A WEB-BASED INTERACTIVE TOOL FOR URBAN FABRIC GENERATION

A Case Study of Chinese Rural Context

QIYAN ZHANG[1], BIAO LI[2], YICHEN MO[3], YULONG CHEN[4] and PENG TANG[5]

[1,2,3,4,5]*School of Architecture, Southeast University, Nanjing, China.*
[1]*zhangqiyan@seu.edu.cn, 0000-0002-1702-2041*
[2]*jz.generator@gmail.com, 0000-0002-8713-4954*
[3]*moyichen@seu.edu.cn, 0000-0002-2844-7678*
[4]*skadeshat@gmail.com, 0000-0001-9015-131X*
[5]*tangpeng@seu.edu.cn, 0000-0003-1658-6774*

Abstract. The design of rural fabric is significant for making sustainable communities and requires innovative design models and prospective work paths. This paper presents an interactive tool based on the web to generate block fabric that responds to the Chinese rural context, consisting of streets, plots, and buildings. The tool is built upon the Browser/Server (B/S) architecture, allowing users to access the generation system via the web simply and to have interactive control over the generation process in a user-friendly way. The underlying tensor field and rule-based system are adopted in the backend to model the fabric subject to multiple factors, with rules extracted from the rural design prototype. The system aims to integrate the procedural model with practical design constraints in the rural context, such as patterns, natural boundaries, elevations, planning structure, and existing streets. The proposed framework supports extensions to different urban or suburban areas, inspiring the promising paths of remote cooperation and generative design for sustainable cities and communities.

Keywords. Generative Design; Web-based Tool; Urban Fabric; Rural Context; Procedural Modelling; Tensor Field; SDG 11.

1. Introduction

Making sustainable rural communities with better diversity, green and liveable environments, local distinctiveness, and cultural identity is essential for developing sustainable cities and communities. With the enormous impact of urbanization comes the attendant rural decline and loss of organically grown fabric (Liu and Li, 2017; Kiruthiga and Thirumaran, 2019), while the homogenizing pattern in urban sprawl is severed from the local context. There exists an urgent need to propose a more scientific and prospective methodology to inspire integrated and sustainable urban planning and

the rural community′s ongoing progress, which would simultaneously contribute to promoting positive regional development and urban-rural linkages.

Urban and architectural design is concerned with an integrated complex adaptive system (CAS) that requires responding to internal and external constraints from the local environment (Li and Han, 2011). With the development of computer-aided design (CAAD) recently, the generative design method for cities have shown significant advantages: content abstraction into a set of procedures, synthesis of complex correlated rules, effective generation of various schemes, and user operation through parametric control without understanding the internal mechanisms (Smelik et al., 2014). Since the pioneering research of Parish and Müller based on L-systems (Parish and Müller, 2001), procedural modelling for urban layout has gathered much attention. Several algorithms have been applied to model cities in previous studies, such as rule-based systems, multi-agent systems, stochastic geometry, tensor fields, data-driven.

The grid model was experimentally implemented by Gretel et al., proposing a real-time procedural system that generates individual buildings from an integer grid (Greuter et al., 2003). Jing Sun et al. converted frequent road patterns into templates to generate a traffic network within the constraints of input maps of the site boundary, terrain elevation, and population density (Sun et al., 2002). Many studies have begun to concentrate on organically grown settlements (Duarte et al., 2007; Emilien et al., 2012). The study carried out by Li et al. introduced a model of evolutionary multi-agent system (Li et al., 2015). Given the morphological prototype of Ji Village, the system achieved the optimal generation of natural village fabric. Several researchers have developed interactive tools to utilize the approach better and indicated some methods to provide intuitive control for users, including sketch-based techniques (de Villiers and Naicker, 2006) and merging operations (Lipp et al., 2011).

The above procedural approaches show great potential in enhancing the urban fabric design process. However, the correspondence between the procedural model and the specific design context for sustainable rural fabric has not been well addressed. As a result, this paper introduces an interactive tool that users can access via a web page and generate site-specific rural fabric that responds to the local environment and cultural characteristics. Two aspects are crucial to developing the system:

- The system uses the tensor field and rule-based system to establish a complex adaptive system with multiple constraints to adapt the generated fabric to the rural context. Chen et al. firstly employed the tensor field to offer interactive control over the streets generation process (Chen et al., 2008). In this research, the tensor field is used to simulate the impact on physical forms from potential forces of rural context. The system constructs a procedural model for organically grown fabric using the rules from rural prototypes. This paper mainly describes methods for generating tensor fields, streets, and plots, not involving methods for buildings.

- The web tool can provide simplified access and novel media to a large number of users, along with flexible and intuitive operations, showing the potential to provide co-design access to participants in different roles. This tool was developed based on the open-source web-based framework proposed by Yichen Mo (Mo, 2021). Specific work involves data structure design, display style design, detailed operation steps and interactive control, and data transfer between backend and frontend.
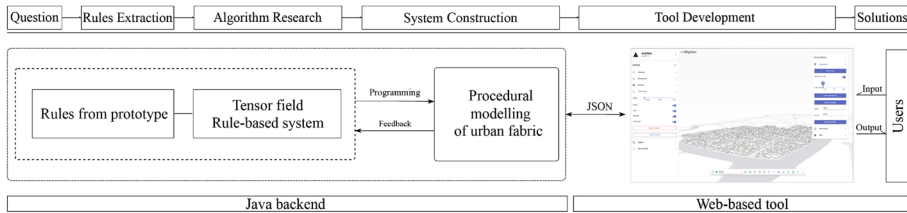
Figure 1. Research overview

2. Generation system

2.1. UNDERLYING TENSOR FIELD

There exist underlying forces from the local context that shaped and reshaped the physical forms of the urban fabric (Meng, 2015). This paper presents a generative system that uses tensor fields to model potential mechanisms and control the range and intensity of forces exerted by different constraints (such as boundaries, rivers, elevations, and axes). Thus, the generated fabric can respond flexibly to the environmental conditions and planning intentions, with the perspective to shape sustainable rural communities and realize a symbiotic relationship between the fabric and the natural environment.

Tensors are mathematical objects defining the multilinear mapping between sets of algebraic objects in a vector space. In order to form a smooth tensor field T, each point $p = (x, y) \in R^2$ in the space is associated with a second-order tensor $T(p)$ (Delmarcelle and Hesselink, 1994), and then derives the value of each tensor to make the whole into a continuously varying state. Streamlines tangent to the eigenvector field in space can be used to model roads in cities (Chen et al., 2008). This paper implements tensor field generation in the constraints of geometry and images via java and Gurobi Solver, and contributes to relating the method to specific design situations.

2.1.1. Tensor Field Generation

Factors that affect urban texture can be identified in two types based on the data format input: geometries, such as site outlines, natural boundaries, road lines, axes, and central nodes; images, such as the grayscale map of elevation or population density. Though the specific data processing methods are different, both types follow a unified framework for constructing the underlying tensor field.

The tensor t defined in this system consists of four symmetric unit vectors, with basic properties including the position $p(x, y)$, the angle θ of the vector in the first quadrant, and its projection on the coordinate axes: x_{vec}、y_{vec}. Four major steps are adopted to evaluate the results. First, after inputting the constraints, an underlying two-dimensional mesh with Half-Edge Data Structure is generated, along with a hash map that stores each vertex and its related tensor. Secondly, the framework calculates the values of each tensor to derive a smooth field, following which the bilinear interpolation is applied to obtain the values at any other location. Finally, along the eigenvector field, traces the streamlines through moving the agent until it reaches outside the boundary or irrational region. The details for the second step of the above

two types are described below.

Geometric elements include polygons, polylines, and central nodes (for radial field). Let set V represent all the vertices of the underlying mesh. The first step involves identifying all the vertices of the mesh that overlap with these geometric elements (stored into set Q) and setting the tensors of these vertices along the direction of the geometries (stored into set T). Next, the system employs a quadratic programming model to solve the tensors of other vertices on the mesh. For vertices in set V with total n, the projection values of their related tensor could be described as $P = \{var_1, var_2, \cdots, var_n\}$. Due to the unit length of the vector, the variables are subject to: $-1 \leq var_i \leq 1$, $var_i \in P$. Meanwhile, the variables associated with the vertices in $V \cap Q$ should be consistent with the values in set T. The optimization goal is to minimize $\sum_{i=1}^{n} (var_{i1} - var_{i2})^2$ (the vertices corresponding to var_{i1} and var_{i2} are adjacent). Gurobi is used to solve the model and finally obtain the results. Figure 2 shows the generation process.

For Images, the system applies the gradient to calculate the value of each tensor, by which the developed tensor field reflects the features of elevation or population density (Figure 2). The expressions for the gradient are as follows: $\nabla f(x, y) = [\partial f / \partial x, \partial f / \partial y]^T$, $mag(\nabla f) = \sqrt{((\partial f / \partial x)^2 + (\partial f / \partial y)^2)}$, $\phi(x, y) = \arctan ((\partial f / \partial y) / (\partial f / \partial x))$. 2D kernel (Sobel or Canny operator) is used to scan the x and y axes to obtain the gradient.

The generative approach described above can be extended to a variety of design conditions and reflects the integrated effect of geometric and graphical constraints (Figure 3), shaping a space of forces that would control the forms of the urban fabric. The users can interactively add nodes or polylines of spatial axes for editing the tensor field.
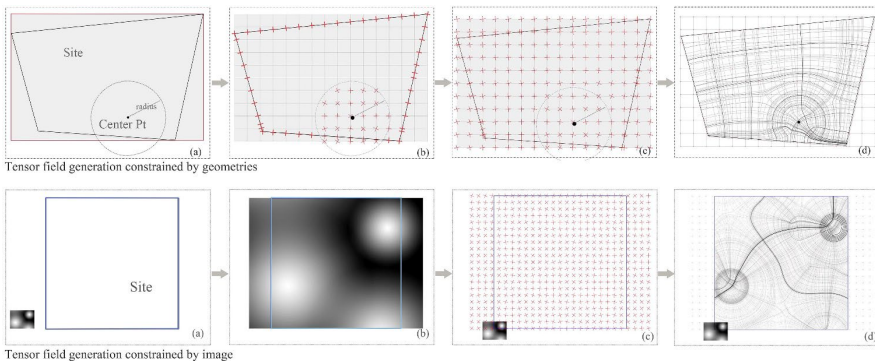

Tensor field generation constrained by geometries

Tensor field generation constrained by image

Figure 2. The process of tensor field generation

(a) The tensor field constrained by geometrics: site boundary, river, axis, planned road, central node.   (b) The tensor field constrained by elevation maps.   (c) The integrated tensor field that combines the effects of lakes and elevation
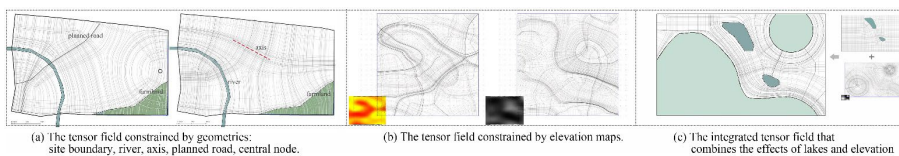
Figure 3. The tensor fields generated under diverse constraints

2.1.2. Application

With a view to further application of tensor fields in design, this study investigates three directions: user adjustment of the weight of constraints, control over the layout of roads, and organization of the road network.

The roads are simulated by the streamlines, forming a graph as a road network consisting of nodes and edges (representing the connection relationships). When adding different factors or changing their weights of influence, the generated tensor field and the consequent road deformation would change accordingly (Figure 5), thus allowing users to operate interactively from design requirements. Figure 4 shows a set of results in comparison: the tensor field when the city is influenced by the natural environment more than the axes, and the results when the city is planned more artificially. With the underlying tensor field, the approach can derive the graph of streets network adapted to the constraints (Figure 6).
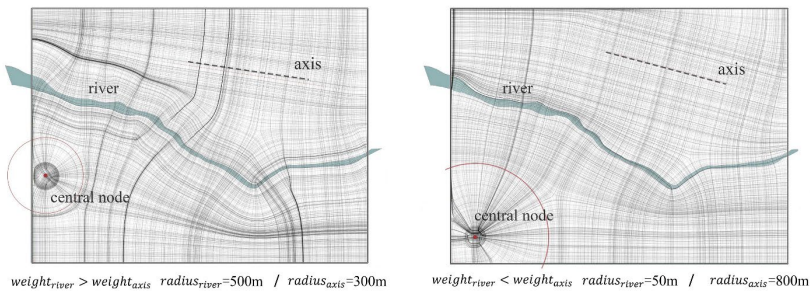

$weight_{river} > weight_{axis}$ / $radius_{river}$=500m / $radius_{axis}$=300m $weight_{river} < weight_{axis}$ $radius_{river}$=50m / $radius_{axis}$=800m

Figure 4. Comparison of the tensor fields constrained by factors of different weights and effect radii
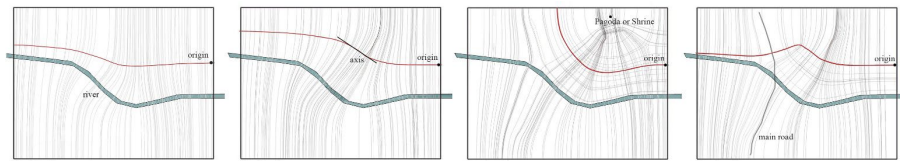
Figure 5. Changes of street deformation correspond to different constraints

(a) Road network generation process

(b) Examples of generated results with three levels of streets

(c) Examples of generated results with four levels of streets
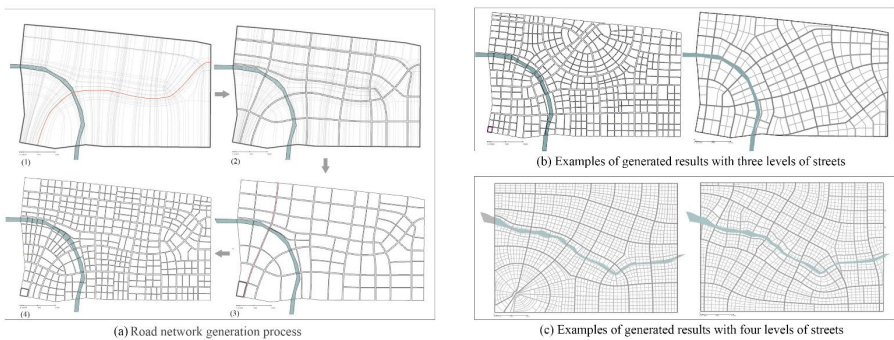
Figure 6. Generation of street network along the tensor field

2.2. FABRIC MODELING FROM PROTOTYPE

Rooted in the rural context, many researchers in China have examined the forms, patterns, and structures of the organic settlements (Shou and Zhong, 2016) and generalized the relevant parameters and factors (Ge and Tong, 2017). These rules from rural prototypes are the key to making settlement humanity in scale and form and achieving local distinctiveness representations. We extracted critical rules for streets and plots from others' previous research on three directions, hierarchy, geometry, and topology. The procedural approach synthesizes complex rules to build a hierarchical rural model of streets and plots, and rough buildings are generated to demonstrate the three-dimensional forms of the results.

2.2.1. Street Network Generation

The system involves four levels of roads (major roads, secondary roads, branch roads, and alleys) that gradually divide the space into districts, blocks, plots groups, and plots. The generation framework focuses on the geometrical and topological sides of the street network.

The system traces the single street along the tensor field and recursively grows the streets to form a network until the area of the divided blocks meets the requirements. To simulate the organic street forms in villages, nodes of streets are defined in three types: intersection, turning, and deflection nodes (Figure 7). Major streets may have no turning points, while for branches and alleys, the higher the proportion of turning and deflection nodes, the higher the irregularity of the street line. Parameters (street length, width, angle, T-junction rate and intersection rate of the network) with randomly given values within a rational range will lead to diverse generation results (Figure 8).

Several street patterns have been designed to provide choice for users, type of branch, radial, and organic network (Figure 9a). The system can organize several levels of streets in different patterns to obtain results that better match the planning requirements. Several practical factors can affect the values of the parameters; for example, different site locations and traffic volumes can correspond to different connectivity, density, and irregularity of the street network, generating fabric with various features (Figure 9b). Some other operations enrich the generated forms, such as the generation of street public spaces, the consideration of qualitative indicators for population and economy.
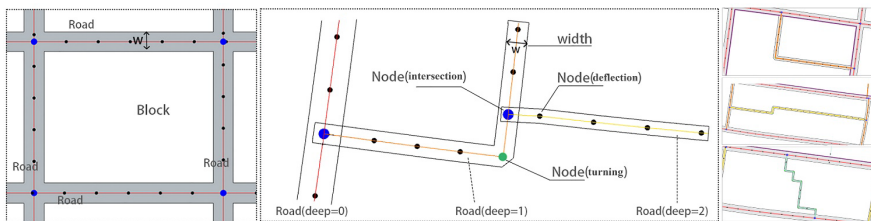

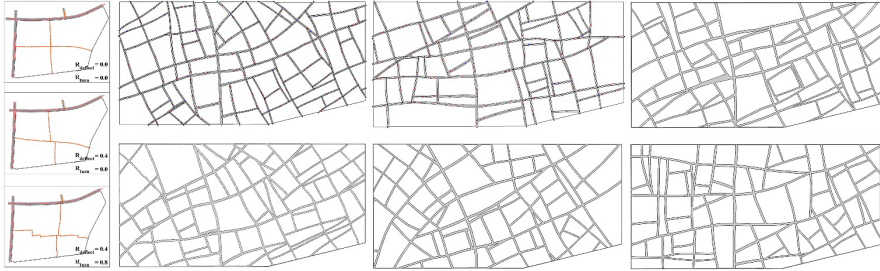*Figure 7. The definition of street lines*

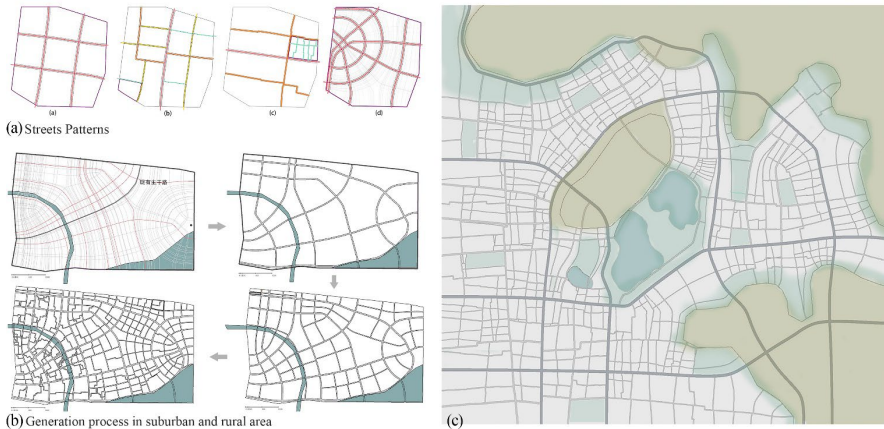Figure 8. Diverse generation results controlled by parameters

Figure 9. Street patterns defined and examples of generated results

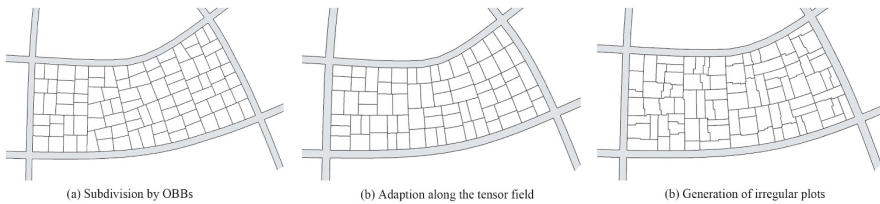(a) Subdivision by OBBs   (b) Adaption along the tensor field   (b) Generation of irregular plots

Figure 10. The process of generating plots

2.2.2. Plots Generation

The plot is the primary unit for the development and evolution of the block fabric, with the area, aspect ratio, orientation, and land use as its essential control parameters. This study implements adaptive spatial partitioning through subdivision based on oriented bounding boxes (OBB). In order to further adapt the orientation and form of the plots to the local site, the optimization process involves reconstructing the split lines along the tensor field during each iteration of the subdivision, selectively adding turning nodes to generate irregular plots (Figure 10). Through the evolution of the overall methods, the system derives results with generated buildings, as shown in Figure 11.

Figure 11. Generated rural fabric via the presented methods

3. Tool implementation

3.1. WEB-BASED USER INTERFACE

This tool on the web uses a WebGL frontend to establish a user-friendly interface. The WebSocket protocol and the JSON data format are applied to connect the ends of the browser and server. Java backend calls the corresponding functions following the received command and passes the user-defined parameters to the functions. It then sends the generated geometries back to the frontend and draws them on the web page (Figure 12).

The tool is designed with a control panel and a settings column that enables mode selection, parameter adjustment, file import, and view conversion. The direct manipulation of geometric elements is supported, for instance, adding or deleting paths in the road network graph, dragging and dropping road nodes, merging adjacent parcels, and adding constraints to alter tensor fields. Also, the results produced on the interface are real-time updated, and relevant statistics can be displayed in parallel. The tool can support both personal use and remote collaboration for future practice, demonstrating the promising paths for sustainable urban planning.
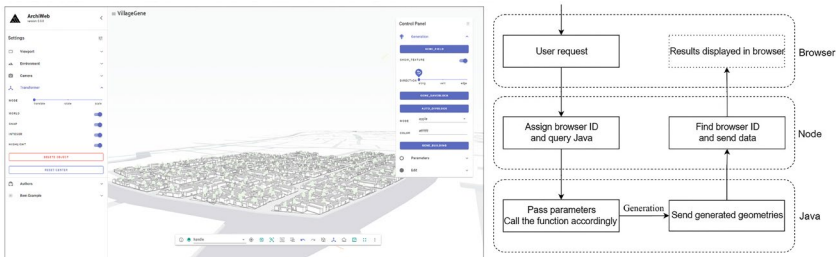

Figure 12. Interface and data pipeline

3.2. DESIGN EVOLUTION PROCESS

In order to finally get a model of the generated block fabric using this tool, the system requires five steps of design evolution when facing application scenarios, including expanding the existing villages and planning new villages nearby, and Figure 13 illustrates the data interaction in the process. The first step is to input the file of the design site, in which each type of polyline is placed in the correct layer as required. Then comes the generation of the underlying tensor field. The user can add axes or nodes based on their design intentions or enter other factor maps as constraints. After clicking on the button to send the command, the field streamlines generated by the backend are drawn on the web page in real-time. A button determines whether the tensor field is visible or not. Next, the streets network can be generated level by level or directly as a whole. The system allows users to locate the critical roads according to the landscape or planning structure before generating the whole network; the road graph can also be edited after generation. The fourth step is to generate the parcels and the general land use layout. The user can define the function and scale of the generated plots and control by editing the partial tensor fields. Eventually, buildings are generated based on the properties of different plots and rendered on the web page. Users can export the model files for further design.
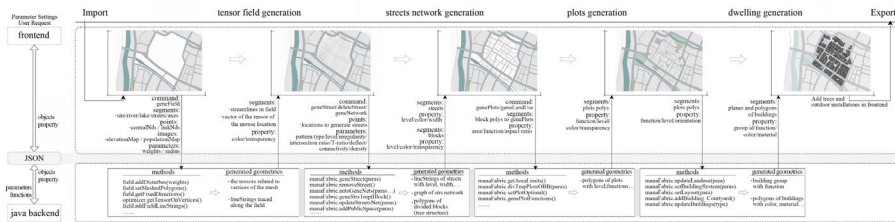

Figure 13. Generation steps and data interaction in the tool

4. Discussion

This paper has provided a deeper insight into the procedural modelling of block fabric in the Chinese rural context and further proposed a web-based generation tool framework that shows important implications for the design of sustainable rural communities. We achieved a more in-depth application of the tensor field to synthesize morphological factors. By complying with the sustainable perspectives, the system realizes the block fabric generation of sustainable rural communities adapted to the local context, natural environment, and local cultural characteristics.

The system's rationality would be more considered in this generation process for further work. More effort needs to be put into analysing the human activities and mechanisms behind the urban fabric. The system can involve more constraints related to social and economic factors for sustainable communities, making it more feasible and flexible. Optimizing the overall tool framework will also be part of further research to supply users with more intuitive and practical control over the design process. The application and development of generative design tools will always be the focus of research in the coming period, illustrating the potential to be an effective way to facilitate the active participation of local residents together with decision-makers,

academics, and professionals in the regional sustainable planning in the future.

References

Chen, G., Esch, G., Wonka, P., Müller, P., & Zhang, E. (2008). Interactive procedural street modeling. *ACM Transactions on Graphics*, 27(3), 1–10. https://doi.org/10.1145/1360612.1360702

de Villiers, M., & Naicker, N. (2006). *A Sketching Interface for Procedural City Generation* [Technical report]. University of Cape Town. https://pubs.cs.uct.ac.za/id/eprint/333/

Delmarcelle, T., & Hesselink, L. (1994). The topology of symmetric, second-order tensor fields. *Proceedings Visualization '94*, 140-147.

Duarte, J. P., Rocha, J. M., & Soares, G. D. (2007). Unveiling the structure of the Marrakech Medina: A shape grammar and an interpreter for generating urban form. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 21(4), 317–349. https://doi.org/10.1017/S0890060407000315

Emilien, A., Bernhardt, A., Peytavie, A., Cani, M.-P., & Galin, E. (2012). Procedural generation of villages on arbitrary terrains. *The Visual Computer*, 28(6–8), 809–818.

Ge, D., & Tong, L. (2017). Parametric analysis and reconstruction method of village's road morphology. *Journal of ZheJiang University (Engineering Science)*, 51(2), 279–286.

Greuter, S., Parker, J., Stewart, N., & Leach, G. (2003). Real-time procedural generation of `pseudo infinite' cities. *Proceedings of the 1st International Conference on Computer Graphics and Interactive Techniques in Austalasia and South East Asia - GRAPHITE '03*, 87. https://doi.org/10.1145/604471.604490

Kiruthiga, K., & Thirumaran, K. (2019). Effects of urbanization on historical heritage buildings in Kumbakonam, Tamilnadu, India. *Frontiers of Architectural Research*, 8(1), 94–105. https://doi.org/10.1016/j.foar.2018.09.002

Li, B., Guo, Z., & Ji, Y. (2015). Modeling and Realizing Generative Design A Case Study of the Assignment of Ji Village. *Architectural Journal*, 05, 94–98.

Li, B., & Han, D. Q. (2011). Understanding and prospects of architectural design generation techniques. *Architectural Journal*, 13, 96–100.

Lipp, M., Scherzer, D., Wonka, P., & Wimmer, M. (2011). Interactive Modeling of City Layouts using Layers of Procedural Content. *Computer Graphics Forum, 30*(2), 345–354.

Liu, Y., & Li, Y. (2017). Revitalize the world's countryside. *Nature, 548*(7667), 275–277.

Meng, J. (2015). *Research of urban intermediate structure*. Southeast University Press.

Mo, Y. (2021). *ArchIndex*. https://index.archialgo.com

Parish, Y. I. H., & Müller, P. (2001). Procedural modeling of cities. *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques - SIGGRAPH '01*, 301–308. https://doi.org/10.1145/383259.383292

Shou, T., & Zhong, W. (2016). The "Matrix" of Ji Village A Study Based on the Construction Strategy of Self-Organization in Rural China. *Architectural Journal,* 08, 66–73.

Smelik, R. M., Tutenel, T., Bidarra, R., & Benes, B. (2014). A Survey on Procedural Modelling for Virtual Worlds. *Computer Graphics Forum, 33*(6), 31–50.

Sun, J., Yu, X., Baciu, G., & Green, M. (2002). Template-based generation of road networks for virtual city modelling. *Proceedings of the ACM Symposium on Virtual Reality Software and Technology - VRST '02*, 33. https://doi.org/10.1145/585740.585747