A Framework for Application of Synergetics for Sustainable Land-Use Planning

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1. Abstract

Since the 1980s', system analysis methods, GIS and Remote Sensing techniques have been increasingly integrating into a Planning Support System, aiming to provide planning and decision-making of sustainable development with information and a simulation tool. Some progress has been made but a main barrier lies in the lack of theoretical breakthrough, that is, how to incorporate the social, economical and environmental indicators into the land-use system and how to systematically coordinate them remains unsolved. Based on Synergetics principles, a new kind of thinking and system approach is presented in this paper for land-use planning. The principle that coordination results in ordering is introduced into land-use planning in detail. Improving the order degree of a spatial system could improve objective and quantitative of land-use planning by coordinating different sub-systems. Firstly, GIS can be used to project social, economic and environmental factors on the land-use system. Secondly, some mathematical models must be created to quantify the order degree of land-use system. Finally, some modules could be developed to dynamically and spatially simulate the effect of different land-use planning schemes with GIS and further enable to determine an optimal one. The study is expected to aid and support the decision and evaluation of sustainable land-use planning.

[Key words] Synergetics, Sustainable land use planning, GIS, Dynamic simulation, Order degree

2. Introduction

Land is the most basic and important of usable resources for human beings, it is where our energy, food, water and raw materials come from and it is also the habitat for wildlife and fauna. Similar to other resources, it is a scare commodity. However, as population increases and the pace of economic development quickens, nowadays the world is being confronted with great threats of land destruction and depletion.

2.1 Soil erosion

Due to the improper land management, some one-third of all arable land in the world is being degraded. 7 percent of all arable land has been destroyed during the period from

1980 to 1990. In China, over 2 million hectares of land resources suffer from pollution, Over 2 million acres were destroyed and lost annually as a result of various disasters.

2.2 Global warming

It is estimated that the global temperature will go up by 0.3 degree every ten years. If it increase 3 degree, the ocean level may rise 1 meter, which will result in 3 percent of the land becoming flooded, including some large cities and farmlands.

2.3 Desertification

About 50-70 thousand square meters of land resources turn to desert annually in the world. It is predicted that nearly one-third of all arable land will be destroyed by the end of the century.

2.4 Urbanization

Urbanization results in irreversible destruction of land resources by the conversion of agricultural land into urban land. Housing and satellite town or city development through land reclamation may destroy wetlands, which are valuable natural habitats for wildlife and may lead to their extinction by upsetting the ecological balance. It will also lead to loss of property and human life in case of flooding. For instance, Chicago metropolitan region’s population grew between 1970 and 1990 by a modest 4.1 percent while the amount of land area consumed had increased by 47 percent (Yeqiao Wang, 1996). In China, as a result of rampant land development spurred by economic reform, arable land in the Pearl River Delta has decreased from 1044.7 thousand hectares in 1980 to 898.2 hectares in 1991, a decrease of 14 percent in ten years (Anthony Gar-on Yeh, 1996). The rate of land conversion to urban use for other Asian cities is also enormous. In Bangkok between 1974 and 1984, the rate was 32 square kilometers of agricultural land per year; in Karachi, 24 square kilometers per year, and in Bangalore, a much smaller city, about 13 square kilometers per year. Even in remote Kathmandu, the pace of land conversion was so rapid that the residential land area of the city doubled between 1971 and 1981 (David E. Dowall, 1991).

Against the backdrop of these growth trends, policy-makers are beginning to recognize that sustainable land management and land use planning is an important facet to coordinate systematically and dynamically population and economic development, environment and resource protection, not only for wealthy nations but also for developing countries. Many countries have put emphasis on research of sustainable development. Some progress has been made, for instance, system analysis methods, GIS and Remote Sensing techniques have been ever increasingly integrating into a Planning Support System, aiming to provide planning and decision-making of sustainable development with information and simulation tools. But one of the crucial barriers lies in the lack of theoretical progress, that is, how to project the social, economical and environmental indicators onto a land-use system and how to systematically coordinate them remains unsolved. This paper aims to argue the possibility and necessity of applying synergetics to the process of sustainable land use planning, followed by an applied framework oriented decision support.

3. Sustainable Development and Synergetics

Sustainable development is becoming a widely acknowledged concept with a long history and as many as 70 different definitions. It can be traced back to two thousand years ago in Greek culture. The modern concept, first set forth in the World conservation strategy (1980) and popularized by the Brundtland report (1987), has been defined as "Sustainable development is a pattern of development that meets the needs of present generations without jeopardizing the ability of future generations to meet their own needs" (World Commission on Environment and Development). Since the United Nations conference on environment and development held at Rio de Janeiro in June 1992, the international society has begun to pay attention to sustainable development. For example, China, as many other countries, has attached great importance to sustainable development. The government has mapped out "China agenda 21" (China's agenda 21) in 1994, emphasizing an overall strategy that sustainable development should be based on the coordination of population, environment, resources and (economic) development (PERD). Nearly 1000 billion RMB was invested in curing environment pollution annually.

But different countries have different perceptions and thus different definitions, generally speaking, these definitions are mainly focused on different aspects e.g. on sustaining economic development, on resources conservation and ecological consideration, on improved living standards and on reduced energy consumption and improved techniques. Different development situations, ideology, cultural background and customs may result in different measurements and indicators of sustainable development.

Spurred by mathematics, computer science, management and other sciences, system science has evolved as an independent field. The former 3 theories, i.e. General System Theory, Cybernestics and Informatics, have been replaced by 3 new theories during the 1970's. Examples are: Dissipate Structure (I. Prigogine), Synergetis (H. Haken) and Catastrophe Theory (R. Thom), which focuses on the general law of open systems, changing from disorder into order or into a higher level order state, (the so-called 'self-organization theory'). Especially, synergetics, introduced by H. Haken in 1969, explains and concludes the basic principles from disorder to order state, its famous statement "coordination results in ordering" successfully summarizes similar phenomena existing in open physical and social systems. The principles have been gradually popularized and applied to socio-economic and ecological systems. In terms of synergetics, sustainable development is in essence a systematic coordination, a process to improve the order degree of the man-earth system through coordinating inter-relating and inter-conflicting subsystems (such as population, resource, environment and development) both dynamically and spatially. This paper will argue that synergetics, supported by GIS and system analysis techniques, may be further applied to sustainable land use planning.

4. Land and Landuse System

In 1992, "Sustainable Development Science" (Chapter 35 of the United Nations' Agenda 21) pointed out that researches on earth systems will form the scientific basis of a Sustainable Development strategy. The inspired some research activities on the application of earth system science to sustainable development. The earth system consists of land, ocean and atmosphere together with exchange of materials and energy across their interfaces, but the land system is the center of socio-economic development (Yang Qingye, 1996). Generally speaking, the land system comprises topography, soil, geology, and vegetation within certain scope of space and time, it can be also divided into urban land systems, farmland systems, forest land systems, mineral land systems and other sub-systems. The basic system functions include production, energy conservation, protection, consumption, loading and preservation. Obviously, the land system itself is a physical and ecological system, but it is not an isolated system, it must interrelate and interweave with socio-economic systems in the same region. Especially, urban land systems sustain stronger social and economic activities. Land use systems may be defined as the integration of a land system and corresponding socio-economic systems or as a hybrid system, of which the land sub-system is carrier. Socio-economic and environment sub-systems may be regarded as the attributes of land spatial units; population is its core, the size of the population determines the demand for land resources, and also the influence of land use activities on socio-economic and ecological systems. The essential features of the land use system are as follows:

Openness: the term “entropy” is cited here to quantitatively depict and explain the openness of the land use system. In the field of systems theory, entropy means the degree of disorder. Supposed that **ds** is the total entropy, **dis** means the entropy created inside the system, **das** means the negative entropy of system inputs for example, created through sustainable land management, technology progress etc. Similarly, **dbs** is the negative entropy of system output, i.e. which are consumed to resist natural disaster, environment pollution and human destruction, therefore

$$ds=das + dbs + dis$$

Generally, $dis>0$, $das<0$ and $dbs>0$, hence, the value of ds is determined by the relative value of das, dbs and dis, for instance, if $das<abs(dbs + dis)$, $ds>0$, i.e. the destruction resulting from human socio-economic activities surpasses the threshold of the land use. Thus, the system will gradually get into disorder.

Nonlinearity: the interactions among elements in a land use system, the system and its external environment are mainly nonlinear.

Other features of land use systems such as stability, changeability, distant equilibrium state, controllability, observability would not be explained here. In summary, landuse systems are complex and dynamic open systems and each sub system may create positive and negative entropy, among which there is a complicated nonlinear interaction. Hence, to allocate all land use activities spatially and dynamically, sustainable land use planning should aim to seek an optimal coordination method achieving a dynamic and comprehensive balance among social, economic and environmental efficiencies. It should be noted that the coordination not only means components inside landuse systems within the selected study area, but also includes the system itself and its external environment in time and (2-dimension) space.

5. A Framework of Synergetics Application

As a land use system is an open, complex system, ordinary system analysis methods like linear programming, input-output analysis, regression analysis etc. can not satisfy sustainable land use planning. Moreover, they are static and linear models, they focus on structured decision-making, while complex systems frequently call for ill-structured or semi-structured types of decision-making, which have only relatively satisfactory solutions, not one optimal solution. The models applying synergetics principles may include nonlinear functions, parameters with little contribution to system changes could be eliminated, order parameters or slow parameters determining system changes could be extracted, which would enable to model the order degree of the land use system. A framework for a sustainable land use planning process, based on synergetics principles, is outlined in figure 1.

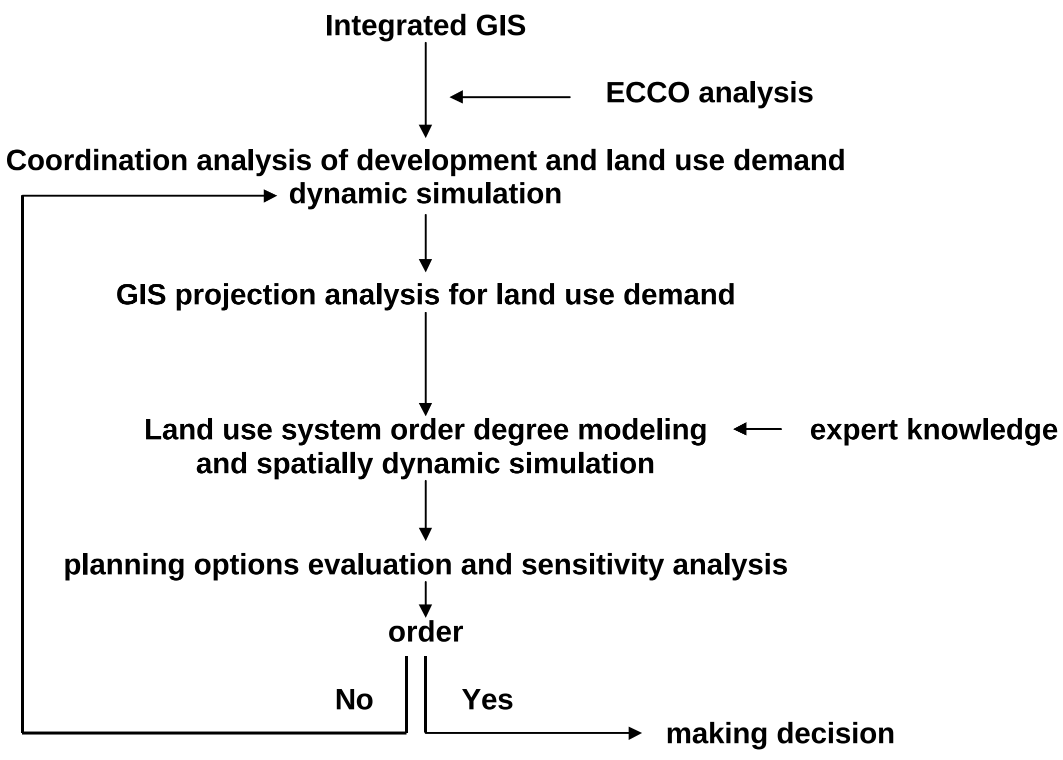

Figure 1. Framework applying synergetics to sustainable land use planning

5.1 Integrated GIS

The GIS should contain various types of graphic data and socio-economic-environmental data, which are necessary for sustainable land use planning and for model calibration. The data collection process focuses mainly on obtaining as much information as possible about time series in the socio-economic and environment.

Spatial data: topography, hydrology, remotely sensed (satellite) images, land use, road and river network, geological etc.

Non-spatial: economic data (economic types, profit, tax, output value, employment, income, pollution etc.), demographic data (population, age structure, household etc.), ecological data (water and soil pollution, forest fires, wildlife distribution etc.).
The data structure (vector or raster) of graphic data depends on the data collection method and accuracy requirements.

5.2 Coordination Analysis of Socio-Economic Development and Land Use Demand

This step is to coordinate development and protection only dynamically not spatially. System dynamics, as a tool and lab of policy simulation, is applied here to simulate socio-economic development and corresponding land use demand, satisfying sustainable development. The crucial point of the model is to design a causal loop according to indicators of sustainable development, different for different countries. The causal structure may qualitatively indicate the complicated interrelations between socio-economic development and land use demand within a study area. The general form of the dynamic model can be written as a set of ordinary simultaneous differential equations as follows:

$$\frac{dX_i}{dt} = F_i(X_1(t), X_2(t), \cdots, X_n(t), Y_1(t), Y_2(t), \cdots, Y_m(t), Z, t)$$

$$\frac{dY_j}{dt} = F_j(X_1(t), X_2(t), \cdots, X_n(t), Y_1(t), Y_2(t), \cdots, Y_m(t), Z, t)$$

$$\text{subject to:} \quad C_k(X_i, Y_j, Z, t) = 0$$

$$i=1,2,\ldots n, \quad j=1,2,\ldots m, \quad k=1,2,\ldots,s$$

Where $X_i(t)$ (i=1,2,…,n) are components of state vector describing socio-economic development such as population, output value in any year. $Y_j(t)$ (j=1,2,…,m) are components of state vectors describing land use demand such as urban land area, transportation area, industrial area of a year, Z is a control parameter vector that affects the changes of X and Y such as birth rate, regional development policies. t is an independent (continuous) time variable. Function F_i and F_j is nonlinear on the whole, which can be determined by tabular functions, based on corresponding time series data. Function Ck expresses the constraints of the land's carrying capacity, which could be analyzed by ECCO evaluation. The dynamic equations can be applied as follows:

1. By using DYNAMO software, the land use demand, namely vector Y can be calculated and simulated, satisfying the objectives of sustainable development. The simulated value of vector Y will be used as input of models in the next section (4.3).
2. The equations presented above contain a number of parameters, which have disparate influences on sustainable development. Applying synergetics modeling techniques, the reduced number of slow order parameters, which determine the order state of the land use system, can be extracted through adiabatic elimination. These order parameters will govern and affect the sustainability of development; the results will assist further qualitative analysis.

5.3 GIS Projection Analysis for Land Use Demand

To achieve spatial coordination, the land use demands from models as discussed above have to be projected onto the land system by GIS spatial analysis; the simulated vector Y needs to be located spatially. The suitability evaluation should be made first for different demand, not only from physical, ecological aspects, but also from social, economic and environmental attributes. Taking urban land demand for example, selectable indicators may include geology, road and water accessibility, population and economic scale, environmental influence. Here, GIS can be used as a tool for spatial analysis, MCE/MOD(Multi-Criteria Evaluation/Multi-Objective Decision) may be used for evaluation means. Some applications have proved that comprehensive evaluation based on fuzzy logic could be better employed for suitability classification and definition.

5.4 Spatially Dynamic Simulation and Order Degree Modeling

This step is to spatially simulate land use structure, to improve the order degree of the macro state of the land use system by optimally matching land use suitability and land use demand. From section 4.3, the thematic layer $A_j(x,y)$ (indicating the suitability class at the location (x,y)), corresponding to land use demand $Y_j(t)$, could be created. The spatial overlay of all thematic layers will create a new integrated layer $B_j(x,y,j)$ (indicating the suitability class of land use demand $Y_j(t)$ at the location (x,y)). The spatial combination varying with variables x,y and t will form quite a number of planning alternatives. The spatially dynamic simulation aims to determine the optimal combination to realize the most satisfactory order degree of the land use system, subject to total land use demand. In terms of synergetics, the bigger the number of alternatives is, the stronger the disorder degree is. A formula to depict quantitatively the order degree:

$$R=1-\frac{H}{H_m}$$

Where **R** means order degree, **Hm** indicates maximum system entropy, a constant determined by the number of alternatives, **H** means uncertainty of micro states of the system, related to the probability of micro states. **H** is affected and determined by different type of factors such as physical, socio-economic, and spatial relationships, and subjective factors. Following the synergetics principle, land use spatial planning is actually about increasing R or decreasing H. The spatially dynamic simulation aims to decrease the uncertainty of parameter H from the aspects of spatial relationship and physical ecological components. For instance, in the process of university campus planning like WTUSM, improving road and facility accessibility is the main part of spatial simulation. But quantifying parameter H is a complicated process, affected by objective and subjective, spatial and aspatial factors. GIS, system analysis and knowledge engineering techniques needed to be integrated for the purpose. GIS focuses on the simulation of spatial relationships, system analysis on socio-economic components and expert systems on the subjective sector. In summary, the meta-synthesis integrating quantitative and qualitative analyses may be an ideal means to assist order degree modeling.

5.5 Planning Options Evaluation

The reasonability and sensibility of spatial planning options generated from dynamic simulation should be evaluated to satisfy sustainable development. This can be done by using MODM (Multi-Objective Decision-Making) techniques such as AHP, DELPHI, stormbrain, fuzzy nerve net etc. GIS could be employed as a tool of spatial query and visualization, the expert opinions should receive much attention. If the evaluation result is not satisfactory, it should go back to the section of coordination analysis, (so-called meta-synthesis method).

6. Conclusions

The framework proposed in the paper focuses on discussing the process of sustainable land use planning, supported by synergetics principles, meta-synthesis and GIS techniques. But there is a long way to go to put thinking into practice. The following opinions need to be noticed:

- In modeling, especially in modeling order degree of complicated social systems, synergetics need further improving. During the application of the framework, meta-synthesis is a feasible method. The integration of system dynamics, MCE, MODM and GIS techniques could be expected to support sustainable land use planning, but expert experience and knowledge will also play important roles.
- 2) To improve the efficiency of the planning process, a GPSS (Group Planning Support System), integrating GIS, model base and knowledge base etc. should be explored.
- Sustainable Development is a global concern, in terms of synergetics, true sustainability will have to depend on complete coordination including cooperation among countries, developed and developing, solutions of relevant theories and techniques, public participation, economic development, environmental awareness etc

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