uniform destiny, i.e. new groups may be generated if an operation is used on the objects in original groups.
• Common region: objects in same region are more easily grouped together.
• Closure: an object group with a closed tendency is easily regarded as being perceptually closed.
• Continuity: the regularity or tendency cannot be easily disturbed, for example, two crossed curves keep their continuity respectively.
• Element connectedness: connected elements can easily form a group.
• Common orientation: distribution along a similar direction.

Table 2 illustrates these factors. Indeed, these factors provide local perceptual constraints for grouping. The local constraints, together with the global ones from urban morphology, play their roles respectively at different stages in the grouping and generalization of buildings.

4.2. Setting up Gestalt parameters as constraints

To group buildings locally, the Gestalt factors should be customized for the case of building to form some new parameters. The thresholds for these parameters should then be set. To clarify these parameters, five definitions are given as follows:

<table>
<thead>
<tr>
<th>Gestalt factors</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximity</td>
<td><img src="image" alt="Proximity Example" /></td>
</tr>
<tr>
<td>Similarity</td>
<td><img src="image" alt="Similarity Example" /></td>
</tr>
<tr>
<td>Common fate</td>
<td><img src="image" alt="Common fate Example" /></td>
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<tr>
<td>Common region</td>
<td><img src="image" alt="Common region Example" /></td>
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<tr>
<td>Closure</td>
<td><img src="image" alt="Closure Example" /></td>
</tr>
<tr>
<td>Continuity</td>
<td><img src="image" alt="Continuity Example" /></td>
</tr>
<tr>
<td>Element connectedness</td>
<td><img src="image" alt="Element connectedness Example" /></td>
</tr>
<tr>
<td>Common orientation</td>
<td><img src="image" alt="Common orientation Example" /></td>
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</table>
Major axis of a polygon: an axis is a line segment joining the mid-points of two edges of the polygon. The longest axis among them is defined as the major axis (i.e. the thick lines of figure 3).

Minor axis of a polygon: this is an imaginary axis. It is perpendicular to the major axis and passes through the midpoint of the major axis. Its length is equal to the ratio between the area of the polygon and the length of the major axis.

Deviation angle: this is an acute or right angle formed by two crossed straight lines (they are generally major axes in building grouping).

Approximate parallels: if the deviation angle of two lines is less than 10° (experimental value), the two lines are regarded as being approximate parallels.

Approximately equal length: if \( L_{\text{max}} - L_{\text{min}} < L_{\text{limit}} \) or \( (L_{\text{max}} - L_{\text{min}})/L_{\text{max}} < 0.5 \), the two line segments are defined as being approximately equal in length. Here, \( L_{\text{max}} \) is the length of the longer line segment and \( L_{\text{min}} \) is the shorter one.

Based on experience, the following thresholds are used for these parameters. A graphic illustration of the parameters and the threshold values is given in table 3.

Table 3. Graphic illustrations of Gestalt parameters specifically for buildings.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation threshold</td>
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</tr>
<tr>
<td>Length threshold</td>
<td><img src="image" alt="Length Threshold" /></td>
</tr>
<tr>
<td>Area threshold</td>
<td><img src="image" alt="Area Threshold" /></td>
</tr>
<tr>
<td>Similar size</td>
<td><img src="image" alt="Similar Size" /></td>
</tr>
<tr>
<td>Similar shape</td>
<td><img src="image" alt="Similar Shape" /></td>
</tr>
<tr>
<td>Similar orientation</td>
<td><img src="image" alt="Similar Orientation" /></td>
</tr>
</tbody>
</table>
• Length threshold, $L_{\text{limit}}$: the length of the shortest edges that can be represented on buildings, generally 0.3 mm.

• Area threshold, $A_{\text{limit}}$: the area of the smallest building that can be represented on maps by its real size, generally $0.6 \times 0.4 \text{ mm}^2$.

• Separation threshold, $D_{\text{limit}}$: the minimum distance between two buildings that is required for clarity, generally 0.5 mm.

• Similar size: if $A_{\text{max}}/A_{\text{min}} < 2$ or both $A_{\text{max}}$ and $A_{\text{min}}$ are less than $A_{\text{limit}}$, two buildings are regarded as being of a similar size. Here:

  $A_{\text{max}}$: area of the bigger building;
  $A_{\text{min}}$: area of the smaller building.

• Similar shape: if $E_{\text{max}}/E_{\text{min}} \leq 1.5$, the two buildings are regarded as being of a similar shape. Here:

  $E_{\text{max}}$: greater edge number of the two buildings;
  $E_{\text{min}}$: lesser edge number of the two buildings.

• Similar orientation: if one of the following two rules is satisfied, the two buildings are regarded as being of a similar orientation:

  Major axes of the two buildings are approximately parallel;
  Major axis of a building and its minor axis are of approximately equal length; meanwhile, the major or minor axis of this building is approximately parallel with the major axis of another building.

5. Building grouping based on urban morphology and Gestalt principles

In the previous sections, the ideas of urban morphology and Gestalt principles are introduced and some parameters are also set for building grouping. In this section, the actual grouping procedures will be described.

5.1. Procedures for local grouping

Two procedures have been developed, one for the case of maps with adjacent scales and the other for maps with non-adjacent scales. Here, adjacent scale means that the ratio between two scales is 2 or 2.5. For example, 1:25,000 and 1:50,000 are adjacent scales, whereas 1:25,000 and 1/100,000 are not. In this paper, the map scale series with the scales $S_s, S_1, S_2, ..., S_n, S_t$. $S_s$ donates the source map scale and is the largest map scale in the series; $S_t$ is the target map scale and is the smallest map scale in the list; $S_1$ the adjacent scale of $S_s$, $S_2$ the adjacent scale of $S_1$, ..., and $S_n$ is the adjacent scale of $S_t$.

The procedure for local grouping for maps with adjacent scales works as follows:

• Topological adjacency relationships are detected using the triangulation network of the buildings, by which the street axes between buildings are extracted. Two buildings with adjacency relations are directly linked and those without adjacency relations are separated.

• Direct alignments between every two topologically adjacent buildings
(figure 3) are identified using the constraints from the Gestalt theory. The indirect alignments (figure 4) among a row/column of buildings are then built upon the direct alignment relations.

- Buildings with strong perceptual relations in each indirect alignment are separated from the other ones to form groups.
- Non-alignment buildings and those alignments with weak perceptual relations are clustered according to their distance, shape, size, and free space relations to obtain the resultant group set. Some useful information (i.e. attributes) is attached to each group, such as the sum of the building area, the sum of the free space area, the minimum distance between the two buildings, the mean distance among buildings, etc.

If the source map scale and target map scale are not adjacent, the procedure is as follows:

- Topological adjacency relations among groups are detected and recorded, which is exactly the same as the step for local grouping for maps with adjacent scales. Let the current map scale be equal to $S_i$ (originally $i = 1$).
- Calculate the free space areas and the separation between every two adjacent groups.
- Merge the adjacent groups if their free space area is less than $A_{\text{limit}}$ or their separation less than $D_{\text{limit}}$. Let the current map scale equal $S_{i+1}$.
- End the procedure if $S_{i+1} \approx S_t$; or else re-calculate and attach the information to the new groups and go to step 1.

5.2. Detection of topological adjacency relationships

The detection of topological adjacency relationships among polygons, based on primitives of computational geometry, such as the convex hull, Voronoi diagramme

![Figure 4. Construction of an indirect alignment. (a) Direct alignment and (b) indirect alignment.](image)

*Automated building generalization*
and Delaunay Triangulation, has been researched in the GIS community for years (Gold 1991, Tsai 1993, Herbert and Tan 1993, Zhao et al. 1999, Li et al. 2002). For this reason, the following discussion will concentrate on the process and principles of detection, but not on the algorithms from Computational Geometry. This process consists of four procedures:

- **Triangulation**: the so-called incremental algorithm (Klein and Meiser 1993) is used to construct triangulation among buildings, by which two kinds of triangles are formed. If three points of a triangle belong to the same building, this triangle is called the ‘building triangle’, or the ‘connection triangle’ if it links two or three different buildings like a ‘bridge’. The building triangles are located either within a building or in the concave part of the building polygon. To detect the building group, we are only interested in the connection triangles. The building triangles are useless for detecting adjacency relationships among buildings, so they are deleted from triangle arrays, and only connection triangles are retained.

- **Adjacency relationships detection**: if a vertex of a connection triangle belongs to a building, this triangle belongs to the building. Hence, every connection triangle belongs to two or three buildings. Two buildings owning the same triangles are defined as topologically adjacent, i.e. with an adjacency relation.

- **Extraction of building cluster axes**: connection triangles between two buildings are examined to form an axis, which stands for a graphic separation but logically for a linkage line between two buildings as far as the topological adjacency relation is concerned. Building cluster axes are very helpful for visualizing groupings of buildings.

- **Construction of an adjacency relation matrix**: if a group consists of \( N \) buildings, an \( N \times N \) matrix \( A \) is used to represent the adjacency relationships among buildings. If building \( m \) and building \( n \) (\( m \) and \( n \) are the sequential numbers of the two objects in the building set) are adjacent, we define:

\[
A_{m,n} = 1 \\
A_{n,m} = 1.
\]

Otherwise,

\[
A_{m,n} = 0 \\
A_{n,m} = 0.
\]

Obviously, \( A \) is a symmetrical matrix, so that a zero may be assigned to all of the elements in the lower triangular matrix. Therefore, only the upper triangular matrix is used in the following discussion. At this stage, the free space area, the separation (the minimum distance) between the two adjacent buildings, is calculated and recorded in the corresponding matrix.

5.3. **Detection of building alignments**

A building alignment is a group of buildings of a similar orientation, size, shape and approximately equal separation. There are two types of alignments, i.e. direct and indirect (figure 4). If two adjacent buildings are perceptually ‘the same’, they form a direct alignment. A direct alignment exists between two adjacent buildings.
The similarity is evaluated by three parameters—size, shape, and orientation—usually used in Gestalt experiments.

Basically, if two adjacent buildings are of the same size, shape, and orientation, a direct alignment is formed between them. But how these factors respectively contribute to the alignment recognition is difficult to represent quantitatively. For the sake of simplicity, we will only consider the adjacency relation and orientation.

There are two kinds of direct alignments that can be differentiated among building groups, i.e. ‘extension alignment’ and ‘parallel alignment’.

- Extension alignment: if the line linking the centroids of the two buildings is approximately parallel with one of the major axes of the two buildings in an alignment, this alignment is an extension alignment, as is shown in figure 3(a).

- Parallel alignment: if an alignment is not an extension alignment, link four end points of the two major axes to form a simple quadrangle. Select the two end points of the short major axis as start points, and draw two perpendicular lines. If none of the perpendicular lines intersects with the longer major axis, this is a false alignment. Otherwise, if:

\[
\frac{M_{\text{max}} - M_{\text{min}}}{M_{\text{min}}} < 1
\]

This alignment is defined as a parallel alignment (figure 3b). Here, \(M_{\text{max}}\) is the length of the longer major axis, and \(M_{\text{min}}\) the length of the shorter one.

After the detection of direct alignments, an \(N \times N\) matrix \(D\) is constructed to record the direct alignment relations between every two buildings for a building set with \(N\) buildings. An element \(D_{ij}\) may be equal to 0, 1 or 2, representing non-alignment, extension alignment and parallel alignment relations, respectively.

As each direct alignment consists of only two buildings of the same nature, it is too fragmental for generalizations to be carried out on them directly. It is then natural to make the group larger if possible. To do so, the further detection of strong alignments with a greater number of buildings is required. The result is termed as indirect alignments here. Indeed, an indirect alignment is the connection of the same direct alignments (extension or parallel) with a common element (building), i.e. an indirect alignment is formed by two direct extension alignments (or parallel alignments) with adjacency relationships. An indirect alignment relation matrix can easily be built upon the direct alignment relation matrix \(D\). Figure 4 is a graphic illustration of the construction process of an indirect alignment.

5.4. Post-processing of building alignments

An indirect alignment is a potential group, but it is still too early to apply a generalization operation to them because some of them belong to common buildings (figure 5). To determine which alignment a common building belongs to in a generalization, three factors should be considered, i.e. the building number, mean distance and standard deviation of distance. These three factors, with building numbers in an ascending sequence and the other two in a descending sequence, are used to sort all of the indirect alignments. Obviously, the perceptually stronger indirect alignments are arranged before the weaker ones after sorting. The following
steps are used to determine to which alignment a common building belongs. At the same time, less useful alignments are deleted from the alignment array.

- Step 1. Take the first alignment from the sorted alignment array.
- Step 2. If this alignment owns common elements with other ones in the array, delete the common elements from the other alignments, and recalculate the attached information of the other alignments and resort the alignment array. If an alignment owns only one element, delete this alignment from the array.
- Step 3. If the array is not empty, repeat the procedure from step 1.

Figure 5 gives an illustration of this process. The common building $O_1$ belongs to the alignment $\{O_1, O_3, O_4, O_5\}$ and $\{O_1, O_2\}$. After the separation process, it belongs to the former group, and the latter one with only one element is deleted from the alignment array.

A retained alignment is a resultant group, with strong connection relations by perception. A formed group means the separation of the buildings from the other groups. To record the separation, the corresponding elements in the adjacency relation matrix need to be changed. Check matrix $A$; if building $m$ and $n$ are not in a retained alignment and $A_{m,n} = 1$, let $A_{m,n} = 0, A_{n,m} = 0$.

After the detection of alignment, local groups will have formed. However, many buildings may still have been left out, due to their irregular orientations. That is, a further process is needed to group them together in order to generalize these buildings. In this step, two rules are employed to cluster these buildings:

- If $d \geq D_{\text{limit}}$, $A_{m,n} = 0, A_{n,m} = 0$; or else $A_{m,n} = 1, A_{n,m} = 1$.
- If $a \geq A_{\text{limit}}$, $A_{m,n} = 0, A_{n,m} = 0$; or else $A_{m,n} = 1, A_{n,m} = 1$.

Here, $d$ is the distance between building $m$ and building $n$; $a$ is the area of free space between them.

5.5. Formation of local groups

In essence, a building set is a connective graph with buildings as nodes and their relations (including topological adjacency, separation, free space, size, shape, orientation, etc.) as edges. After the detection of alignment and non-alignment in buildings, the grouping information, i.e. the connectivity between two buildings, will have been recorded in the adjacency relation matrix $A$. By means of this matrix, the connective graph can be divided into several subgraphs. Each subgraph is a building group—a local group. The separation of the matrix $A$ into subgroups is a very popular process in graph theory, which has been discussed in detail in many studies (Alan et al. 1993).

The information attached to a resultant group is for the selection of appropriate
generalization operations and algorithms (operator) for it. Below is a list of the information items attached to every group, expressed in Visual C++.

```c
Struct tagAttachedInfo
{
    int ID; // group ID
    int Num; // building number of the group
    short alignType; // alignment type of the group. 0, 1, 2 for non-, parallel, and parallel alignments respectively
    double SumBArea; // sum of the building area of the group
    double SumFArea; // sum of the free space area of the group
    double MeanDis; // mean distance of the group
    double DisDev; // standard deviation of the distance of the group
    double FareaDev; // standard deviation of the free space area of the group
    double MiniDistance; // the minimum distance to all adjacent groups
} AttachedInfoStruct;
```

Because the values of the area of free space and the separation between buildings have been obtained during the detection of adjacency relations, the calculation of these attached items is not difficult work. An array G with m elements (m is the number of the groups) is defined to record the attached information for all groups.

5.6. *Hierarchical structure of building groups: from enclave to neighbourhood*

If $S_1 = S_n$, the groups in the local grouping process are the resultant groups. Otherwise, the following needs to be done to make the groups hierarchical.

1) Detect and record the topological adjacency relations among groups: to consider topological consistency, the Voronoi region of each group should first be derived from the triangulation network. The relationship between the triangulation network and the Voronoi regions is shown in figure 6. If two groups own a common Voronoi edge (the thick lines in figure 7), they

![Figure 6. Relationship between a triangulation network and Voronoi regions.](image)
are defined as being topologically adjacent. The topological adjacency relations among groups can be easily obtained from the adjacency relations among individual buildings.

2) Merge adjacent groups: if two groups are topologically adjacent and own the same alignment type, and the minimum distance between them is less than \( D_{\text{limit}} \) (the logical value of \( D_{\text{limit}} \) is calculated by current scale and is \( S_2 \) at first) or the free space area between them is less than \( A_{\text{limit}} \), they are combined together to form a new group.

3) Attach the information to each group, as described in Section 5.5.

4) If the current scale equals \( S_1 \), end the procedure. Or else let current scale equal \( S_3 \), recalculate the values of \( D_{\text{limit}} \) and \( A_{\text{limit}} \), and repeat the procedure from step (2).

Note that in this experiment the Voronoi diagram is constructed on the basis of skeletons of connection triangles. According to the strict definition in computation

![Figure 7. Grouping of buildings at 1:10 000 scale for generalization to various scales. (a) Grouping for generalization to 1:25 000, (b) grouping for generalization to 1:50 000, (c) grouping for generalization to 1:100 000 and (d) grouping for generalization to 1:250 000.](image)
geometry, the above construction is not a real Voronoi diagram but it has a similar
property, i.e. equal partitions of the space between buildings equally. From the
point of view of application, it can be used to support the detection of building
group. Indeed, the construction of the Voronoi diagram for polygon clusters rather
than point clusters is difficult. Usually, the construction methods are only
approximate, such as the raster extension method (Li et al. 1999).

6. Selection of generalization operations to building groups

In this step, appropriate operations are selected to generalize every group. Aligned building groups are generally typified; non-aligned ones are simplified, eliminated or aggregated according to the attached information.

6.1. Selection of generalization operations for non-aligned building groups

To a non-alignment group $G_i$, the determination of its generalization operator follows the rules listed below:

- If $G_i$.Num $\approx$ 1 and $G_i$.MiniDistance $< D_{\text{limit}}$ and $G_i$.SumBArea $< A_{\text{limit}}$, the operator is ‘elimination’; otherwise
- If $G_i$.Num $\approx$ 1 and $G_i$.SumBArea $\approx A_{\text{limit}}$, the operator is ‘simplification’; otherwise
- If $G_i$.MeanDis $> D_{\text{limit}}$ or $G_i$.MeanArea $> A_{\text{limit}}$, the operator is ‘simplification’; otherwise
- Operator is ‘aggregation’.

6.2. Selection of the generalization operations for aligned building groups

To an alignment group, the determination of its generalization operator follows the following rules.

- If $G_i$.MeanDis $> D_{\text{limit}}$ or $G_i$.MeanArea $> A_{\text{limit}}$, the selected operator is ‘simplification’; or else.
- If $G_i$.Num $> 2$, the selected operator is ‘typification’.

To ensure that the local configuration and characteristics of each building group are consistent before and after typification, an iterative process is designed to calculate the separation, length and width of $N$ buildings in an alignment group in the following steps:

1. Calculate the sum length of the linear scattered alignment.
2. Let the resultant building number in the group equal $N$, calculate the separation, length and width of the buildings.
3. If the separation is $\geq D_{\text{limit}}$ and the orientation of major axes is consistent with the original ones, end the process; or let the resultant building number in the group equal $N-1$, and repeat step 2 until step 3 is satisfied.

When a group is typified, the first and last buildings are arranged at their original positions to ensure the preservation of the group structure. The other buildings are then filled between the gaps.

After all of the groups are generalized, the generalization constraints within each group have been resolved. However, between different groups, the conflicts...
among buildings may still exist and will need to be detected and solved. For this purpose, the generalized buildings are triangulated again to detect spatial relations among buildings, and a compromise method, i.e. reducing the areas or moving positions of the conflict objects, is used to settle the dilemmas.

7. Practical example

To demonstrate the method discussed in previous sections, an example is presented for purposes of evaluation. Indeed, the evaluation of generalization results is a very difficult issue. The adequacy of a generalization result is dependent on various factors such as the algorithms and constraints used to select the algorithms and operations. The emphasis here is on the use of urban morphology and Gestalt theory for the formation of constraints for grouping buildings in urban areas. Therefore, two parameters should be considered, i.e. (1) the adequacy of the groupings and (2) the adequacy of the decision automatically to make a particular generalization operation (e.g. aggregation). In other words, how good an aggregation/or typification algorithm is will not be discussed here.

The original dataset is from a developed city on the mainland of China. The scale of the source map is 1:10 000. There are 66 buildings in the source map. The target map scales are 1:25 000, 1:50 000, 1:100 000 and 1:250 000. Figure 7 shows the grouping process. The triangulation network and clustered groups are given as Voronoi regions. The generalized results are shown in figure 8.

For the purpose of this study, the generalization results can be evaluated using parameters at three levels, i.e. the characteristics of individual groups, the relation alteration among the groups, and the harmony of the whole map before and after generalization.

Using the proposed method for generalization, the ratios between the building area and the free space area, orientation relations and distance relations are preserved for buildings in every group before and after generalization.

![Figure 8](image_url)

Figure 8. Generalization of grouped buildings to various scales. (a) For 1:25 000 scale, by typification, (b) for 1:50 000 scale, by typification and aggregation, (c) for 1:100 000 scale, by aggregation operation, and (d) for 1:250 000 scale, by aggregation operation.
The preservation of relations among groups ensures the harmony of a neighbourhood (or superblock, block and enclave) before and after generalization. Its consistency is an important index for assessing the quality of generalization on a higher level. To evaluate the results, a global estimator, SumDev, is designed as follows:

\[
\text{SumDev} = \sum \text{abs}(i - j),
\]

where \(\text{abs}(k)\) is the absolute value of \(K\), \(i\) is \(G_i\.ID\)'s position in array \(G\), \(j\) is \(G_j\.ID\)'s position in array \(H\), \(G\) is an array for recording the information of the groups before generalization, in which all elements are sorted in ascending order by the sum of the building area, sum of the space area, mean distance and building number of each group, and \(H\) is the counterpart of \(G\) for recording the same information for all groups after generalization.

If \(\text{SumDev} = 0\), obviously the result is ideal on the level of the neighbourhoods, superblocks and blocks; otherwise, the larger the \(\text{SumDev}\), the worse the result.

After the generalization of the buildings, the topological relations among them are maintained. The partitioned neighbourhoods, superblocks, blocks and enclaves can be correctly and harmonically embedded on the target map with these arteries of cities after this step, by which the harmony of a generalized map is ensured.

Using these parameters as criteria, an evaluation of the generalized maps by the proposed method is presented in Table 4. It is concluded that the proposed methodology works well.

8. Conclusions

This paper has presented a method for building groupings and then generalizations. The method makes use of the concepts developed in urban morphology for the global organization of the building groups and the formation of hierarchies. The neighbourhood model in urban morphology provides global constraints for guiding the global partitioning of buildings set on the map as a whole by means of roads (and/or rivers), by which enclaves, blocks, superblocks or neighbourhoods are formed. Local constraints are formed from Gestalt principles and provide the criteria for the further grouping of enclaves, blocks, superblocks or neighbourhoods. After the grouping, some useful information, such as the sum of the building area, mean separation and standard deviation of the separations, is attached to each group. By making use of the attached information, an appropriate operation is selected to generalize a building group.

<table>
<thead>
<tr>
<th>Map scale</th>
<th>Group number</th>
<th>Building number</th>
<th>Characteristic of individual groups</th>
<th>Group sequence</th>
<th>Harmony of the whole map</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:25 000</td>
<td>19</td>
<td>53</td>
<td>no change</td>
<td>no change</td>
<td>yes</td>
</tr>
<tr>
<td>1:50 000</td>
<td>11</td>
<td>29</td>
<td>no change</td>
<td>slightly changed</td>
<td>yes</td>
</tr>
<tr>
<td>1:100 000</td>
<td>6</td>
<td>6</td>
<td>slightly changed</td>
<td>slightly changed</td>
<td>yes</td>
</tr>
<tr>
<td>1:250 000</td>
<td>1</td>
<td>1</td>
<td>slightly changed</td>
<td>changed</td>
<td>yes</td>
</tr>
</tbody>
</table>
Building grouping is a critical step for building generalization. This is due to the difficulty involved in the detection and analysis of spatial information because some critical information is fuzzy and not easy to quantify, and is even unclear to people. As summarized by one of the reviewers, this paper ‘brings together some well developed fields of research (graph theory, Delaunay triangulation, Voronoi diagram, urban morphology, and Gestalt theory) in such a way that multi-scale products could be derived’. This adds another possible solution to the existing list.

Note that the methodology described herein is so far solely based on geometric analysis. That is, the semantic/thematic aspect of the buildings has not been considered. Indeed, it is possible that the resultant groups, which are very reasonable based on the geometric analysis, may no longer be reasonable if semantic/thematic meanings are considered. It is also worthy of note that in this study, an implicit assumption of convex buildings is made. Therefore, there is a potential difficulty in dealing with U-type buildings and other buildings with complex shapes. Based on Gestalt principles, the factors having an impact on the recognition of building alignment have been listed. But how to integrate all types of impact to build a proper algorithm to detect building patterns as a cartographer does is difficult and is a subject for future work.

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Automated building generalization


