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Optimization of Land-use Based on the Theory of Cellular Automata and Value of Ecosystem Services

Abstract The main objective of the study was to confirm the location and configuration of "Habitat Conservation Area" in Dongguan City. The land utilization condition in the target city was simulated using Arc GIS and Geo SOS software basing on multi-criteria decision model of Cellular Automata (CA). Both the simulation result and accuracy satisfied well the basic requirements. In addition to multi-criteria decision model, space optimization technique was used as well in simulation experiments.

Keywords: Cellular Automata (CA), Ecosystem service function, optimization of land use

1 Introduction

Plummer defines "the goal of land use structure optimization" as "to achieve a certain optimal solution of ecological economy". This definition based one valuation of characteristics and suitability on land resources to arrange amount and spatial distribution reasonable for various types of land resources in the region. It is used to improve the land use efficiency and effectiveness, to maintain the relative balance land ecosystems to realize sustainable use of the land resources (Plummer & Zhou, 1993).The traditional technology and methods of land use structure optimization is to determine the objective function, benefits and constraints of coefficient correlation coefficient. It is usually on the basis of economic statistics, such as the method of equal efficiency and cost method (Yan, 2001). Although these methods reflect the economic function of land use objectively, it ignored the land value of ecosystem services. The result lead to loss of ecosystem services function for the price. Cellular Automata (CA) is a dynamical system defined on the cellular discrete, finite-state cellular space, according to some local rules, in the discrete evolution time dimension. Studies have shown that simulated CA characteristics mimics closely the actual city characteristics, hence validate the theory of urban development, and predict the development of the city and trends of the land use. This trend provides an important basis upon which decision for urban and land use planning can be made.

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2 Overview of cellular automata and ecosystem services

Cellular automata were proposed by Stanislaw M.Ulam and Von Neumann (Von, 1996) in 1948. Originally, it was a mathematical model describing the nature of complex phenomena and used to simulate the unique phenomenon of the life self-replicating system. Codd (1968) simplified the cellular automata of 29 states, and established the self-replication and a general-purpose computing capabilities cellular automaton model. As the realization of cellular automata models required a huge number of cellular elements, the early research of cellular automata focused on the theoretical aspects. In the 1980s, Stephen Wolfram (1983), an American mathematician simplified the cellular automata state space and the radius. At the same time, he introduced the dynamical systems theory and methods to study it. In 2002, Wolfram's (2002) theory of "A New Kind of Science" made the cellular automata theory as a new natural explanation discipline and developed the theory in a high level.

In recent years, CA has been used in urban simulation increasingly. The important feature of city automata is CA coupled with geographic information systems. This coupling results into better simulation of cellular automata, in fact closer to the actual results. The basic principle of urban cellular automata is to stimulate the completed and complex urban development model by local rules. Liu pointed out the CA model was the most extensive, high maturity research method in the urban land use issues in research report of urban land use dynamics simulation (Liu, Wang, & Li, 2013). Qin developed Bengguigui's urban

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space dimensional cellular automata simulation (3DCA) model, which has been added evaluation factors of transport distance and center distance (Qin, Fang, & Wang, 2013). To establish the model of center distance and transport distance on three-dimensional growth of urban. This model simulates the urban structure in visual level.

The concept of the value of ecosystem services was put forward by Costanza, Daly and Daily. In 2005, the United Nations Millennium Ecosystem Assessment reported that human activities have caused tremendous damage to the global environment in the last half century. The concept of the value of ecosystem services are able to help people make better decisions in the future and consider more about the impact of the ecological environment (Zhang, Wu, & Tan, 2013).

Chinese scholars focused on analyzing and exploring the concepts related to ecosystem services, theories, methods and valuation. The main research points are summarized in few points below.

2.1 Theoretic analysis of ecosystem services

This area includes restoration of ecosystem services, the content and value of the function classification, ecosystem services and ecological quality, ecological security systems and sustainable development-related research. The impact of human interference with the natural ecosystem services, as well as the protection and sustainable use of ecosystem services.

2.2 Comparative assessment of the value of ecosystem services

It includes comparison of the valuation methods, such as expenses and Market Act and discussions about ecosystem services value, calculation method of farmland and forest.

2.3 The valuation of urban ecosystem services

The value assessment of urban ecosystem service provides basis for regional decision-making about the sustainable development. Rational land use helps to improve the urban ecosystem service functions. Therefore, it will be helpful to improve the urban ecosystem service value and enrich the study field of the urban ecosystem services by the optimization of the choice of ecological protection zone in the urban city.

Yang (2013) used Dongguan as a case study and selected the degree of landscape ecological security as the evaluation criteria; the resulting simulations showed that as the pressure of urban landscape ecological decreases, the status of ecological security and overall landscape ecology increase. The study shows that the CA model can be an effective tool to explore the research on safety of urban ecology.

3 Cellular automata transition model

The standard conversion rules of cellular are often defined on the cellular in the homogeneous space, the cellular own property does not affect the conversion rules. Urban Cellular Automata is running in the two-dimensional space, urban cellular automata divides the simulation space into uniform rules grid. Cellular cities have two states generally: urban land and non-urban land. The cellular near the center cellular have a greater effect on the central Cellular than the far one. The conversion rules of the cities cellular automata are often reflected by the neighborhood function. The attention should be paid to the change of dynamic iterative neighborhood during the simulation.

The main conversion rules of cellular automata models are: principal component analysis model, decision tree model, logistic regression model and multi-criteria to determine model. According to the land resource allocation process, the formation of land structures is constrained by many targets. It's basis for selecting the multiple criteria to determine the model for analyzing the questions of the case study case in this article.

There are many criteria to be considered in the issues of the value of ecosystem services and land resource configuration, which is constrained by several factors. The first step of using the multi-criteria to determine model is determining the conversion rules, which is the core of CA. In Sim City cellular automata, the cellular in higher suitability development will have a higher probability. The development of suitability can be measured by a series of variable factors. Such as the traffic development, distribution of hydrology geographic, condition of regional economic development and other variable factors are usually be considered. The suitability of development can be achieved by usage of multiple determination criteria assuming that the probabilities in a given region area series of independent variables such as; the distance from the highway, the distance to the city and functions such as terrain elevation and the posed slope. In this model, the dependent variable is the binomial classification constants; Logistic regression can be used for analysis when the conditions do not satisfy the Normal Distribution.

The land development suitability of an area can be described by the following equation in the logistic regression models:

$$P_g(S_{ij} = \text{urban}) = \frac{\exp(z)}{1 + \exp(z)} = \frac{1}{1 + \exp(-z)} \qquad (1)$$

where P_g is the probability of global development, namely the suitability of development; S_{ij} is the condition of cellular (i, j); z is a feature vectors to describe the development of cellular (i, j).

$$z = a + \sum_k b_k x_k \qquad (2)$$

where, a is a constant; b_k is a coefficient of Logistic regression model; x_k is a set of regional variables.

P_g is estimated from land use pattern of two intervals with a relatively long period of time, and is kept stable for the entire simulation process. It is just a messy space distribution based on maximum suitability of the site, which cannot achieve the desired effect. This is not only the conditions that affect the suitability of the land use criteria but also the surrounding land use types in considerable proportion (Guo, Xue, & Zhao, 2004). Therefore, the impact of neighborhood on cellular centers also needs to be taken into consideration.

Besides the factors mentioned above, the constraints of the external environment to the cellular should be considered; such as, the probability of water, mountains, and high-quality farmland and ecological protection zones which are changed into the urban land in low usage. These conditions must be incorporated into the cellular constraints. The scope of local neighborhood and the cellular constraint conditions need to be considered into the impact of the probability of the whole development. In the process of urban development, there are also a variety of political factors, human factors, accident, etc. The human factors in particular make the problem even more complicated.

In order to achieve a better result and make the result of the model more consistent with the actual situation, random items are introduced. The expression formula of the random items is as follows:

$$RA = 1 + (-\ln \gamma)^{\alpha} \tag{3}$$

where, RA is an introduction random variable; γ is a random item, which range from 0 to 1; α is a parameters which control the effect of random variables, and an integer ranges from 1 to 10.

In the actual simulation, the various parameters should be modified in order to make the results effective, such as Switching threshold and the number of iterations. CA model includes four elements which are cellular space, neighborhood, cellular state, and transition rules. The cellular does not have a complex interaction. It always represents status of any specific cellular in the space.

4 Application of city cellular automata model

4.1 Study area

Dongguan City is in the south central of Guangdong Province, China. From the east to the west it is about 70.45km and has a 46.8km north-south width. The land area of city is about 2,465km^2. The residential land within the region, industrial sites and research sites substantial growth and other issues have become increasingly prominent in the past three decades of rapid development. The city background characteristics are significant and ideal for this type study; that is the reason why Dongguan City was chosen as the research object for this study.

4.2 Data and instructions

In this paper, the data of urban development was acquired from the TM remote sensing images in 2001 and 2006, and then processed by the Arc Map software, Grid data were transposed into the ASCII data, and later used in simulation using the Geo SOS software. Although the data is obsolete, the aim of this study intended to verify the feasibility and improvement and provide theoretical support for the follow-up study. The size of the grid data used was 193 × 133 and the resolution was 400m.

4.3 Simulation of cellular automata model

The simulation of the Multi-criteria cellular automaton model needs the information of land-use change and remote sensing images. The regional land use change model is established by the training data of remote sensing. The paper created the conversion rules of CA by using the history remote sensing data of 2001 and 2006, which can predict changes in the urban development and land use by comparing with the actual situation in 2006. Before digging into conversion rules, the following spatial variables were prepared: ① distance from city center; ② distance from the road; ③ distance from the highway; ④ distance from the railway.

The overall development probability calculated by a logistic regression model based on the various spatial variables. The dependent variable is a binary value, which was used to describe the land use change or not from 2001 to 2006. CA model needs to loop iteration several times to reflect the interaction between neighborhoods. In general, the normal range of titeration is100–200.

The initial year of remote sensing images begins at 2001 and terminated at 2006. The spatial variable data has been mentioned before. The blank part of the image is not included in the simulation during the conversion process, and the data is considered as null value. The developed urban land is difficult to convert into the farmland, orchards, and land-based ponds. These changing settings of the land are irreversible in the simulation. In the various types of land, farmland, orchards, land-based ponds are urbanization types and can easily convert to each other; this type of land is set as the land which could be converted. Some other types, such as mountains, forests, waters and others are not easily converted to other types and they are defined as non-converted land. This multi-criteria model simulation is mainly related to urban land, farmland, orchards, waters, forests. The weights of each variable parameter are set in Table1.

The CA Global factors are assigned the ratio of 0.6 and the neighborhood factors are assigned the ratio of 0.4. The diffusion parameter of the model is 1.There is total of 33,027 grids in the analog simulation process. The simulation results are shown in *Figure 1* to *Figure 3*.

5 Simulation analysis and evaluation

The result of the cellular automata model simulation of 2001 and 2006 in Dongguan is showed in Table 2.

Table 1

Parameters Table of the Variable Weight

	D is To City	D is To Highway	D is To Railway	D is To Road
D is To City	1	1/3	1/5	3
D is To Highway	3	1	1/3	3
D is To Railway	5	3	1	5
D is To Road	1/3	1/3	1/5	1

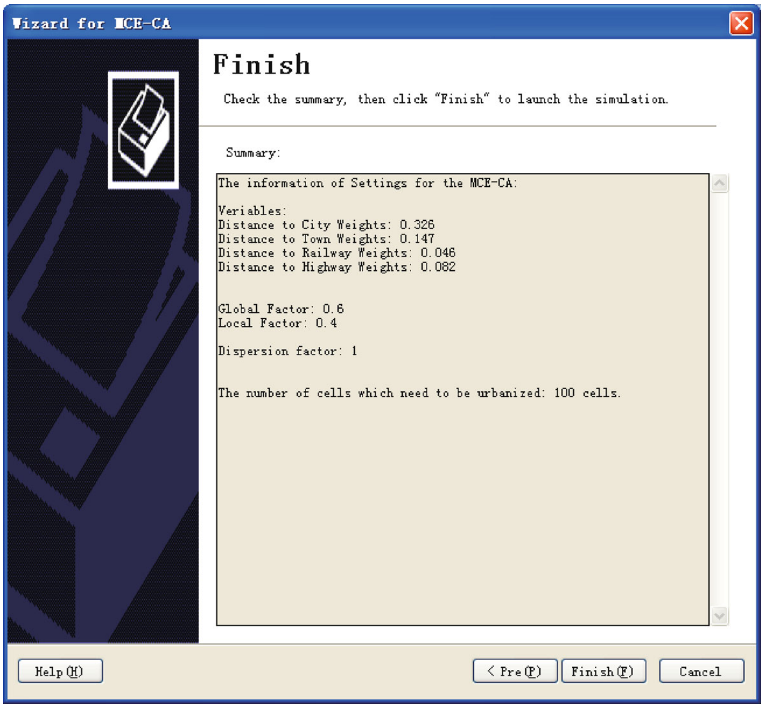


Figure 1. The parameters settings of the multiple criteria the model calibration.

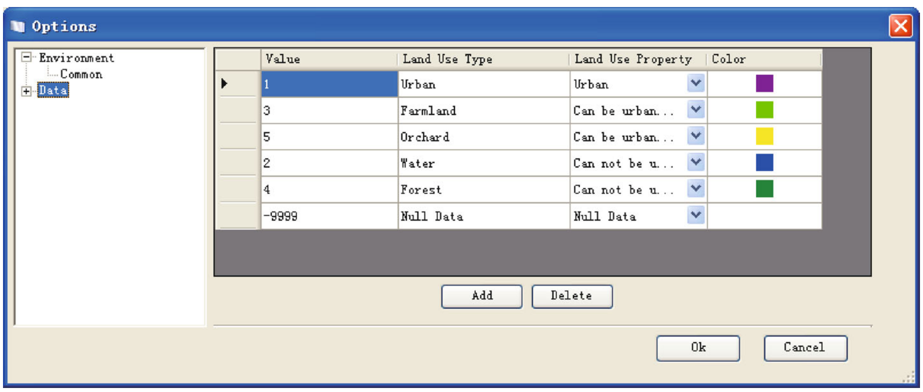
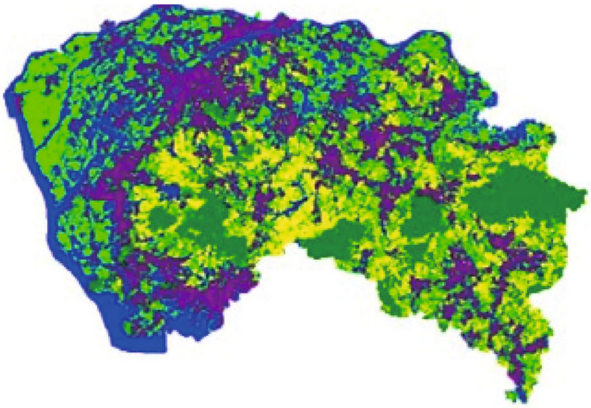
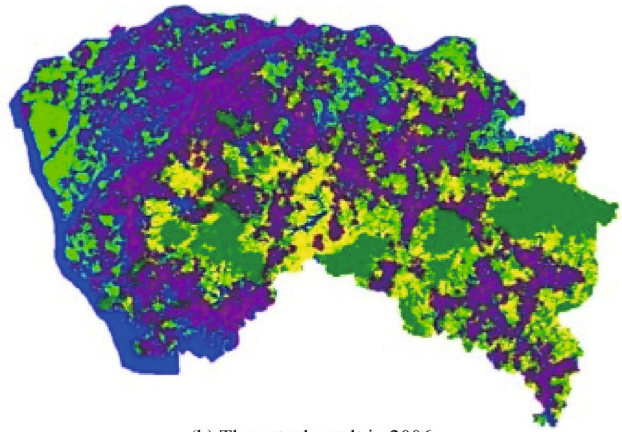


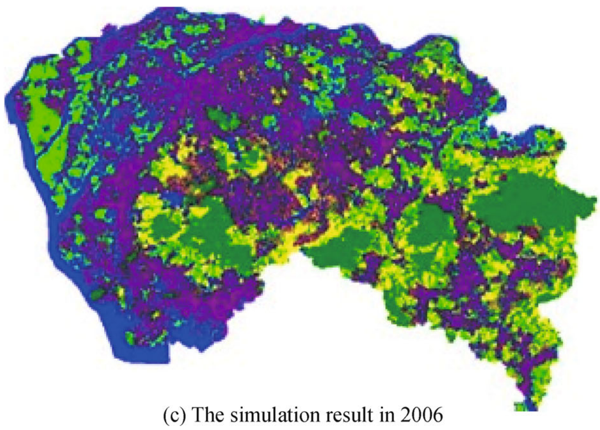
Figure 2. The land use type settings.



(a) The actual result in 2001



(b) The actual result in 2006



(c) The simulation result in 2006

Figure 3. The status and simulation results of Dongguan City land use (2001—2006).

Table 2

Analog Data Analysis Table

The number of units that the actual non-urban land was simulated as the non-urban land	The number of units that the actual non-urban land was simulated as the urban land	The simulation accuracy of the actual non-urban land use	The number of units that the actual urban land was simulated as the non-urban land	The number of units that the actual urban land was simulated as the urban land	The simulation accuracy of the actual urban land use	Total accuracy
164,312	24,594	97.3%	37,519	42,495	53.1%	83.1%

From the result, the simulation accuracy of the actual non-urban land use is 97.3%; the simulation accuracy of the actual urban land is 53.1%, and the overall total accuracy is 80%. From 2001 to 2006, the proportion of urban land has risen and non-urban land fallen from the city development simulation figure. Farmland, orchards, water, forests and other land use types still has an absolute advantage. In the spatial distribution, the new construction sites mainly focus on the city center, and the agricultural land is mainly distributed in the northwest and southeast. When compared to the simulated land use map and the actual use map for year 2006, the analysis shows that the results of model simulations are relatively consistent with the actual remote sensing data. Although there are some existing differences, the overall trend could reflect changes in the land use situation. The trend of the non-urbanized land decreased unchangeable, but this type of land is very important to the sustainable development of the city. Without proper management measures it may affect the sustainable development of the urban, the ecological safety and the environment.

6 Simulation analysis of the urban ecological protection zone

As the result of urbanization, the proportion of urban land use gradually increased. The urban ecological environment has been damaged in a certain extent. The most simple and effective method is to establish an urban ecological protection zone to keep the cities sustainable development and protect the valuable ecosystem services. It is of utmost importance to make significant and reasonable choices of ecological protection zone for the optimization of urban ecosystem services. This paper used Geo SOS space optimization techniques to choose the reasonable location of urban protected areas on the basis of urban cellular automata model.

According to the ecological construction plan in Dongguan City, the 37.5% of the city will be the ecological land area and 924km^2 of the land should be chosen as the ecological protection zone. The resolution ratio of grid data is 400m.

What is needed is to set the multi-criteria cellular automata model to simulate the urban development and ecological protection zone based on the ant colony optimization. The selection of ants is according to object function in each iteration in Ant Colony Optimization. The object function consists of two parts, ecological protection suitability and compactness. The compactness is generated to ensure that the ecological protection zone has certain continuity.

Goal function:

$$\text{GoalFunction} = \text{EcoSuitable} \times \text{Compactness} \quad (4)$$

The ecological suitability function requires a specific definition. The factors considered in this paper consist the urban development suitability, normalized difference vegetation index(NDVI), improved Normalized Difference Water Index(MNDWI), Urban Density, Relief Amplitude (species diversity), the difference of NDVI in a moving window (vegetation diversity). After assigning different weights to each function factor, the suitability mathematical expressions becomes:

$$\begin{aligned}&\text{Suitability Function}\\&= 0.159 \times (1 - \text{UrbanSuitable})\\&\quad + 0.214 \times \text{NDVI} + 0.214\\&\quad \times \text{MNDWI} + 0.138\\&\quad \times \text{ReliefAmplitude} + 0.138\\&\quad \times \text{NDVIStd} + 0.137\\&\quad \times (1 - \text{UrbanDensity}) \qquad (5)\end{aligned}$$

The Protected areas need $924 \times 10^6 \div (400 \times 400) = 5775$ rasterand has generated the initial distribution of ecological protection zone based on the ACO model, which was scattered (*Figure 4*). As the optimization progressed, the ideal result of ecological protection zone eventually formed (*Figure 5*).

The formed ecological protection zone is mainly in the non-urban land, which can be seen from simulation results of multiple criteria (*Figure 6*). It is not only using the non-urban land effectively, but also avoiding the selected protected areas conflicting with the urban land to some extent. Overall, the results of space optimization were in line with our expectations and form the ecological

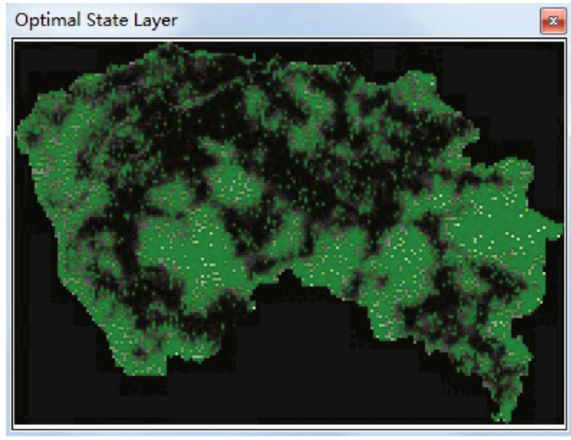


Figure 4. The initial distribution image of optimization.

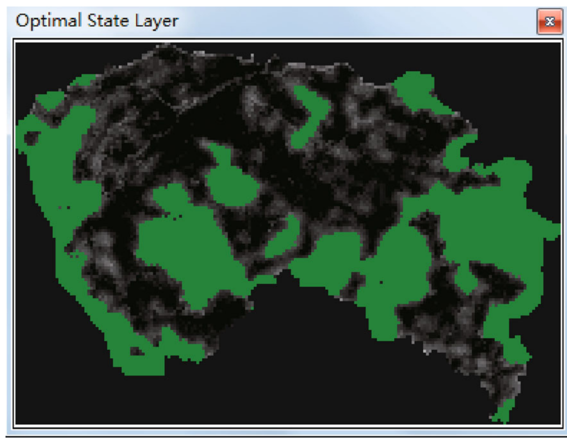


Figure 5. The final distribution image of optimization.

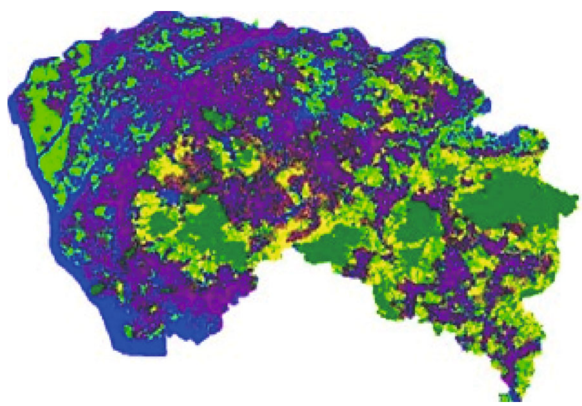


Figure 6. The simulation results of the multiple criteria to determine cellular automata.

protection zone needed easily and effectively to improve the scientific planning of ecological protection zone.

7 Conclusion

This study applied the cellular automata theory on the development of cities and made Dongguan City as the case study. The result of cellular automata simulation meets the actual land usage case of Dongguan in year 2006. The approach and techniques used in this study can prove useful for the urban land plan and land allocation policy. About 924 km^2 of land has been selected as the ecological protection zone based on the space technology. The study adds significance to the task of planning the urban ecological protection zone and enhancing the value of ecosystem services for the government.

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