A Topology Analysis of Urban Street Spatial Network

Yan Xiao, Xixuan Fan, and Haiyang Meng
Dalian University of Technology/School of Architecture and Fine Art, Dalian, China
Email: xiaoyan@dlut.edu.cn, fxx@dlut.edu.cn, menghy@dlut.edu.cn

***Abstract*—The Network Theory and its increasing application to social sciences are challenging the modeling of urban spatial research, in which new concepts and methods have been proposed to reformulate the urban street research frames. Therefore, it is demanding to make a connection between the Network Theory and urban spatial research, so as to estimate complex urban phenomenon and to solve urban problems. This paper discusses network topology analysis methods on urban spatial complexity research and their possible applications on urban street morphology research. To better understand the urban street spatial topology structure, network topology analysis methods in introduced in simulating the evolution of urban street spatial structure over long periods of time. The research is expanded by comparing Semi-lattice street topology structure with Network street topology structure, so as to summarize the essence for describing and analyzing urban street spatial morphology. It is demonstrated that complex networks is a powerful tool in formation and maintenance mechanisms research of urban street.**

***Index Terms*—Network Theory, Urban Street, Spatial Topological Structure, Semi-lattice Topological Structure, Topological Network Structure**

I. INTRODUCTION

Network Theory emerges in a wide range of disciplines in the natural and social sciences, which includes Random Network and Small World Network, as well as Scale Free Network [1]. Common examples of complex networks, such as bacterium structure, nervous system, internet, ecological system, social system and urban system, can all be modeled, simulated and analyzed by network topology approaches. (Fig.1)

It is widely recognized today that Network Theory has become a powerful tool for describing and analyzing the topological structures and morphology of various types of complex systems. The wide application of the Complex Network Theory has broadened the scope of urban complexity research and changed its way of thinking, which provides a new paradigm shift in urban morphology research and urban spatial planning strategies. The reason Complexity Science can be applied to urban spatial research is that urban systems are complex spatial structures with fractal properties, and the inherently self-organizing of urban street morphology, whose dynamics of formation are too complex to be shaped or changed by urban spatial planning and design [2]. So it is nature to explore multidisciplinary methods on urban spatial planning research.

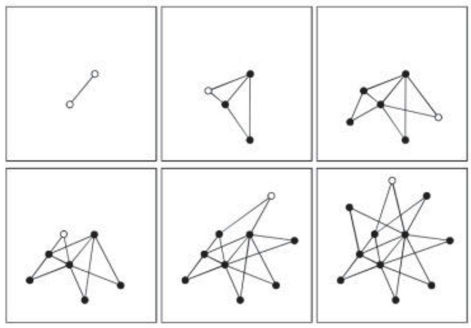

Figure 1. The formation process of Scale Free Network.

II. SPATIAL COMPLEXITY OF URBAN STREET

Jane Jacobs pointed out the view that cities and its streets are problems of organized spatial complexity in The Death and Life of Great American Cities from a non-professional perspective [3], which directly points to the fact that cities are some kind of open complex systems. An essential quality shared by all living cities is the high degree of organized complexity. Since then, cities and its streets have gradually been viewed as organic structures with complexity and diversity, so that scholars began to explore its complex fabric characteristics, as well as the interactions and connections of inner spaces, which is one of the broadest fields of urban morphology research in recent years.

It's widely accepted that urban street as well as its fabric structure are typical, open complex system whose formation mechanisms can be effectively analyzed and understood by applying the network models of Complexity Theory [4]. The complex and diverse component elements of urban street and its fabric function and structure such as roads, pavements, parks, green spaces, residential districts, commercial districts and industrial districts are strengthened through vertical growth or horizontal expansion, organizing organically

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by certain rules so as to create a lively and vibrant city. (Fig.2)

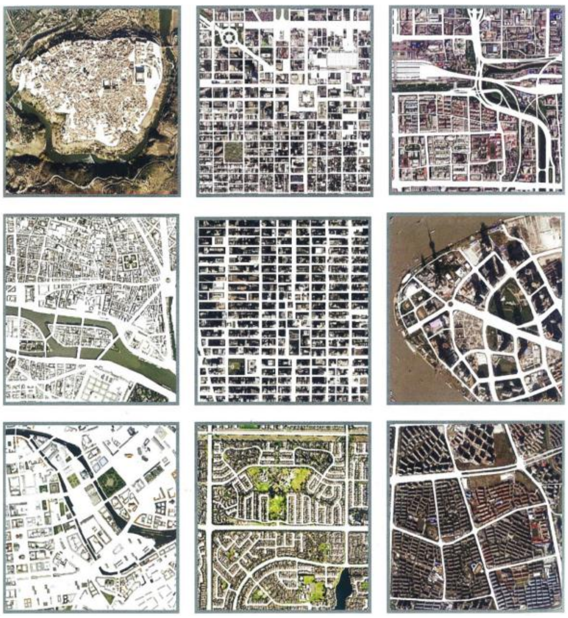


Figure 2. Different types of urban street morphology.

III. URBAN STREET TOPOLOGY ANALYSIS BASED ON NETWORK THEORY

The various elements and connections of the urban street follow a natural complexity order, which presents a high degree of network characteristics through the evolution of street morphology in space and time [5]. Therefore, we can make the simulation and evaluation of the street fabric organization by Network Theory.

A. *Semi-lattice Street Structure*

Christopher Alexander, along with Jane Jacobs, first grasped the organization of urban street spatial complexity, proposing the model of Semi-lattice structure, with the axiom going like this: A collection of sets forms a Semi-lattice if and only if, when two overlapping sets belong to the collection, the set of elements common to both also belongs to the collection, which is contrary to the traditional view that assumes cities as structures of Tree with single hierarchy [6].

In addition, Alexander has demonstrated that a lively city and street has far more structural complexity than a Tree model of comparable size has, with the characteristics of overlap, ambiguity, diversity, which means a thicker, tougher, more subtle and more complex view of structure (Fig.3). In Semi-lattice City, the mix of lands and building urban function uses can create spatial vitality, increasing diversity of urban space and its users, promoting urban complexity (Fig.4). Therefore, a lively city should have the structure of Semi-lattice.

B. *Network Street Structure*

Based on frontier science, such as Topology Theory [7], modern computer technology, Small World Network Theory and Scale Free Network Theory, Nikos A. Salingaros put forward a feasible model for imitating, shaping and analyzing the urban and street complexity, advancing the theory of architecture and urban complexity theory [8].

By making analogy to molecular structure in which chemical bonds combine atoms together to make molecules, Salingaros demonstrated that cities and streets can be decomposed into a large quantity of modules which made up of nodes with connections [9]. The processes that generate the urban street spatial structure can be summarized in terms of nodes and connection structured in hierarchy of levels. Therefore, urban street spatial structure has to do with the connections, and the topology of those connections (Fig.5).

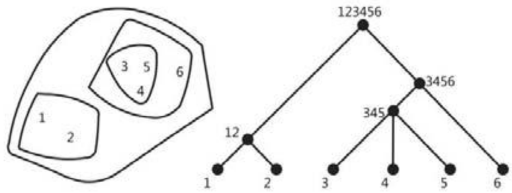


Figure 3. The Structure of Tree.

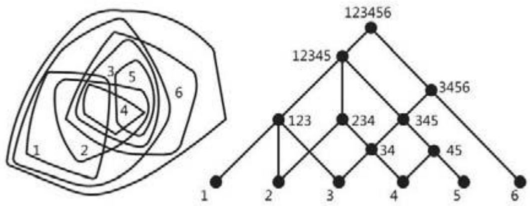


Figure 4. The Structure of Semi-lattice.

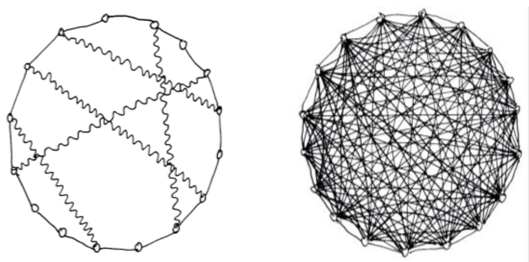


Figure 5. (left) The Overlapping Degree Increases Along With the Increase in Connections' Number, (right) Urban Street Network with High Overlapping Degree

Residences, working places, shopping malls, restaurants, public places and community places can all be regarded as basic nodes elements of the city. Modules, nodes and connective forces are basic componential elements of Network structure in which diverse nodes and modules are linked by the connective forces (Tab.1). Only when nodes are dynamic with intricate connectivity can cities and streets have self-organizing features and fractal characteristic [9].

TABLE I. COMPONENTIAL ELEMENTS OF STREET NETWORK

Component	Definition	Examples	Characteristic
Node	buildings and the spaces between them	residence, working place, shopping mall, restaurant, public place, community place, etc.	the key component of urban network system
Module	a group of nodes with a large number of internal connections	mixed-use districts that provide residences, working places, restaurants, shopping malls and other services	to facilitate nodes' interaction
Connection	a relation or physical path structure between nodes or modules	highway, roads, pavement, etc.	to carry out the physical and information exchange

In Semi-lattice structure, buildings and urban spaces are seen as basic units, whose relationships are also used to understand the structure and organization of urban street fabric and how to define a lively and vibrant city and street. In the fabric structure of Tree, there is only one connection between every two units.

Compared with Tree, there are more overlaps and connections in the structure of Semi-lattice with the same scale. Alexander argues that streets in modern cities have the typical structure of Tree, lacking the necessary amount of overlaps and connections, which damages the diversity and complexity of urban spatial space. However, what is the exact amount and where is the quantitative criterion of the above mentioned overlaps and connections of nodes. Since Alexander have not solved this key problem, his urban street spatial model of Semi-lattice still lacks in quantized spatial analysis, which can just be seen as a beginning of urban street spatial fabric study [10].

IV. THE OVERLAPPING DEGREE ANALYSIS OF URBAN STREET WITH SEMI-LATTICE STRUCTURE

In Semi-lattice structure, buildings and urban spaces are used as basic units, whose relationships are also used to understand the structure and organization of street fabric and how to define a lively and vibrant urban street. If we look at a vibrant urban street with Semi-lattice structure from the air, the picture is obviously fractal, which is not a visual coincidence. By contrast, a picture of an artificial city with Tree structure looks highly regular in urban morphology.

As it is can be seen in Figure5, these three vibrant urban street instances possess fractal urban morphology with hierarchy of networks, from an expressway down to footpaths (Fig.6). These vibrant urban streets have a common necessary characteristic that all the elements of urban streets are interrelated, and on different scales. Urban vitality is derived from the essential fractal nature of the urban street structure.

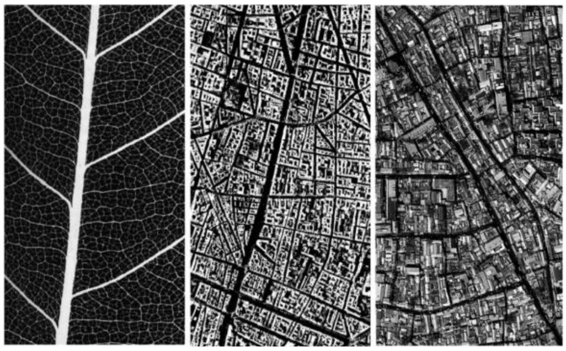


Figure 6. (left) Partial Picture of a Leaf, (mid) Vivienne District, Paris, with Hausmann Street in the middle, (right) Dashilan District, Beijing

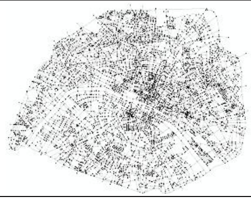
In the fabric structure of Tree, there is only one connection between every two units. Compared with Tree, there are more overlaps and connections in the structure of Semi-lattice with the same scale. Modern cities have the typical structure of Tree, lacking the necessary amount of overlaps and connections, which damages the diversity and complexity of urban spatial space.

As a result, the urban street morphology is an interaction between streets nodes with different functions. However, what is the exact amount and where is the quantitative criterion of the above mentioned overlaps and connections, so Semi-lattice still lacks in quantized spatial analysis, which can just be seen as a beginning of urban fabric study.

In contrast, there's perfect positive correlation between the overlapping degree of Network Street and the ratio between the number of connections and the number of nodes. Therefore, in cases where a certain number of nodes of Network Street are prescribed as a condition, the overlapping degree of Network Street increases along with the increase in connections' number. Moreover, according to the mechanism of ER Network, a critical value of the number of connections can be expected to influence the evolutionary process of street from a lower level to a higher level [11]. In a city with N nodes, at the threshold, when the number of connections is approaching $(N/2)\ln N$, cities would evolve to a self-organized critical state characterized by order, nonlinearity, self-organization and complexity, because of the interactions and connections among the large number of nodes [12]. Furthermore, if all the nodes within the Network City are totally connected with each other, the number of paths needs to be $(N/2)\ln N$ at least.

As mentioned above, the ideal number of paths in a lively and vibrant city with N nodes should have more than $(N/2)\ln N$ connection paths [13]. As an example, the topological connectivity of Urban Area of Paris is calculated based on the above theory (Tab.2). This step is done in Arcmap10.3.1 by using network analysis module. The connections number and nodes number of each street topology network can be obtained in Arcmap10.3.1. As it is seen in the table, the nodes number of urban area of Paris increased sharply from 1850s to 1910s, and the connections number is approaching to the critical value in 1910s, with the improvement of urban vitality of Paris. Applying these important mathematical results, due to the features of complex network, Network structure has provided lower and upper bounds for the required number of connections, describing urban spatial space and the morphological evolution of urban system accurately [14], which has established a promising standard for quantitative evaluation of lively and vibrant street.

TABLE II. TOPOLOGICAL TRANSITION DIAGRAM AND STATISTICAL DATA OF STREET NETWORK SAMPLE

Sample	Urban Area of Paris	
Year	1850s	1910s
Topological Morphology Diagram		
Connection Number	2783	12117
Nodes Number	1911	8180

V. CONCLUSIONS

As Network Theory is one of the most promising branches in Complexity Science, network-based urban spatial research is certain to go beyond the previous research with traditional approaches. So it is nature to explore urban spatial complexity by Complexity Network Theory.

This article analyzes and compares the inheritance and commonality of the network-based urban street topology models of Semi-lattice and Network. By comparing with Semi-lattice structure and Network structure, it can be seen that their topology analyzing methods have changed from two-dimensional, static paradigm to three-dimensional, dynamic evolutionary paradigm. The spatial analyzing methods, based on the complexity of the urban spatial topology structure, have provided great foundation and clear direction for future research. In addition, the new methods help to find a new way to understand and to solve urban complexity spatial problems. A topology analysis method has introduced the concepts of diversity and connection into the field of urban street spatial morphology, which are neglected by modernism architect after World War II. The analyzing methods can be applied to describe and estimate the characteristics of urban street, in perspective of urban complexity.

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Yan Xiao is a Lecture at School of Architecture and Fine Art, Dalian University of Technology, Dalian, China. She received her Bachelor of Urban Planning from Dalian University of Technology, China in 2009; she received her MSc degree from University of Technology, China in 2012 and PhD in Architectural Design and Theory at Dalian University of Technology, China in 2015. She completed two-year postdoc training at Faculty of Infrastructure Engineering Dalian University of Technology in 2017.

Xixuan Fan is a Lecture at School of Architecture and Fine Art, Dalian University of Technology, Dalian, China. She received her Bachelor of Architecture from Tianjin University, China in 2010; she received her PhD in Architectural Design and Theory at Tianjin University, China in 2015.

Haiyang Meng is a graduate student for a Master's degree on Urban Planning at School of Architecture and Fine Art, Dalian University of Technology, Dalian, China. He received his Bachelor of Urban Planning from Anyang Institute of Technology, China in 2017.