Smart city evaluation using non-equilibrium statistical mechanics method

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Abstract

In recent years, with the rapid development of network information technology, such as IoT, cloud computing, big data and so on, smart city presents a development trend of networking, distributed, intelligence and systemization. Because smart city system is a dynamic, complex, distributed, uncertainty and heterogeneity system, in which sub-element has large influence on each other in the respective field. More research should be done to smart city, especially in the development evaluation. In this paper, we firstly define and put forward the physical model of complex smart city system which includes smart people, smart economy, smart mobility, smart environment, smart living, smart governance,. Then, a non-linear information dynamics mode for integrated smart city evaluation is introduced based on the maximum flux principle during the modeling process. The integrated evaluation frameworks of smart city can be done by giving reasonable weights of each influence factors to stabilize the system. Finally, using empirical analysis method, we obtain the ideal results to prove the correctness and efficacy of the evaluation model.

Keywords: smart city, non-equilibrium statistical mechanics, development evaluation

1 Introduction

With the rapid development and more applications of the internet of things, mobile broadband network, next generation, cloud computing and etc., infomatization is popular in the world which integrates relative application, and has a tendency of higher smarter stage[1]. At the same time, the rapid growth faced by several cities has generated traffic congestion, pollution and increasing social inequality. In this context, a debate has emerged on the way new technology-based solutions, as well as new approaches to urban planning and living, can assure future viability and prosperity in metropolitan areas[2] [3]. According to this continuous discussion, the concept of smart city has been proposed and become the subject of increasing attention and it now appears as a new paradigm of intelligent city development and sustainable socio-economic growth, whose origin can be traced back to the Smart Growth Movement of the late 1990s[4]. Nowadays, the large and small districts are proposing the new development frameworks and concept model, called smart city, which represents a community of average technology size, interconnected and sustainable, comfortable, attractive and secure [5] [6]. For example, the smart city is incentivized by the European Commission using the strategic energy technology plan and American, and China also started the smart urban construction in 2010.

But relative to the practice of construction growing vigorously, the theoretical study of academia for smart city obvious still lags behind [7]. There are a few research on smart city mainly concentrated in the concept frameworks, information system design, key technology, application prospects and other aspects[8] [9]. Nam and Hader presented that smart city was to make the city smarter, also to make the people smarter in the city [10] [11]. Giffinger thought that smart city started with a number of households, vehicles and power stations. A city can run as a standalone or connected to others [12]. Deren and Morvaj suggested that a smart city provided interoperable, Internet-based government services that enabled ubiquitous connectivity to transform key government processes, both internally across departments and employees and externally to citizens and businesses[13] [14]. At present, there is no longer a unified standard and evaluation concept framework, according to the rank index of smart city [15]. In different countries, the characteristics of smart city shown are very distinct, we must put forward an overall analysis and corresponding evaluation method for smart city system. Rodzi proposed a model to evaluate the environmental performance of urban energy use planning [16]. Schaffers applied the fuzzy method to determine the relative importance of the indicators and sub-indicators, and analyze the sustainability and development assessment of urban systems [17]. Lombardi presented a fuzzy logic approach for measuring the sustainability of an innovative city system [18]. Many smart cities distributing in the world have achieve massive success in different domain, which can provide good experience for our government [19].Therefore, operation state and development evaluation of smart city system is very important and beneficial for constructing and management of a smart city in the future.

In current researches, there are few articles and no uniform standard about smart city system performance and development level evaluation. Only some related researches for the evaluation parameters for smart city, and evaluation indexes usually are very limited to the scope of

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information technology, smart management, smart resources and information dependability, availability [20]. The other factors which can largely influence on smart city system are ignored in the process of smart city research [21]. Meanwhile, the smart city is a complex operation system, where sub-indexes of smart city have huge impact on each other. Therefore, with considering the different feature of smart city in distinct country and region, in this paper, we firstly define smart city as a complex evolution system, and then a comprehensive evaluation model of smart city which consists of smart people, smart economy, smart mobility, smart environment, smart living, and smart governance is proposed to analyze the development pattern. Secondly, we build a non-equilibrium statistical mechanics model for integrated smart city system evaluation from an evolutionary perspective. Finally, we collect related data of smart city in various sources, and then we verify the proposed model, the evaluation results demonstrating us that it is efficient and effective, and give some future works in smart city domain.

2 Evaluation model based on non-equilibrium statistical mechanics

The competitive process of complex smart city system obeys the principle of a complex system evolution [22]: An open smart city system far from the steady state is always looking for an optimization process, which can make the generalized flux of the system maximal under the given constraints. Figure1 shows the real model for driving forces of the complex smart city system, where there are various complex interactions and interconnections among the elements of the complex smart city system. The natural smart city system composed of "people-system-environment" is a complex system far from its steady state, and the symbiotic process of typical smart city can be treated as the mutual competing process of material flow, energy flow and information flow among the various bearing bodies in the complex smart city system, and the sharing formulation process of various typical influence factors(include smart people, smart economy, smart mobility, smart environment, smart living, smart governance.) is the competition process with each other, so the smart city evolution system is in accordance with the principle of maximum flow[23] .

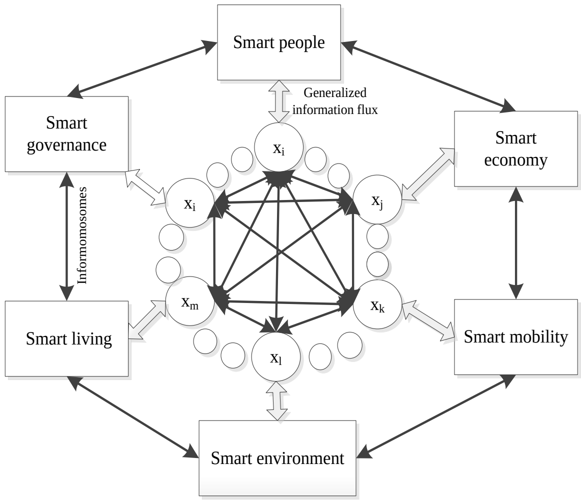

FIGURE 1 Physical model of complex smart city system

Assuming the index property of sub-elements in smart city is $x=(x_1,x_2,\cdots,x_n)$, while there is competition and cooperation among x_i. $x_1,x_2,\cdots,x_n$ respectively is the driving force of each subsystem evolution. All micro subsystems in gamma space Γ form a continuous unit, and then $dx=(dx_1,dx_2,\cdots,dx_n)$ is a volume element of gamma space Γ. If the generalized flux is J when the state of the system exists within the volume unit dx at time t, then the averaged flux over all possible micro-states can be expressed as follows:

$$\bar{J}=\int \rho(x,t)J(x)dx \tag{1}$$

Among them, $\rho(x,t)$ is the time-varying probability density distribution function, the generalized flow function can be expressed as:

$$J=\eta+\sum_i r_i x_i+\sum_{ij} r_{ij}x_i x_j+\sum_{ijk} r_{ijk}x_i x_j x_k+\sum_{ijkl} r_{ijkl}x_i x_j x_k x_l+\cdots \tag{2}$$

Where η and r are constants, and i,j,k,l are the numbers of elements. The remaining summation terms indicate the coupling effect between distinct components or indexes, R as the coupling coefficient. The subsystem reflects the performance of smart city system, its character is expressed by the interaction of each influence element under the generalized flow. The generalized flow's function must satisfy certain constraints, these constraints are that the components should meet certain conservation or the complex boundary reflecting the open characteristic, and it can be generalized to write to one to four order effect matrix form:

$$\begin{cases} f_1=\langle x_i\rangle \\ f_2=\langle x_i x_j\rangle \\ f_3=\langle x_i x_j x_k\rangle \\ f_4=\langle x_i x_j x_k x_l\rangle \end{cases} \tag{3}$$

According to the principle of maximum flow, given the constraint formula (3) we can achieve the maximum generalized flow by formula (1), use Lagrange optimization calculation, there can obtain the probability density function:

$$\rho=c\left(J-\alpha-\sum_i \beta_i x_i-\sum_{ij}\beta_{ij}x_i x_j-\sum_{ijk}\beta_{ijk}x_i x_j x_k-\sum_{ijkl}\beta_{ijkl}x_i x_j x_k x_l\right)^{-1} \tag{4}$$

In the formula, c is the constant. α and β are the optimization parameters in Lagrange optimization. Put formula (2) into formula (4), we can get:

$$\rho = c\begin{pmatrix} \eta-\alpha+\sum_i\left(r_i-\beta_i\right)x_i-\sum_{ij}\left(r_{ij}-\beta_{ij}\right)x_ix_j-\sum_{ijk}\left(r_{ijk}-\beta_{ijk}\right)x_ix_jx_k- \\ \sum_{ijkl}\left(r_{ijkl}-\beta_{ijkl}\right)x_ix_jx_kx_l+\cdots \end{pmatrix}^{-1} \tag{5}$$

In formula (5) the parameters α and β directly regulate the Micro dynamic rules of component interaction. According to Taylor, formula (5) can be unfolded as the following:

$$\rho = \exp\left(\mu+\sum_i\sigma_ix_i+\sum_{ij}\sigma_{ij}x_ix_j+\sum_{ijk}\sigma_{ijk}x_ix_jx_k+\sum_{ijkl}\sigma_{ijkl}x_ix_jx_kx_l+\cdots\right) \tag{6}$$

In the formula (6) the index items can be used as a potential function ϕ, it can ensure the asymptotic stability of system reference state, effectively control the properties of structure of the complex evaluation subsystem. Here potential function ϕ is defined as:

$$\phi(\sigma,x)=\mu+\sum_i\sigma_ix_i+\sum_{ij}\sigma_{ij}x_ix_j+\sum_{ijk}\sigma_{ijk}x_ix_jx_k+\sum_{ijkl}\sigma_{ijkl}x_ix_jx_kx_l+\cdots \tag{7}$$

Give the potential function in formula (7), a parallel transformation and make the constant terms of transformation by a diagonalization of matrix, we can get:

$$\xi_j=\sum_{i=1}^{n}a_{ji}x_i \tag{8}$$

And the potential function turns into:

$$\bar{\phi}(\lambda,\xi)=\zeta+\sum_j\lambda_j\xi_j^2+\cdots \tag{9}$$

From formula (9) we can see, ξ_j is the combination model of components' driving force x_i, it reflects the entire possible structure model, it is similar to the order parameter. Based on the potential function and evolution equation of dynamic function, from (9) we can conclude the ordered structure evolution dynamic equation as:

$$\dot{\xi}_j=\lambda_j\xi_j+S_j\left(\xi_1,\xi_2,\cdots,\xi_n\right)+F_j\left(t\right) \tag{10}$$

(9) and (10) are the foundation of stability of all state patterns during the evolution of the WSNs system. The competition, coordination and other interactions (numerical value and plus sign or minus sign of a_{ji} are employed to describe the relation and degree of interaction in the model) between internal elements, system elements form distinct composite patterns ξ_j (corresponding to distinct values of λ_j) through distinct patterns of cooperation and competition in Figure 1.

Thus, in formula (10), when $\lambda_j>0$, it corresponds to active composite patterns. In other words, among these composite patterns, only the structure with the largest λ_j is the most active, predominant and reasonable. Other potential patterns all belong to transient fast variables, which will be eliminated. The smart city system is damped and can be eliminated when $\lambda_j<0$ .The method which selects active and predominant patterns and eliminates driven patterns through competition based on corresponding control conditions constitutes the theoretical foundation of identifying and evaluating development state patterns of smart city. The method which choses the active and leading function model and generously abandons the driven model according to the control condition makes the theoretical basis of analyzing and evaluation of the smart city development level.

3 The self-organizing feature mapping and simulation for the new evaluation model

Applying non-equilibrium statistical mechanics for integrated smart city development level evaluation from an evolution perspective, the principle of maximum flow for integrated performance assessment of smart city system provides a method of pattern recognition. When the values of coefficients β and r are determined, the corresponding systematic structural pattern ξ_j can be obtained. The competition characteristic of SOFM network in Figure 3 is the same to the MFP arithmetic.

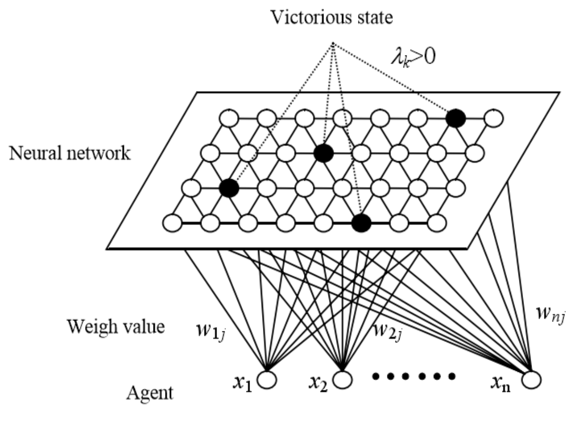

FIGURE 2 SOFM illustration of dynamic simulation system

In a given neuron network, the number of nodes in input layer nodes is *m*, hidden layer node is *l*, output layer nodes is g. To facilitate the representation, we take i as input layer node, k as hidden layer node, p as output layer node in Figure 1.

There are m samples, the input value of *ith* sample is r_{ij}, $i=1,2,\cdots,m$ $j=1,2,\cdots,n$. Node i in input layer deliveries information to node k in hidden layer directly, and input value is equal to output value, $u_{ij}=r_{ij}$.

According to node k in hidden layer, the input value is $I_{kj}=\sum_{i=1}^{m} w_{ik} r_{ij}$, and its output value is:

$$u_{kj}=\frac{1}{1+\left[\left(\sum_{i=1}^{m} w_{ik} r_{ij}\right)^{-1}-1\right]^{2}}=\frac{1}{1+\left(I_{kj}^{-1}-1\right)^{2}} \tag{11}$$

In the formula, w_{ik} is connection weight between node i and k.

According to node p in output layer, the input value is ${}_{pj}=\sum_{k=1}^{m} w_{kp} r_{kj}$. And its output value is:

$$u_{pj}=\frac{1}{1+\left[\left(\sum_{k=1}^{m} w_{kp} r_{kj}\right)^{-1}-1\right]^{2}}=\frac{1}{1+\left(I_{pj}^{-1}-1\right)^{2}} \tag{12}$$

In the formula, w_{ik} is connection weight between hidden layer and output layer.

The actual output value u_{pj} is responsive to input r_{ij} in fuzzy optimal selection of neural network. Assuming that the expected output value of the jth sample is $M\left(u_{pj}\right)$, we can calculate the square error as follows:

$$E=\frac{1}{n}\sum_{j=1}^{n} E_{j}=\frac{1}{2n}\sum_{j=1}^{n}\sum_{p=1}^{g}\left(u_{pj}-M\left(u_{pj}\right)\right)^{2} \tag{13}$$

Then, the connection weight between nodes of the hidden layer and the output layer node is adjustment:

$$\Delta w_{kp}=\frac{2\eta}{n}\sum_{j=1}^{n} u_{pj}^{2} u_{kj}\left[\frac{1-\sum_{k=1}^{m} w_{kp} u_{kj}}{\left(\sum_{k=1}^{m} w_{kp} u_{kj}\right)^{3}}\right]\times\sum_{p=1}^{g}\left(M\left(u_{pj}\right)-u_{pj}\right) \tag{14}$$

In the formula, η is learning coefficient. The connection weight between the input layer nodes and the hidden layer nodes is also an adjustment:

$$\Delta w_{ik}=\frac{2\eta}{n}\sum_{j=1}^{n} r_{ij} w_{kp} u_{kj}^{2}\left[\frac{1-\sum_{k=1}^{m} w_{kp} u_{kj}}{\left(\sum_{k=1}^{m} w_{ik} r_{ij}\right)^{3}}\right]\times\delta_{pj} \tag{15}$$

The weight adjustment formula is as follow:

$$w_{ik}\left(t+1\right)=w_{ik}\left(t\right)+\Delta w_{ik}\left(t+1\right)+\alpha\Delta w_{ik}\left(t\right) \tag{16}$$

$$w_{kp}\left(t+1\right)=w_{kp}\left(t\right)+\Delta w_{kp}\left(t+1\right)+\alpha\Delta w_{kp}\left(t\right) \tag{17}$$

In which α is momentum coefficient, $0<\alpha<1$.

Using the model referred to above, we can determine the network connection weights, according to the training algorithm of neural network, and make the error between the actual output and the expected output error minimized.

Neurons in distinct areas of the space have distinctive functions. The network has unique characteristics reacting to the external input information. The connecting weights between neurons can be obtained by self-organization training, thereby the characteristic property of the entire system can be determined. The connecting weight corresponds to a_{ji} in formula (8). Pattern ξ_{j} obtained by selecting certain parameters is just the result of competition and optimization of the system. Figure 2 displays the pattern of winning, which also needs recognition and evaluation. In a given neuron network, the number of nodes in input layer nodes is m, hidden layer node is l, output layer nodes is g. To facilitate the representation, we take i as input layer node, k as hidden layer node, p as output layer node. The neural network model is not different to appear provincial minimum, and has the disadvantage of slow convergence rate. Therefore we integrate non-equilibrium statistical mechanics which get the characteristic of global search and efficiency, with fuzzy optimization neural network algorithm together.

4 A numerical example

An integrated smart city evaluation index system of the complex city system has been established in terms of smart people, smart economy, smart mobility, smart environment, smart living, smart governance based on the physical model of smart city proposed in section 2. The index of smart economy includes innovation spirit, entrepreneurship, productivity, and ability to transform; the index of smart people includes level of qualification, flexibility, creativity, participation in public life; the index of smart mobility includes local accessibility, national accessibility, available of ICT-Infrastructure and so on.

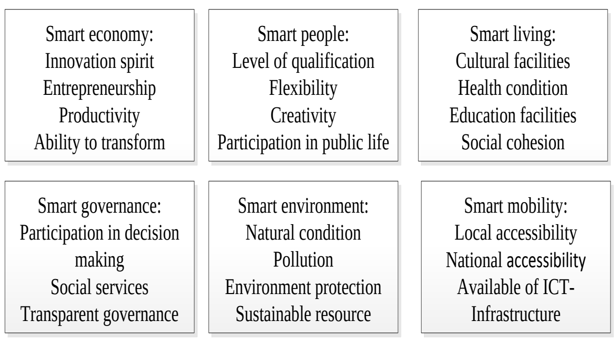

FIGURE 3 Evaluation index of smart city

The factors from x_1 to x_6 belong to the same type in which the bigger of the value the better. The data of ten smart cities in China mainland are shown in Table 1, which is collected from the listing Corporation annual report and China economic database, part of the collection comes from the Wind information, hexun.com and various financial securities website. For the missing data of individual city, we have deal it with the mean substitution method. In this paper, the selected sample cities covered the east, middle and west area, distributing in the different development level.

TABLE 1 Statistical practical data of smart city in China

Name of city	Evaluation index					
	Smart people (x_1)	Smart economy (x_2)	Smart environment (x_3)	Smart mobility (x_4)	Smart governance (x_5)	Smart living (x_6)
Beijing	0.89	0.95	0.75	0.98	0.94	0.86
Shanghai	0.75	0.96	0.97	0.84	0.87	0.90
Nanjing	0.85	0.76	0.85	0.77	0.68	0.93
Hefei	0.55	0.62	0.76	0.62	0.86	0.73
Nanchang	0.59	0.84	0.63	0.62	0.75	0.68
Wuhan	0.85	0.83	0.65	0.85	0.75	0.92
Chongqing	0.72	0.76	0.83	0.69	0.73	0.88
Dalian	0.84	0.68	0.67	0.86	0.85	0.71
Fuzhou	0.75	0.62	0.67	0.64	0.72	0.60
Kunming	0.62	0.65	0.85	0.54	0.72	0.87

4.1 SMART CITY EVALUATION PROCESS

Simulation was carried out by putting the pre-processed data into the self-organization feature mapping network. Grid scale was 8×4, and the training step was 900. The integrated performance grade of each smart city was calculated by the model and method mentioned above. Variable ξ reflects boundary characteristics of development level of each smart city. According to its values to cope, variable ξ can be divided into five intervals. Lowest-level (I) $\xi < 3.50$; Lower-level (II), $3.50<\xi <3.85$; Moderate-level (Ⅲ): $3.85<\xi < 4.65$; High-level (Ⅳ): $4.65<\xi <5.0$;Upper most-level (Ⅴ): $\xi> 5.0$. The empirical results of performance grade for each smart city concert are shown in Table 2.

The evolution process that reflects how the complex smart city development level evolves to a steady state by interaction of indices is illuminated in Figure 3. The contacting weight values reflect the constant competition, cooperation and self-organization of indices (Table 3). The system starts at various combination models. After a certain amount of time, only one dominant model that reflects its status is produced at last.

4.2 ANALYSIS OF THE RESULTS

From Table 2, the complex smart city development level is closely related with factors such as smart people, smart economy, smart mobility, smart environment, smart living, and smart governance. The performance grade distribution is distinct one by one. The upper-most-great level distribute in Beijing, Shanghai. Taking Beijing as an example, hazy weather and sand storm occurred frequently so that the smart environment level is low.

TABLE 2 ξ simulation values and evaluation grades of ten smart city

Name of city	Value of ξ	evaluation grade
Beijing	5.62	V
Shanghai	5.03	V
Nanjing	4.70	Ⅳ
Hefei	3.85	Ⅲ
Nanchang	3.73	II
Wuhan	4.83	Ⅳ
Chongqing	4.54	Ⅲ
Dalian	4.65	Ⅳ
Fuzhou	3.54	II
Kunming	3.67	II

Although its low smart environment level has partly offset smart people and smart economy, the integrated smart city development level is still high. In Kunming, because the smart people, smart economy, smart mobility are low, and the smart environment, smart living are high, but the integrated smart city development level is still as low as Fuzhou and Nanchang . In order to further analyze the interaction of component indexes, contacting weight values of indexes are selected from the system model in Table 3, which reflect the crossover influence between indexes of smart city.

TABLE 3 Contacting weight values of index

Number of WSNs	Smart people (x_1)	Smart economy (x_2)	Smart environment (x_3)	Smart mobility (x_4)	Smart governance (x_5)	Smart living (x_5)
Beijing	0.874	0.136	0.268	0.147	0.806	0.368
Shanghai	0.284	0.689	0.806	0.621	0.306	0.129
Nanjing	0.596	0.657	0.306	0.874	0.589	0.348
Hefei	0.268	0.258	0.589	0.284	0.657	0.118
Nanchang	0.806	0.596	0.874	0.596	0.258	0.159
Wuhan	0.306	0.621	0.284	0.478	0.596	0.136
Chongqing	0.589	0.874	0.596	0.589	0.621	0.689
Dalian	0.136	0.284	0.621	0.369	0.874	0.657
Fuzhou	0.689	0.596	0.874	0.746	0.621	0.258
Kunming	0.657	0.621	0.284	0.865	0.874	0.854

A non-linear information dynamics model has explicit physical meanings, and is applied to evaluate smart city performance of ten cities in China, and empirical results analysis shows its precision and efficiency. Meanwhile, our model also gives us some meaning conclusion, indexes have crossover large impact on each other, and they have contacting weight values between each other. Each component of smart city evaluation index such as smart people, smart economy, smart mobility, smart environment, smart living, smart governance, has a great contribution to the evaluation model of smart city system.

5 Conclusion

In recent years, smart city provides the required infrastructure for citizens and officials to make more intelligent decisions. In doing so, it plays an essential role in dealing with challenges relating to ecological, social, cultural, and economic sustainability. Smart cities provide citizens with information on various urban services and allow them to track the impact of their resource consumption on the overall sustainability of their city. Because smart city is a complex evolution system, hence, it is very important to put forward an overall analysis and corresponding evaluation method for smart city system. In order to compare with smart cities and make better development policy, a comprehensive evaluation model considering smart city as complex system is firstly presented to better study the evaluation rules. To our knowledge as we know, it is the first time that we apply non-equilibrium statistical model to smart city system evaluation, and we prove the value and suitability of the model proposed above. In this paper, we only give the rank results of smart city in one year, the dynamically evolving trend should be analyzed in the next work. In addition, more evaluation method should be employed to demonstrate which one is better.

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