A METHOD FOR ROAD NETWORK GENERATION BASED ON TENSOR FIELD AND MULTI-AGENT

X. Zhang [1, 2], X. Shi [1, 2*]

[1] College of Architecture and Urban Planning, Tongji University, Shanghai, China - (zhangxinkai, 20101)@tongji.edu.cn
[2] Key Laboratory of Ecology and Energy-Saving Study of Dense Habitat, Ministry of Education, Shanghai, China

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ABSTRACT:

Urban form generative design and optimization, through searching the whole design solution space efficiently to approximate the optimal ones, is a powerful means for supporting energy-efficient urban design. In this whole workflow, urban form generation is of great significance. It provides prototypes for the following steps of urban performance evaluation and optimization, and receives feedback to refine urban forms iteratively. For top-down urban form generation methods, road network generation is a prerequisite for the following generation of blocks, buildings, etc. This paper presented a method for generating hierarchical road networks based on tensor field and multi-agents. Compared to traditional generation methods based on tensor field, this approach introduced road planning indices, including density of road network, distance between road intersections, etc., to constrain the movement of agents to make the networks more reasonable. According to the method, a prototype of a tool for road network generation was developed based on ArcGIS Engine. Generation experiments were conducted through the developed tool. And the generated road networks can well reflect the impact of the geometry of the on-site elements. What's more, the desired density of road networks and the requirement about distance between road intersections can be well satisfied.

1. INTRODUCTION

Cities consume more than two-thirds of the world's primary energy and emit over 70% of global GHGs (Stocker et al., 2014). With the current prevailing population growth and urbanization rate, 68% of the world's population will live in cities by 2025 (Nations, 2018), and the global urban area will triple compared with that at the beginning of the 20th century by 2030 (Seto et al., 2012). This trend will undoubtedly exacerbate the energy shortages and carbon emissions in cities. To address these issues and guide sustainable urban development, energy-efficient urban design (EEUD) is of great significance.

Traditional urban design process which is mainly driven by designers' knowledge, experience and even intuition has limited ability to devise alternatives. And performance evaluation is usually introduced at the end of conceptual design stage, which can only make local improvement of the candidate design alternatives. As a linear process (Nault et al., 2018), this design paradigm cannot guarantee finding optimal or suboptimal schemes of EEUD. However, since relevant design variables, constraints, objectives of EEUD can usually be quantified and expressed mathematically, this design problem can be naturally formulated as an optimization problem (Braibant and Sander, 1987). And urban form generative design and optimization (UFGDO) is a promising means for addressing it. With the help of generative design methods, various urban forms could be generated automatically under constraints. Then, the energy performance of these urban forms will be evaluated which is also the objective functions of the next optimization process. Driven by optimization engines, urban form generation will be conducted iteratively to approximate the optimal solutions. Compared with traditional methods, UFGDO techniques are more capable for developing elaborated and novelty solutions to support EEUD.

In the whole workflow of UFGDO, urban form generation provides prototypes for the following steps of urban building energy evaluation and optimization, and receives feedback to refine urban forms iteratively. It may involve multi-scale and masses of elements, including sites, road networks, blocks, plots, buildings, etc. These elements can be generated and organized in a bottom-up or top-down ways. For the former, methods based on cellular automata for urban form generation are good examples. For the latter, road networks should be generated first to divide the site into blocks, providing boundary condition for building generation. For top-down methods, urban form generation and optimization process can be naturally divided into multiple stages. The generation and optimization results of the current stage will be input as constraints for the next stage. In this way, the complex optimization problem involving a large number of design variables can be addressed more efficiently. From this perspective, road network generation which is a prerequisite for the generation of blocks, buildings, etc. is of great significance.

There are several approaches for network generation, such as methods based on L-system (Parish and Müller, 2001), tensor field (Chen et al., 2008), templates (Sun et al., 2002), etc. The road network generation method based on tensor field (Chen et al., 2008) can simulate a variety of road patterns. Meanwhile, the form of generated road network can well reflect the impact of the geometry of the on-site elements such as rivers, lakes on it. However, relevant road planning indices were not fully considered in the generation process. As a result, some characters of the generated road network may not meet relevant requirements of road planning. Another problem that needs

* Corresponding author

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attention is that although there are some urban form generation methods or tools like the City Engine, etc. The urban forms these methods generated usually used for visualization or preliminary analysis for inspiring design idea. These urban form models usually cannot be used for urban building energy evaluation to feedback and refine the EEUD.

This paper presents a method for road network generation base on tensor field and multi-agent. Road planning indices, including density of road network, distance between road intersections, etc., has been introduced to constrain the movement of agents (the trajectories represent roads) to make the generated road networks reasonable. According to this method, a prototype of tool for road network generation has been developed based on ArcGIS Engine. And road network generation experiments have also been conducted to examine the method and the prototype of tool.

2. METHODOLOGY

2.1 Definitions and principles in regard to tensor field-based road network generation

The detailed definitions of tensor field and principles for road network generation can be found in (Chen et al., 2008). Succinctly, a tensor field is a medium between affecting factors and the form of the generated road network. Affecting factors can include the geometry of natural elements such as the contours of rivers and green spaces, the built environment, and desired road network patterns. The geometrical characters of these factors should be converted into a basis tensor field. Then, guided by this tensor field, road networks can be generated fitting with the on-stie environment and desired patterns.

In this study, a more simplified definition of tensor (Zhang, 2021) has been adopted. As shown in Figure 1, in a two-dimensional space, a tensor *t* comprises a position and four vectors perpendicular to each other. The angle θ between the vector in the first quadrant and the positive direction of the X-axis is used to represent the direction of this vector, $\theta \in [0, \pi/2)$. And the direction of the other three vectors can be easily calculated. Since it's the direction of tensor vectors rather than the modulus that guide the road generation process, these vectors were set as unit vectors. A tensor field is a continuous domain of these tensors.

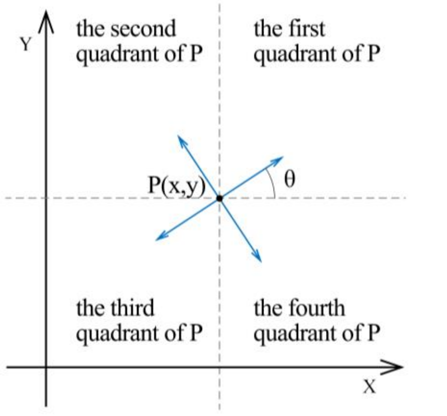

Figure 1. A simplified definition of tensor in a two-dimensional space

2.2 A method for Road network generation based on tensor field and multi-agent

Based on the above definition of tensor and the basic principles, this paper proposed a method for road network generation. It contains two major parts, namely (1) the establishment of a basis tensor field which takes account the influences of various affecting factors comprehensively, and (2) road network generation based on multi-agent.

2.2.1 Establishment of basis tensor field: The workflow for establishing a basis tensor field mainly comprises three steps, namely (1) confirm factors that may have impact on the form of road networks, (2) tensor field establishment, and (3) tensor field optimization. Firstly, according to the boundary of the site to be built, the domain of a basis tensor filed which is denoted by an axis aligned bounding box covering the site should be defined. Inside this domain, affecting factors whose geometry have an impact on the form of road network and their scopes of influence should be determined. For example, a river can be considered as an affecting factor. Because that it usually causes nearby roads to spread along the river frontage, affecting the form or road network. Affecting factors could be natural topographic entities such as rivers and lakes, or built elements such as existing roads and buildings, or designer specified elements used to control the patterns of road network. When affecting factors and their scopes of influence are defined, three types of areas in the basis tensor filed will appear, namely (a) areas influenced by none factor, (b) areas influenced by a single factor, (c) areas influenced by two or many factors.

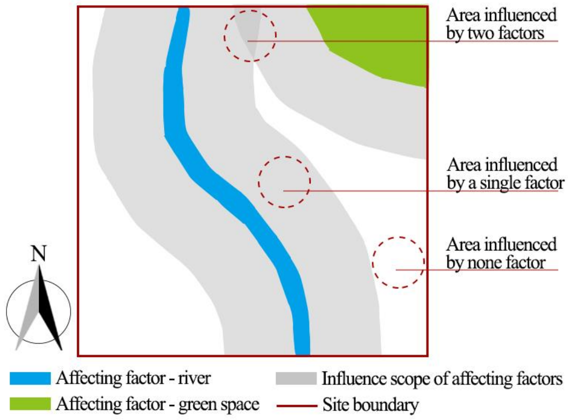

Figure 2. Affecting factors and their influence scopes

Secondly, as shown in Figure 3, an orthogonal grid covering the tenser field is built, and the direction of tensor vectors at each vertex of the grid is calculated and stored in a hash table. For grid vertices within areas influenced by none factors, the direction of tensor vectors can be set according to the direction of local road networks. For vertices within influence scope of a single factors, the nearest point of each vertex to the geometric contour of the affecting factor is calculated first. Then, vectors of each vertex tensor are set parallel to the tangential or normal direction of the contour segment at the corresponding nearest point. In regard to affecting factors without geometric contours like a point, inside its influence scope, the tensor vectors can be set as centripetal or tangential. For linear factors, geometric contours can be denoted by polylines of themselves. For vertices within influence scopes of two or more factors, vectors of each vertex tensor are also influenced in the same way as the above conditions of single factor. However, the influences of these factors should be combined to determine the direction of tensor vectors. The basic principles are that (a) the smaller the distance between the vertex and a factor is, the greater the effect is, (b) the more important the factor is (weighted by areas, volume, or designer's preferences, etc.), the greater the effect is. Referring to the formula of universal gravitation, the influences of affecting factors on a certain tensor can be expressed as Equation 1. The combined influence of these factors can be calculated based on the principle of force composition. As for a tensor inside a cell of the grid, its vector direction can be calculated according to that of the adjacent four vertex tensors by method of bilinear interpolation (Chen et al., 2008).

$$F(p)_i = \frac{W_i}{d_i^2} \tag{1}$$

where $F(p)_i$ = the influence of factor i on the point p
W_i = the weight assigned to factor i
d_i = the distance between position p and factor i.

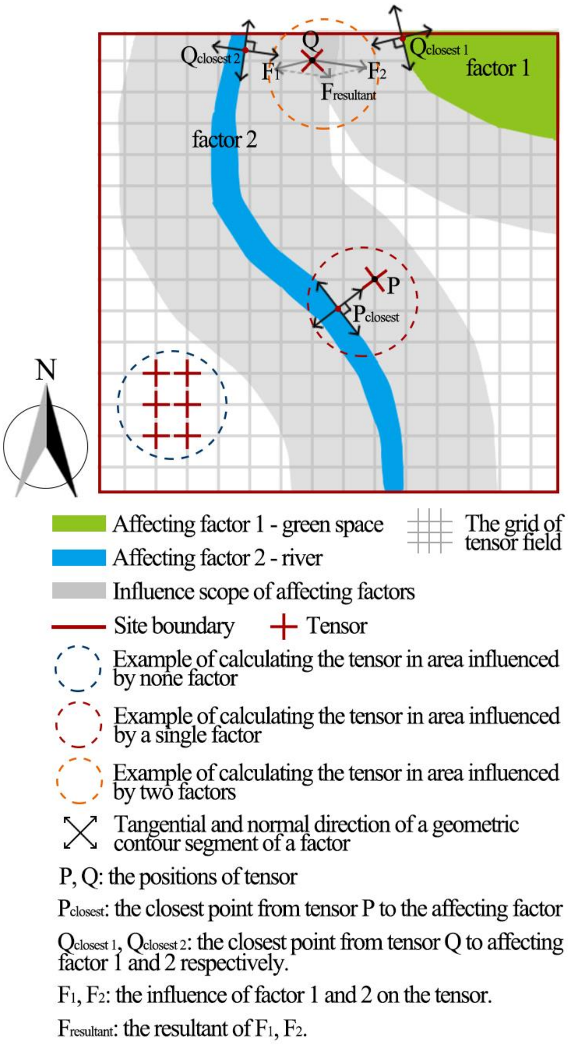

Figure 3. Illustration of tensor calculation

Finally, an optimization should be conducted to smooth the basis tensor field. In the above steps, tensors within different influence scopes of affecting factors are calculated separately. As a result, tensors within the entire domain comprising these areas do not vary continuously. This condition may cause the road orientation at some certain segments changes dramatically. To avoid this problem, an optimization problem was constructed. The optimization objective which is smooth the basis tensor field can be expressed by Equation 2. The decision variables are vectors composed of the direction of all the vertex tensors in the first quadrant (denoted by θ). Relevant constraints include: (a) $\theta \in [0, \pi/2)$, (b) the vector direction of vertex tensors within influence scopes of affecting factors should remain unchanged. The function module *quadprog* of MATLAB was introduced to address this quadratic programming problem.

$$Minimize \sum_{i=1}^{n} (\theta_{i1} - \theta_{i2})^2 \tag{2}$$

where n = number of edges of the tensor field grid
i = the i-th edge of the grid of tensor field
θ_{i1}, θ_{i2} = angles of the tensor vectors (in the first quadrant) at both ends of the i-th edge of the grid.

2.2.2 Road network generation based on multi-agent: Road networks were generated in a hierarchical way. Within the basis tensor field, a series of agents were generated in turn and moved under guidance until reaching the boundary. The trajectories formed the road network and automatically divided the site into sub-sites. Within each sub-sites, the above steps were repeated to generate minor road networks and so on. In this process, indices like density of road networks, distance between road intersections, etc., were introduced to ensure the rationality of the road networks. The detailed workflow of road network generation is shown in Figure 4.

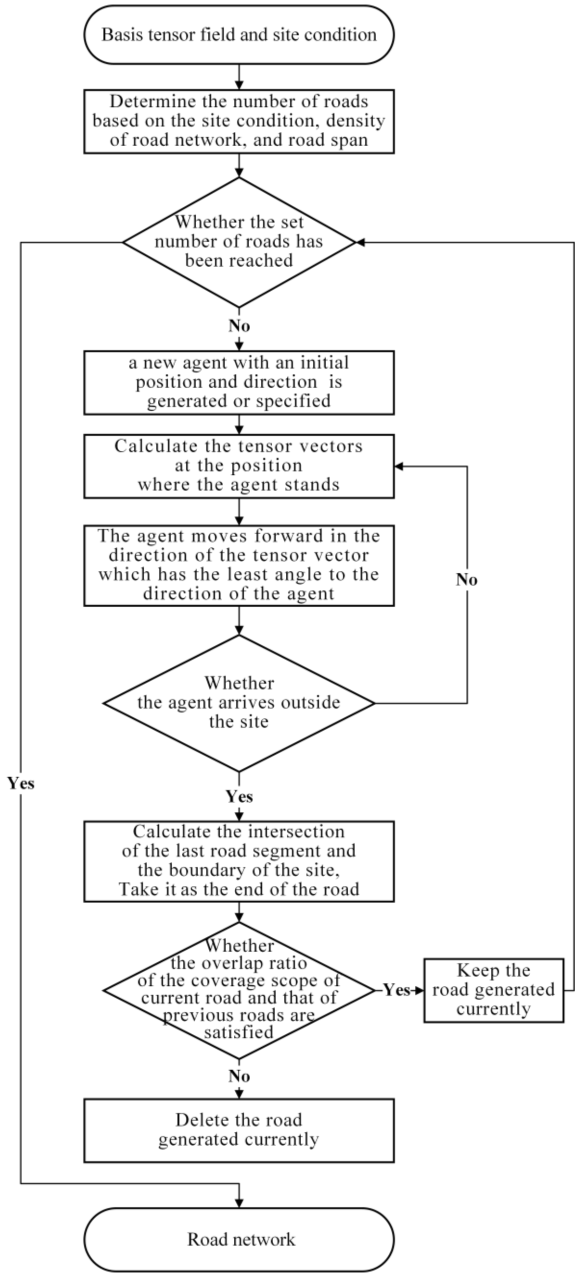

Figure 4. The workflow of road network generation

Firstly, according to the site area and the desired density of road networks, the total length of roads to be generated should be calculated. Then, the oriented bounding box of the site geometric contour should be obtained. Based on the length of the long and short sides of this box and desired distance between parallel roads, the numbers for roads to be generated along the two directions could be roughly estimated. Alternatively, the number of roads can also be determined by designer. Then, a series of agents will be randomly generated within the site in turn, or assigned by designers with certain locations or direction. It should be noted that an agent owns three types of parameters namely position, direction and step size. And it always moves forward from its current position to another along its direction in the step-size. As shown in Figure 5, the point P is the current position of an agent. The direction and length of the green arrow denote the direction and step-size of the agent respectively. As a result, the agent will reach point Q in the next step. And it will update its parameters there. It's obvious that the new position of the agent is Q. As for the new direction, it will be updated by the direction of the vector of tensor at Q that has the least angle to the last direction of the agent, which is represented by the red arrow. The agent will move forward and update information iteratively until reaching the outside of the site boundary. And the intersection of the last step and the boundary of the site is calculated to work as the end of the road.

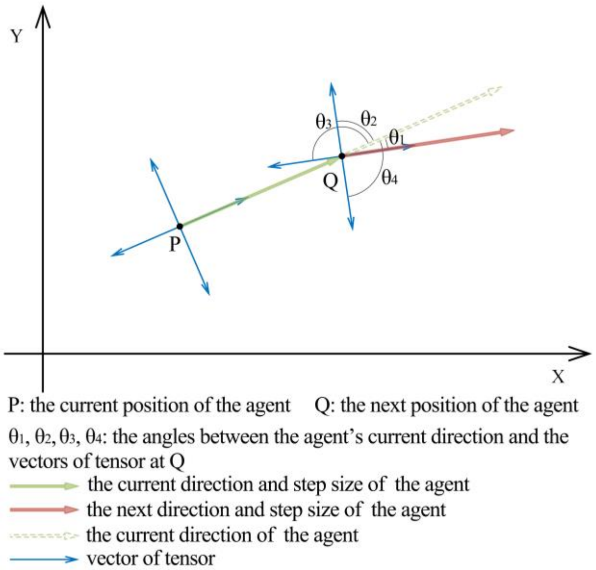

Figure 5. Basic moving rules of agent in tensor field

Without specific design requirements, the entire road network should be designed relatively even. In other words, the blocks divided by this road network should be relatively uniform. To guarantee this character, an evaluation process was introduced to determine whether a newly generated road should be kept. As shown in Figure 6, when a new road was generated, a so-called road coverage scope should be established with this road as the center line and a specified distance as the width. This distance can be the average spacing distance between a group of parallel roads to be generated. The overlap ratio refers to the ratio of the overlap between the coverage scope of a road and that of adjacent roads to its entire coverage scope. Obviously, the closer the two parallel roads are, the larger the overlap ratio is. For two roads that cross each other, the overlap part is usually the scope around the intersection. And the overlap ratio usually falls in a relatively fixed range which can be calculated. To keep the overlap ratios of a newly generated road with previous roads within a desired range can make the entire road network relatively even. For example, road 1, road 2, road 3 were generated in sequence as shown in Figure 6. When the road 2 was generated, since its overlap ratio (the ratio of the area of the green scope to the area of its coverage scope) was acceptable, it can be kept. However, when the road 3 was generated, it should be deleted due to its large overlap ratio.

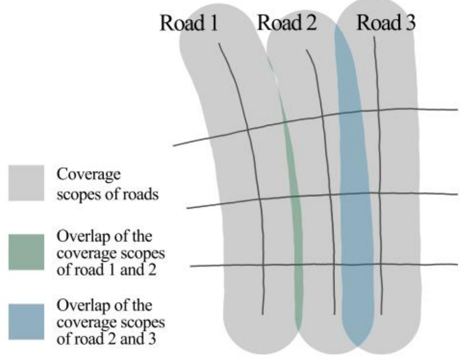

Figure 6. Coverage scopes of roads and their overlaps

The intersections of newly generated roads and the previous network should also be examined or refined. To avoid distance between two road intersections being too short, some means can be taken as shown in Figure 7. For conditions as shown in Figure 7a, since roads AA_1 and BB_1 on the same side of the road segment AB, intersection A can only get away from B to avoid a short road segment. In condition as shown in Figure 7a-1, the entire road AA_1 was translated to the position of the yellow line. However, in this process, the overlap ratios of the new AA_1 and its adjacent roads should be satisfied. Otherwise, instead of translation, another means should be taken as shown in Figure 7a-2. The agent that generated AA_1 should return to its previous states until a position, where the angle between its direction and its orientation to the point T met a specified value. The line connecting the position and point T worked as a new segment of AA_1. In the conditions as shown in Figure 7b and 7c, roads AA_1 and BB_1 were located on different sides of road segment AB. If the distance between intersection A and B at the range of 1/2 ~ 1 times the specified minimum distance, AA_1 can be translated or partly regenerated as shown in Figure 7b-1 and 7b-2 respectively. If the distance between intersection A and B is less than 1/2 times the minimum distance, AA_1 can be refined in the ways as shown in Figure 7c.

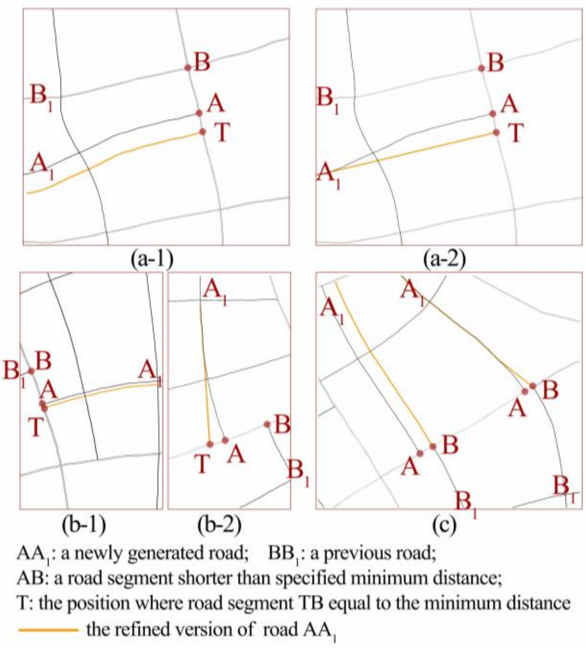

Figure 7. Ways to refine road intersections

3. RESULTS

According to the proposed method, a prototype of a tool for generating road network is developed based on relevant functional modules of ArcGIS Engine. The development platform and programming language are Visual Studio 2012 and C# respectively. This tool can input files in format of .shp, select or draw the geometry of affecting factors, set the grip number of tensor field, generate and optimize tensor field, set the density of road networks or the number of roads, generate hierarchical road networks, etc.

To examine the validity of the method and the tool, this paper constructed a 2km × 2km square site with a river and a green space. The river can be crossed by trunk roads, but not by branch roads. The green space cannot be crossed by roads. Based on relevant standards and research, (Liu, 2018) summarized the recommended density of road networks for China's small cities with a population less than 500,000. For network of trunk roads, the recommended density is 2.6 ~ 4.0km/km^2 and the suggested distance between roads is 450 ~ 650m. In regard to network of branch roads, the recommended values for the above two indices are 5.0 ~ 6.0km/km^2 and 150 ~ 250m respectively. Experiments for road network generation were conducted for two conditions. For the first condition, the desired densities of networks of trunk roads and branch roads were set as 2.6 and 5.0km/km^2 respectively, and the minimum distance between road intersections was set as 100 m. In the second condition, values of the above three indices were set as 4.0 km/km^2, 6.0 km/km^2, and 100 m respectively.

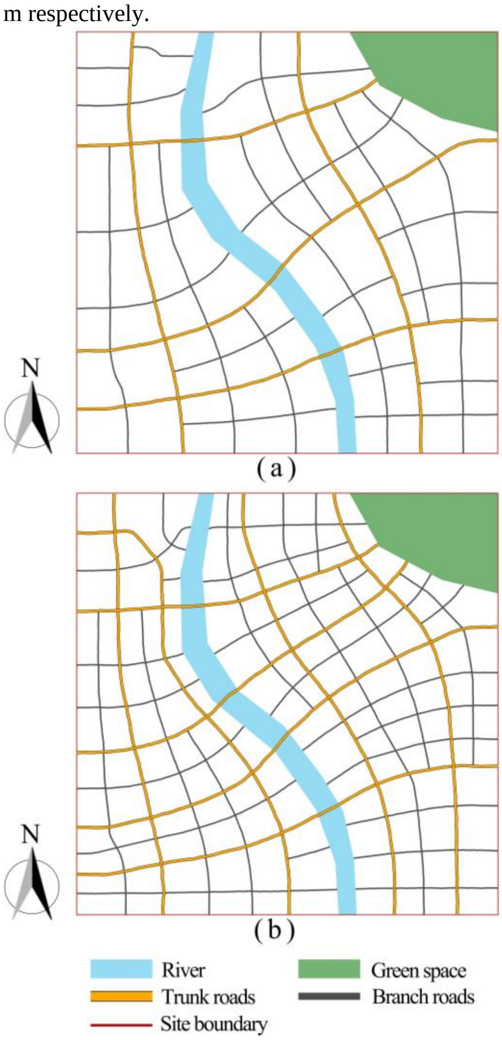

Figure 8. The results of road networks generation

The experiments were carried out through the developed tool, and the generation results were shown in Figure 8. In the first experiment, five trunk roads were generated according to the desired density and the area and shape of the site. The density of the generated trunk road network was about 2.50km/km^2, and the deviation from the desired value was about 3.8%. The density of the generated branch road network was about 4.52km/km^2, and the deviation was 9.6%. Among the generated 134 road segments between adjacent intersections, only 2 road segments had a length less than 100m. In the second experiment, a network consisting of eight trunk roads was created. Its density was about 4.11km/km^2 with a deviation about 2.8% from the desired value. The density of the branch road network was about 5.92km/km^2, and the deviation was about 1.3%. Among the generated 256 road segments between adjacent intersections, 12 road segments had a length less than 100m. However, all of them were longer than 75m, and 75% of them were longer than 90m which was close to the specified minimum distance.

4. CONCLUSIONS

This paper presented a method for generating hierarchical road networks based on tensor field and multi-agents. Compared to traditional generation methods based on tensor field, this approach introduced road planning indices, including density of road network, distance between road intersections, etc., to constrain the movement of agents to make the networks more reasonable. What's more, a prototype of a tool for road network generation was developed based on this method and ArcGIS Engine. Experiments for road network generation were conducted through the developed tool. And the generated road networks can well meet the set targets of road planning indices.

It must be acknowledged that there are some limitations in this study. First, since the prototype tool is not so complete, some processing needs to be carried out manually through human-computer interaction. Second, the number of tensor field grid cannot be set too much, otherwise the quadratic programming process for optimizing tensor filed will be time-consuming, or even cause program crash. In future studies, the proposed method and the tool should be further improved. Block division and building generation methods should be developed and integrated with the current method to form an integral urban form generation workflow. Meanwhile, corresponding development should also be carried out based on GIS. This research is just a beginning to realize a systematic methodology of "urban form generative design, urban performance evaluation, and urban performance optimization" to support energy-efficient urban design.

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