Analysis on System Structure and Complexity of Urban Development

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Abstract — **It is systematic to develop the environment of urban geographical spatial system. The system structure is not complete tree type or complete semi-tree scale, neither semi-mesh structure in complete grid pattern. But it is a complex structure of fractal and overall combination. From the perspective of modern geography research content and task, this paper carries out scientific definition and analysis on basic connotation, boundary and environment, structure and configuration, complexity features in urban geographical spatial system. Our research achievement enriches and develops complexity theory of urban systems and provides theoretical basis for regulating urban systems through developing urban planning and solving complexity in urban system.**

Keywords: urban geographic spatial system, complexity, interaction,traffic network

I. INTRODUCTION

Urban is always one of core fields in human geography, economics and sociology study. It is replacing village to become humans' primary settlement pattern and its external environment, internal composition, structure, function and development are becoming more complex [1]. With technological development, people's understanding and research on urban system complexity are continuously deepening. Although complexity research method is a bit different from general systematic dynamics research method, for instance, systematic dynamics research method mainly depends on setting up differential equations or systematic dynamic flow diagram and performs research on systematic dynamics features through mathematical analysis or computer simulation while complexity research method mainly has CA(cellular automata)GA(Genetic Algorithm), game theory, combinatorial optimization[2-6],these methods depends heavily on computer simulation. Meanwhile, dynamics feature is also important content in complexity system research.

Most of the past researches of urban systems [7-8] in economics, sociology, ecology etc, are used to adopt the reductive methods, and focus on partial, local characteristic study of urban system. Owing its wholeness, the laws of urban system can't be revealed completely by the reductive researches only. The traditional geographical researches of urban system exist two inclinations: one is looking urban system as an even entity, and studies its temporal evolution, however neglects its spatial characteristic simultaneously; the other mainly researches the static spatial differences and combinations of urban system, however neglects its process research at the same time. The researches of urban system in complexity science are in the ascendant, but their fruit are sporadic, partial and less advancement because of the immature theories and methods of complexity science. How to advance the abovementioned researches is the actual problem. Therefore, this paper puts forward a new concept: urban geographical spatial system first, and tries to research the urban system complexity in systemic and synthetic view based on the contemporary geography paradigm by integrated using of the theories and methods of urban geography, urban economics, urban planning, system science, complexity science etc.

II. URBAN GEOGRAPHIC SPATIAL SYSTEM

A. Conceptions

Ward [9] believes that one urban system is mainly made up of people's activities (housing, job, different services), groups' activities (they are often called economic activities in narrow sense) and supporting their substantial infrastructure and transport system. This is the narrow sense of urban system as is shown as figure 1.

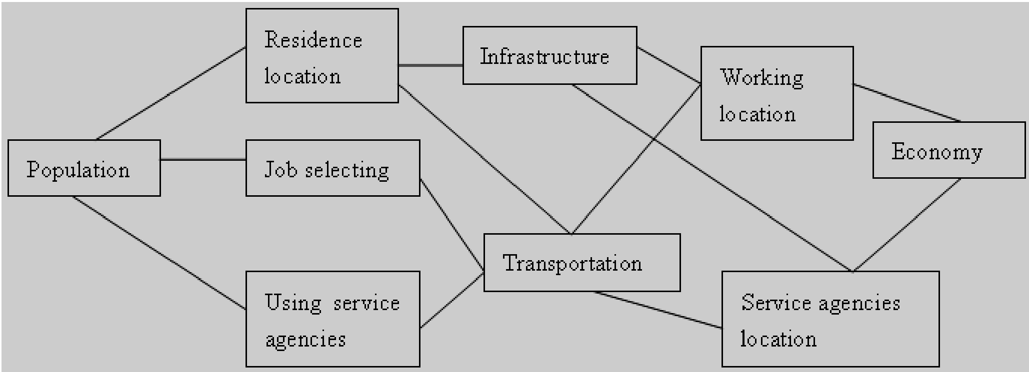

Fig. 1. 1 Main Componets of Urban System

The urban is a group of filled layout in geographical spatial and a group of congregation with endowed ranking concept, functional complementarities and overall efficiency maximization, which forms a structural harmonious, smoothly circulating, mutually sequential and overall efficient system. Modern urbans are in a certain urban system and they can not only possess ordered structure from large to small in vertical direction but they can also be functionally complementary to those urbans with the same rank in horizontal direction. The network effect and interactive influence in these two main directions trigger urbans to have self-learning, self-adaptive and self-organizing capabilities.

Urban geographical spatial system is the coupling formed by natural subsystem, social subsystem, economic subsystem and spatial subsystem. It is on the basis of natural subsystem, leaded by economic subsystem and based on social subsystem as the target. The “natural-social-economic-spatial” complex system based on spatial system as the carrier contains spatial structure, spatial form, spatial interaction and its evolution.

B. Complexity Features of Developing Urbans

(1) Multi-level, Multi-scale and Fractal Characteristics:Urban is made up of many mutually interactive subsystems and the urban’s subsystem is hierarchy on the basis of structure till our satisfying the lowest level of one basic subsystem. Multi-scale feature: the scale in geography is the most complex and diversified, which is one of the core problems on geographical research. Fractal Characteristics: urban geographical spatial system sometimes performs scale-free and self similarity characteristics, that is, fractal characteristics. Urban geographical spatial system often performs self similarity feature in time, spatial or phase spatial and also between parts and whole.

(2) Nonlinear features: A nonlinear characteristic is the core characteristic in urban system and is one of the basic reasons to cause urban system complexity. Urban system is a classical, complex and nonlinear dynamics system. In this system, there generally exists nonlinear interaction between each element and subsystem. Therefore, most of their function relationship is nonlinear.

(3) Self-organizing Feature:From the validity perspective and according to modern self-organizing theory raised by Zhang [10], if one quantity N in the system can be represented by another power of quantity s, that is, there exists power-law relationship between N and s, as is shown is formula 1, the system has self-organizing quality.

$$N(s) = s^{-r} \tag{1}$$

Generally, urban system is not the one piece of iron plate but to be made up of many patches’ agglomeration assemblage with different sizes. The research shows there has power distribution phenomenon between size and quantity on urban system patches, that is:

$$N(q) = N(1)q^{\alpha}, \alpha < 0 \tag{2}$$

III. COMPLEXITY RESEARCH ON INTERACTION

A. Conceptions

Any present system is limited in time and spatial. The finiteness and its result are included in urban system, which defines the quality of urban system in corresponding aspects. Finiteness which is a nonlinear and important mechanism in urban system will inevitably result in nonlinear characteristics under certain conditions. Speed finiteness, temporal-spatial finiteness, structure mode finiteness, etc, between urban system and environment on mutual interaction cause urban system evolution to appear local short-time instability, overall medium-term stability and long-term evolution.

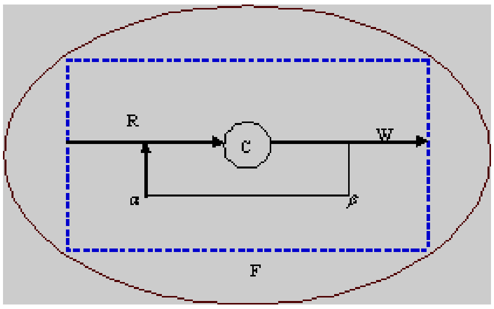

Fig.2. Nonlinear Interaction between Urban System and Surroundings

Linear model is unlimited in time or spatial only when it is approximate to local idealization of nonlinear interaction rather than it is the nonlinear model which can more accurately simulate systematic behavior. Zhang Yan, etc, [11] discuss the interactive relationship between urban social as well as economic system and ecological environment system and put forward conceptual model of urban metabolism, which is shown as figure 2.C is urban geographical spatial system, E is environment, R is negative entropy flow offered by environmental system. W refers to urban metabolites on environment (N), commodity, service, technology(P), etc. N is positive entropy flow, P is negative entropy flow,W = N+P. W have positive or negative value, which is determined by production efficiency of urban system. Usually, in primary stage of urban system evolution, W>0 while W<0 in advanced stage with α denotes to original circular degree and β denotes to terminal circular degree.

Generally, dynamics model in urban system can adopt logistic growing form:

$$\frac{dC}{dt} = S_R + \alpha\beta C(1 - C / C_{\max}) - S_W \qquad (3)$$

Dynamics model in environmental system can be expressed by means of exponential decay form:

$$\frac{dE}{dt} = S_R + S_W - \delta E \qquad (4)$$

With urban system's development, α and β will increase gradually. We simply suppos that there has linear relationship between α , β and negative entropy stock C in urban system.

$$\alpha = \eta C, \beta = \varepsilon C \qquad (5)$$

Actually, self-cleaning capability of positive entropy flow in environmental system is determined by negative entropy stock in environmental system. In one moment, negative entropy stock in a certain scope on earth surface is the fixed value. In one moment, the total negative entropy stock in urban system and environmental system is set as M, thus, negative entropy stock is negatively correlated to negative entropy stock in urban system. Therefore, δ is related to negative entropy reserve C in urban system, which can be simply hypothesized as linear relationship.

$$\delta = \lambda(M - C) \qquad (6)$$

λ is self-cleaning ratio in unit environment stock. The more its value is, the stronger environmental absorption of positive entropy flow. With positive entropy concentration increase, since environmental system accumulates higher positive entropy, environmental system is degenerated.Degeneration process of environmental system is non-linear with positive entropy concentration increase, usually with certain sudden change. When positive entropy concentration is low, the function and the structure of environmental system are not affected basically. When positive entropy concentration is increasing to a certain level, environmental system suddenly degenerates to visually perform "S" curve. So Hill function can be applied to perform description:

$$F = FCE^q / (E^q + E_d^q) \qquad (7)$$

F is degeneration speed,q is inducing degenerating rate, E^q is half-inducing degenerating rate and E_d^q is the parameter.To generalize above specific coupling relationship between urban system and environmental system, the two-dimension dynamic model between urban and environment can be written as:

$$\frac{dC}{dt} = S_R + \eta\varepsilon C^3(1 - C / C_{\max}) - S_W \qquad (8)$$

$$\frac{dE}{dt} = S_R + S_W - \lambda(M - C)E + fCE^q / (E^q + E_d^q) \qquad (9)$$

The complex system between this urban system and environmental system will present abundant dynamics behavior. When developing pressure of urban system is small and support capability of environmental system is strong, it is easier for the complex system between urban and environment to follow the route of sufficient development.Developing curve DGB, IFK, HEJ in figure 3 are developmental function projections on right angle plane. It refers to the maximized development degree a urban can reach under fixed condition of technological knowledge and invested resource quantity, under certain effect of environmental system supporting power and urban systematic pressure. It is brought forward on the basis of using producing possible curve for reference.

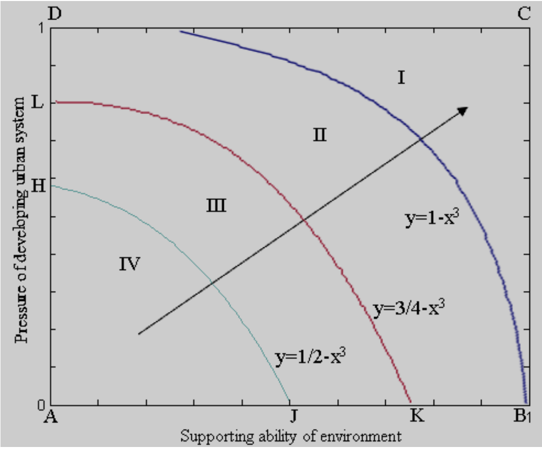

Fig.3. Nonlinear Evolution of Urban System and Environment System

B. Nonlinear Interaction in Inner System

The evolution of urban single element or subsystem is nonlinear.such as the growth process of urban population system.The growing Malthus model of traditional urban population is the unbounded model which is suitable for simulating population scale change in urban system during fast development of urbanization,But it is not suitable for later period of urbanization. However, the realistic urban population growth is limited by resource and environment, which cannot increase to infinite.The nonlinear logistics model $P(t) = P_m / 1 + (\frac{P_m}{P_0} - 1)e^{-\tau(t-t_0)}$ can describe relatively integrated evolution of urban population scale, as is shown in figure 4.

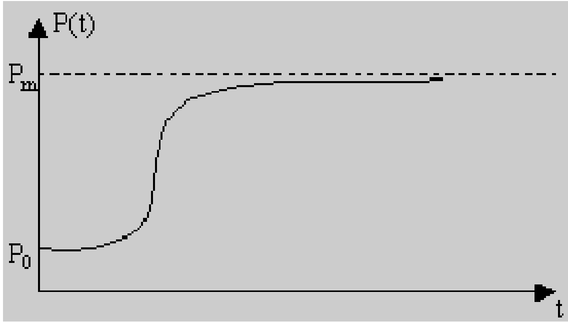

Fig. 4. Nonlinear Change for Urban Population Scale

There also exists nonlinear interaction between urban subsystems. Taking nonlinear interaction among urban population, urban area and urban value as examples, urban systematic change can perform increase or reduction of population gathering or diversion in social aspect, can perform urban built-up area spread and land use type succession in spatial aspect and can perform increase or reduction of urban value in economic aspect. These three aspects are nonlinear relationships of interactive promotion, interactive influence and interactive restriction. It is believed in experience that urban built-up area, population scale and economic output are increasing repeatedly with urban systematic development. However, urban land per capita tends to reduce while production value per capita tends to increase. With the aid of allometric models of urban dynamic system and Cobb- Douglas function, Chen Yanguang [12] analyzes fractal geometry graph of nonlinear relationship among population P, land S and output Y. The result shows that these three aspects exist the feature of double logarithmic distribution.

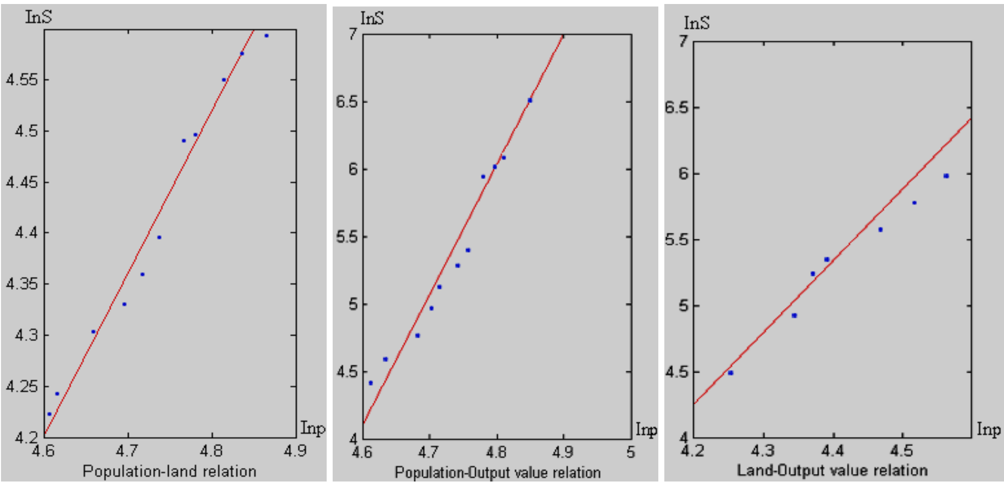

Fig. 5. Log Coordinate of Non-rural Population, Urban Construction Area and Industrial Output

Gravity model is one of the most important function to describe urban spatial functions and its usual form can be expressed:

$$T_{ij} = \alpha O_i^{\alpha_1} D_j^{\alpha_2} d_{ij}^{-\beta} \quad (10)$$

On the basis of the maximum entropy principle, Wilsom [13] proposed another model of spatial interaction:

$$T_{ij} = A_i B_j O_i D_j \exp(-\beta d_{ij}) \quad (11)$$

Differed from gravity model, the spatial interaction of Wilson model does not appear negative power relationship with distance but appear exponential decay with reflecting distance variable. The negative exponential model of Wilson possesses clearly theoretical deduction basis so it has the tendency to surpass the formers in spatial interaction model. However, the expressed system of Wilson model is an isolated system which is not communicating with regional substance, energy and information. Therefore, the genuine urban spatial system is not the complex interaction of nonlinearity and needs to rely on time-varying function and time-delay parameters to perform correction and extension. At first, the function is introduced according to time-vary quality of action.

$$O_i^{\alpha_1} = f_i(t), D_j^{\alpha_2} = f_j(t) \quad (12)$$

In this formula, O_i and D_j denote the "quality" in time t in two urban subsystems i and j. Considering spatial interaction and response delay process, time-delay parameter τ can be introduced and formula 13 can be transformed into:

$$T_{ij}(t) = \alpha f_i(t) f_j(t+\tau) d_{ij}^{-\beta} \quad (13)$$

What the above formulas reflects is still instantaneous relationship on spatial interaction. In order to depict the comprehensive process on spatial interaction of two urban subsystems to perform integral of above formulas, the following generalized integral equation can be acquired:

$$F(D_{ij}, \tau) = \int_{-\infty}^{+\infty} T_{ij} dt = \alpha d_{ij}^{-\beta} \int f_i(t) f_j(t+\tau) dt \quad (14)$$

C. Complexity Research on Traffic Network System

When measuring the complexicity of urban traffic associated structures,the traffic network system can be abstracted as connected digraphs composed of several nodes and links.The digraph is described as $G(V,E)$. $V = \{v_1, v_2, ..., v_n\}$ is set of nodes and E is set of links.For simple calculation we can describe a connected, undirected and unweighted network as adjacency matrix

$$R(G) = \lfloor r_{ij} \rfloor_{n\times n}, r_{ij} = \begin{cases} 1 & v_i v_j \in E \\ 0 & otherwise \end{cases} \quad (15)$$

$R(G)$ is symmetrical for undirected G . $\forall r_{ij} \Rightarrow r_{ij} = r_{ji}$, separation degree between any two nodes $v_i, v_j \in V$ can be denoted by their shortest distance $d_{\min}(i,j)$ .Then average path length of v_i is

$$L(v_i) = \frac{1}{n} \sum_{i=1}^{n} d_{\min}(i,j) \quad (16)$$

n is all nodes in networks and $L(v_i)$ is the separation degree measurement of urban traffic network, whose indication is the shortest distance mean between random two nodes in urban traffic network. We study the small world property of bus traffic network in Beijing and discover that the average distance between random two nodes is 17.3866, that is, the bus will pass 15 or 16 stops. The farthest distance is 103 stops, distribution between random two nodes basically follows Γdistribution and the probability that distance equals 16 is the maximum.

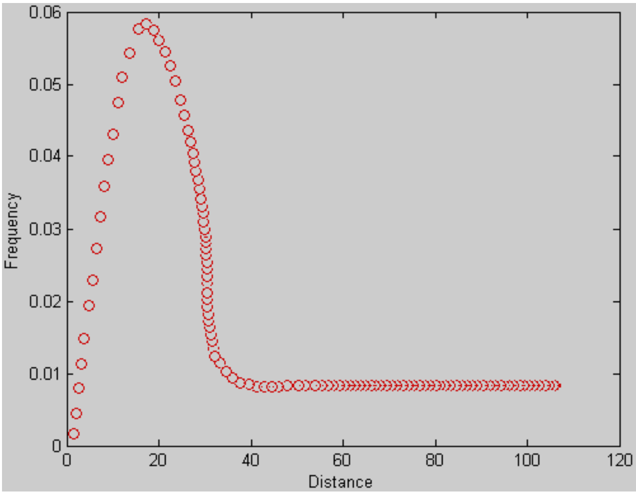

Fig. 6. Minimum Distance Distribution of Bus Top Network

Through actual measuring average path length and clustering coefficient on traffic network among three cities of Gavle, Munich and San Francisco, the small world property in urban traffic network is proved. L_{random} and $C_{random}^{(1)}$ are average path length and clustering coefficient of random network with the same nude numbers and nude continuity. $\overline{m}$ is average edges of each vertex. As is shown in table 1, the average separating degree or average path length of random selected two streets is smaller than 7, which indicates random two streets are only far away from several streets. In addition, clustering coefficient of traffic network in three cities are far more than random network clustering coefficient with 27 times, 36 times and 12 times respectively.

TABLE 1. AVERAGE PATH LENGTH AND AGGLOMERATION COEFFICIENTS OF TRAFFIC NETWORK IN THREE CITIES

City	Streets amount	$\overline{m}$	$L_{truevalue}$	L_{random}	$C^{(1)}_{truevalue}$	$C^{(1)}_{random}$
Gavle	565	4.00	6.05	4.78	0.188	0.007
Munich	785	4.76	6.32	4.72	0.215	0.006
San Francisco	637	7.5	3.52	3.23	0.142	0.012

IV. CONCLUSION

Depending on some subjects' theory and methods, urban geography, urban economics, systematic science, complexity science, etc, this paper discusses boundary as well as environment and element as well as constitution in urban geographical spatial system, interactive mechanism complexity of presenting urban geographical spatial system, structural and functional complexity, evolution complexity and complexity theory of developing urban system. On this basis, this paper also discusses optimization theory and methods in urban geographical spatial system. Spatial complexity research in urban geographical system can provide services for urban planning and design, urban construction and management. This paper has stronger significant application towards regulating and optimizing structure and function in national urban spatial system.

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