CHINESE GEOGRAPHICAL SCIENCE
Volume 14, Number 1, pp.1–8, 2004
Science Press, Beijing, China

APPLICATION OF ARTIFICIAL NEURAL NETWORK IN COMPLEX SYSTEMS OF REGIONAL SUSTAINABLE DEVELOPMENT

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ABSTRACT: Meeting the challenge of sustainable development requires substantial advances in understanding the interaction of natural and human systems. The dynamics of regional sustainable development could be addressed in the context of complex system thinking. Three features of complex systems are that they are uncertain, non-linear and self-organizing. Modeling regional development requires a consideration of these features. This paper discusses the feasibility of using the artificial neural networt(ANN) to establish an adjustment prediction model for the complex systems of sustainable development (CSSD). Shanghai Municipality was selected as the research area to set up the model, from which reliable prediction data were produced in order to help regional development planning. A new approach, which could help to manage regional sustainable development, is then explored.
KEY WORDS: complex systems; sustainable development; artificial neural network; regional development

CLC number: F119.9 Document code: A Article ID: 1002-0063(2004)01-0001-08

1 INTRODUCTION

Since 1949, the government of China has adopted a long-term planning system based on a series of sequential Five-year Plans (FYPs). The FYPs provide the general development strategy at the both national and regional levels. The "Tenth FYP" came into effect in 2001 and covers the time period up to and including 2005. A regional FYP is usually generated on the basis that each government department has developed its own FYP with limited coordination with other departments. The general FYP is then a kind of summation from the separated departmental FYP.

Following the Earth Summit in 1992, sustainable development has increasingly become a main theme in the FYPs. Sustainable development could be defined in numerous ways (PEZZEY, 1989). However, central to all the definitions is an approach, which requires the integration of environmental, economic and social issues. However, the effectiveness of regional FYPs is restricted by the current practice of seeking to integrate separate departmental and sectional plans into one regional plan. The problem lies in the conflicting of departmental plans, thereby, preventing "joined-up" plan being worked out.

Complex systems thinking may offer a workable approach to understanding progress towards sustainability. This approach is based on the study of complex adaptive systems in a state " At the edge of chaos". It first emerged in the physical sciences (KAUFFMAN, 1995; LEWIN, 1992; WALDROP, 1992). Some have argued that this model is also powerful in understanding the function of social systems (HWANG, 1996; KAUFFMAN, 1995; KIEL, 1991; WHEATLEY, 1992). This kind of thinking provides planners with ways to understand the interrelationships between economics, public finance, and the environment and to avoid the simplistic thinking that results in policies with counterintuitive and unanticipated negative consequences (INNES and BOOHER, 1999).

In this study sustainable development is understood as a process which includes a complex system in

Received date: 2003-09-09
Foundation item: Under the auspices of the National Natural Science Foundation of China (No. 40131020), and British Council's Academic Links with China Scheme (SHA/992/304)
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which human activities play an important role and which is composed of three sub-systems: environment and resources, economic development and social progress. A wide range of recent studies can be found which address explicitly the regional aspects of sustainability issues (NIJKAMP and VREEKER, 2000). A regional system may be thought of an open system with flows of energy, matter and information into and out of the system. Such an open system presents complications when compared to a closed system. The progress of regional sustainable development is not only driven by the function of forces inside the system, but it is also influenced by external factors. Humans with the capacity for cognition, behavior, decision-making and regulation have the ability to adjust and manage the complex regional system. Hence, it is possible for rational adjustment to be made to the process of sustainable development, and therefore it is essential to understand the complex system more fully.

There exists a lot of research on sustainable development, which explains the quantitative relationships among each sub-system or factor. However, this often based on methodologies which examine individual sub-systems. Such an approach presents great difficulties when trying to understand the features of a complex system as a whole. This paper aims to use the artificial neural network (ANN) as a tool to simulate and predict the complex system of regional sustainable development. It is anticipated that this approach will provide useful information for guiding the development of the FYPs and government decision-making, as well as demonstrating that ANN can be a useful decision support tool.

2 COMPLEX SYSTEMS

Conceptually, complex systems are a group of interacting, interdependent parts linked together by exchanges of energy, matter and information. They are specifically characterized by strong interactions between the parts; complex feedback loops that make it difficult to distinguish cause from effect; and significant time and space lags, discontinuities, thresholds, and limits (COSTANZA *et al*., 1993). The complex systems of sustainable development (CSSD) is formed by complicated coupling functions among the environment and resources sub-system, economic development sub-system and society sub-system, and is more than the sum of these sub-systems.

Contemporary theories support the concept that complex ecosystems possess multiple stable states (WESTOBY *et al*., 1989), and their development are characterized by nonlinear systems behavior, discontinuous change, self-organization, and multiple development pathways (HOLLING, 1995). Non linearity is one of the important features, and a great number of complex systems are described by nonlinear differential equations. These nonlinear dynamic systems are always generated by a number of nonlinear elements (sub-systems) whose composition and inter-relationships are naturally different from those of linear elements. The behavior of the whole system cannot be understood by simply decomposing it into pieces, which are added or multiplied together. Uncertainty is another important feature of complex systems. Uncertainty of the whole system includes the uncertainty of sub-system structure or parameters, the uncertainty of the coupling function among sub-systems and the uncertainty of external disturbance. All these uncertainties add to the complexity of the system. Thus, to the CSSD, only by dealing with the non-linearity and uncertainty of the system directly could the nature of the complex system behavior be understood and a model reflecting the real dynamic quality of the system be formed.

An important consideration is that the CSSD is also a self-organizing system whose dynamics are dominated by both positive and negative feedback processes operating over a range of spatial and temporal scales (KAY *et al*., 1999). This self-organizing system exhibits a set of behaviors, which are coherent and organized within limits. A self-organizing system has the ability to maintain itself despite changes in its environment. Hence, it is possible for a system's environment to change substantially, without the system exhibiting major change. Although it is human who construct the social and economic system, and modify the structure and try to manage the system by selecting different policies, human themselves are also limited within the system. The part that humans can control is only one part of a bigger self-organizing system. Thus, more precisely, the CSSD is a complex open system with both features of self-organizing and human-made systems which is dominated by the former. It cannot be managed by any single mind or even by a complicated set of formal policies; there is too much going on at once, too many linked components, and too much feedback and adaptation (INNES and BOOHER, 1999). A complex system is, in a basic sense, out of control (KELLY, 1994). Managing a complex system effectively requires and intimates understanding of its dynamic behavior and control variables through capturing its essential factors, variables and interrelationships in a holistic systems framework (GREINER, 1999).

3 ARTIFICIAL NEURAL NETWORK AND COMPLEX SYSTEM

Computer modeling is the preferred way of implementing holistic systems frameworks (GREINER, 1999). However, it is difficult to establish precise models for complex systems, for mathematical equations, describing the relationships among different elements in each system, are necessary to establish a series of model simulating laws of the real system. Certain objective laws of complex systems do exist, which are diversified by the complicated functions of sub-systems. However, great difficulties for traditional control theory to establish precise models will be created if the relationships between factors can be not described by precise mathematical equations.

Neural networks are particularly suited to complex problems, where the relationships between the variables being modeled are not well understood (GREINER, 1999). The concept of ANN has been used widely in nonlinear time series modeling of multivariate signal processing and controls (HAGAN *et al.*, 1995). Generally, quantitative models can be divided into statistical and process-based models. Statistical approaches examine historical data sets and, through estimating the relationship between key variables, often serve forecasting purposes. Process-based models require an explicit description of underlying functional relationships. Neural networks are classified as data-driven statistical approaches, whereby the system is trained to produce outcomes on the basis of strategically chosen model input. It is possible, therefore, through learning and training by using known sample data, that ANN could be used to simulate laws and set up adjustment prediction models for CSSD and, thereby, suggest optimal management strategies.

3.1 Structure of Neural Network

An artificial neural network, which could simulate many basic functions and simple modes of thinking of human brains, consists of a large number of simple processing elements that are variously called neurons or nodes (HUANG and FOO, 2001). Each neuron is connected to others by means of direct communication links, each with an associated weight. The weights represent information being used by the net to solve a problem. The neural network usually has two or more layers of neurons in order to process nonlinear signals. Through learning, the ANN could obtain and store external knowledge to solve a series of problems such as knowledge settlement, optimal design and intelligence control which can not be solved by traditional computer programmes.

Among many neural network architectures, the three-layer feed-forward back-propagation (BP) network is the most commonly used (HAGAN *et al.*, 1995; HAYKIN, 1999). This network architecture consists of input layer, hidden layer and output layer of neurons. The schematic diagram of a three-layer neural network is given in Fig. 1, where W_{ij} is the interconnect weights of neuron i in input layer and neuron j in hidden layer, V_{jt} is the interconnect weights of neuron j in hidden layer and neuron t in output layer. A nonlinear differentiable log-sigmoid transfer function exists in the hidden layer.

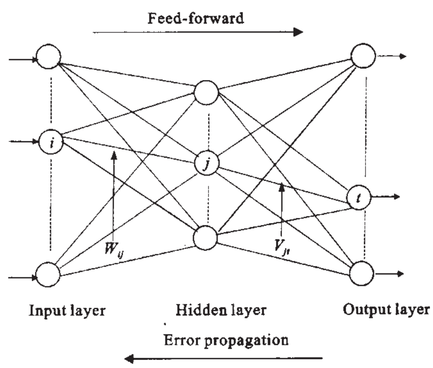

Fig.1 Three-layer BP network structure

3.2 Training BP Network

A neural network must be trained to determine the values of the weights that will produce the correct output. The basic training weight changes move the weights in the direction where the error declines more quickly. Training is carried out by assigning random initial weights to each of the neurons (usually between −1.0 and 1.0) and then presenting sets of known input and target value. The network estimates the output value from the inputs, compares the model predicted output to the target value, and then adjusts the weights in order to reduce the mean squared error between the network output and the target values. Training of the network is accomplished by repeating the feed-forward process alternating with error propagation process until the mean squared error is below a given value (Fig. 2).

There are several optimization methods to improve the convergence speed and the performance of network training (HAYKIN, 1999). In this study, the momentum algorithm was applied to training the network.

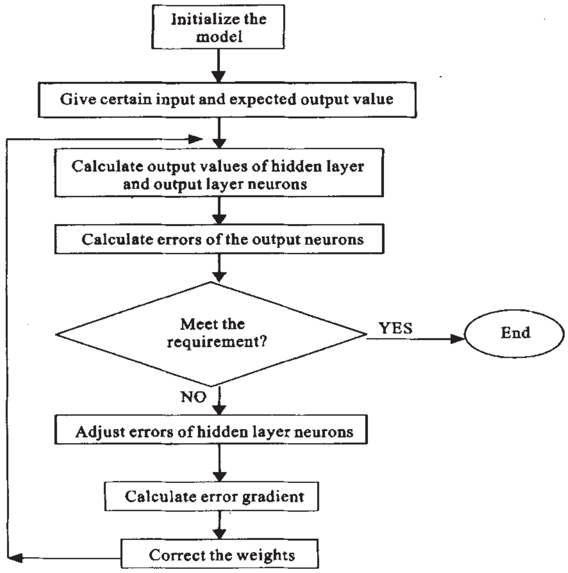

Fig. 2 The flow chart of BP Algorithm

4 CSSD ADJUSTMENT PREDICTION MODEL

The feature that ANN is used to approach arbitrary nonlinear functions makes it feasible to establish a sustainable development adjustment prediction model to manage the complex system. This has value in policy appraisal processes as data on the assumptions of the policy can be fed into the model in order to produce predictions of possible futures.

4.1 Study Area

As the largest coastal metropolitan area in China, Shanghai was chosen as the study area. Situated at the confluence of the Changjiang (Yangtze) River and the East China Sea, Shanghai is rich in nature resources for wildlife, aquaculture and port development. It also has abundant labour resources, oceanic energy resources and tourism resources. The combination of all these resources makes it a region full of special functions such as land accretion as sediment transport by the Changjiang River is deposited in its estuary, freight handling and ecological conservation. During the 1990s, the economy grew dramatically due to the exploitation of these resources. In 1998, GDP in Shanghai reached US$368.8×$10^9$ and surpassed US$3400 per head (Shanghai Statistic Bureau, 1999), which matched the level of a medium developed country. Meanwhile great investment was focused on social development and environmental improvement. Situated on the costal zone, predicting the future development of Shanghai requires the integration of three systems: land, ocean and atmosphere. The frequent, concentrated and sensitive exchange of matter, energy and information on the costal zone makes it become the best epitome of the global system of man-land relation and global environmental change (YANG, 1999). The development process of Shanghai from 1990 to 1999 was used to set up the ANN and make predictions based on the politics contained in the Tenth FYP (2000–2005). Such analysis will examine the regional development planning and policy-making, and provide an example to test integrated policies.

4.2 Research Procedure

A group of 28 indicators were developed by this study to describe sustainable development of Shanghai (SHI, 2001), which are interrelated with each other to illustrate the development of the complex systems. These 28 indicators were identified as meeting 5 criteria:

(1) Independent and representative. Each indicator should be relatively independent and scientifically valid. Each indicator should measure something important in the sub-system, represents and also reflects something important beyond what the indicator itself is, for example, the development status of the sustainable development of the costal zone.

(2) Simple and measurable. All the indicators should be relatively easy to be understood and be quantifiable for measurement and comparison.

(3) Gradation. The whole indicator system should be clearly structured according to the composition of the complex systems. Indicators at different level should be selected to represent the structure of each sub-system and the whole system, and to reflect reliable information for government management at various levels.

(4) Relatively complete and systemic. The indicator system should be as complete as possible and specifically reflect the character of the coastal zone. To evaluate regional sustainable development, not only the status of each sub-system should be assessed, but also the coordination and restriction among each part should be fully considered. Such restricted relationship is one of the important factors that will influence the future regional sustainability. Thus a system approach is emphasized here to fully consider the linkage among the indicators when the indicator system is set up.

(5) Acquirable. The information itself, or the information it is calculated from, should be already available or be able to be made available easily and cheaply (ANDERSON, 1991). In order to obtain objective results, judgment from qualitative analysis should be avoided to decrease any subjective influence to the e-

valuation results.

It is relatively easy to understand and analyze the CSSD if one theme is concentrated on. As Shanghai is located in the coastal zone, water is one of the most important mediums. Water quality closely connects the land and the sea and is significantly influenced by human activities. Water environment improvement was also a focus of regional management in Shanghai during the 1990s. Hence, in the ANN prediction model, water quality was selected as the main thread for interpreting the regional development system, and indicators related to this theme were selected to establish the model. Since only a limited number of indicators have planned objectives in the "Tenth FYP" of Shanghai, seven indicators were selected as main indicators to set up the model. This decision was also driven by the limitations of data availability in published reports and the very close relationship of these indicators with regional water quality. These seven indicators are integrated fresh water quality index (IFWQI), sea water quality index (SWQI), public greenland area per head (PGAPH) and industrial waste water discharge amount per 10 000 yuan (RMB) output value (IWDPOV) reflecting the environment and resources sub-system; gross domestic products per head (GDPPH) reflecting the economic development sub-system, natural birth rate (NBR) and water usage amount per head (WUAPH) reflecting the society sub-system.

IFWQI is an independent index which reflects the general status of fresh water quality and can be calculated by the equations 1 and 2 (The National Environmental Protection Agency, 1993) .

$$A_j=\frac{1}{n}\sum_{i=1}^{n}P_{ij} \quad (1)$$

$$P_{ij}=\frac{C_{ij}}{C_{oi}} \quad (2)$$

where A_j is the IFWQI of river section j, P_{ij} is the individual pollution index of pollutant i of section j, C_{ij} is the monitoring data of pollutant i of section j, and C_{oi} is the criteria of pollutant i in the National Water Quality Standards (NWQS), n is the number of evaluated pollutants. According to the equation an IFWQI over 1 means the monitored data surpass the set criteria in the NWQS, thus the water is defined as polluted.

IFWQI also could be understood as an indicator driven by the other closely related factors within the complex system of regional sustainable development. Therefore, in the model being developed, IFWQI was selected as the predicted output influenced by the other six factors.

The procedure to set up the prediction model using ANN was as following:

(1) Data of each indicator from 1990−1998 were used as the samples for training, and IFWQI for 1999 was used for verification.

(2) The SWQI, IWDPOV, PGAPH, GDPPH, NBR and WUAPH were used as input factors, and IFWQI as the prediction factor to set up the initial model. To eliminate the influence of progression and units, all data were standardized by applying equation 3.

$$x_i'=(x_i-x)/x \quad (3)$$

where x_i' is the indicator data after standardization, x_i' is the real indicator data of year i, x is the average value of all the x_i. All the standardized indicator data from 1990−1999 for Shanghai are listed in Table 1.

(3) The laws of CSSD were regulated in the network after sample learning and training and the prediction model then achieved.

Table 1 Standardized sustainable indicators of Shanghai

Year	GDPPH	WUAPH	NBR	SWQI	IWDPOV	PGAPH	IFWQI
1990	−0.6667	−0.1979	−4.6842	−0.2136	0.7793	−0.4764	0.79
1991	−0.6062	−0.1928	−2.1579	−0.1341	0.5273	−0.4318	0.77
1992	−0.5090	−0.1615	−1.2105	0.2034	0.4104	−0.4057	1.14
1993	−0.3340	−0.1304	−0.1579	0.2660	−0.1838	−0.3723	0.84
1994	−0.1312	−0.1232	0.4736	0.1024	0.0265	−0.2468	0.79
1995	0.0850	0.1676	1.1053	0.2783	−0.1387	−0.0582	0.69
1996	0.2787	0.1761	1.4210	−0.2121	−0.2789	0.0523	0.71
1997	0.4805	0.1837	1.5263	−0.1152	−0.3223	0.3007	0.62
1998	0.6250	0.1669	2.2632	−0.1131	−0.3457	0.6308	0.51
1999	0.7778	0.1094	1.4211	−0.0620	−0.4742	1.0070	0.51

(4) In the adjusted model, data for six influential factors for the year 2005 in the "Tenth FYP" of Shanghai were used to predict IFWQI for the year 2005. This allowed an evaluation of the FYPs to be carried out.

The network programming was done by using the computer software Matlab5 (LOU and SHI, 1998).

4.3 Network Structure

There are 6 input neurons and 1 output neuron in the model. The number of hidden layer neurons was automatically adjusted by the programme. A small number was given initially and if the network falls into the partial minimum, then 1 more neuron are added at a time until the whole network approached to convergence. Finally there were 8 hidden layer neurons in the model and the whole structure is shown in Fig. 3.

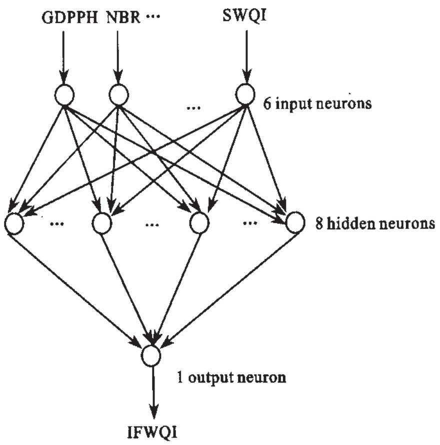

Fig. 3 Network structure of sustainable development adjustment prediction model of the coastal area

4.4 Model Training

The standard three-layer feed-forward back-propagation network, with a nonlinear differentiation log-sigmoid transfer function in the hidden layer, is applied in this study. In the training phase, the network weights were updated in the direction in which the performance function decreased most rapidly. After 1464 time epochs, the predicted IFWQI for 1999 reached 0.5159, while the actual value was 0.51, hence, the relative error is only 1.16%. Such a small relative error indicates that it is feasible to use ANN to establish the CSSD adjustment prediction model. Table 2–4 show the interconnect weights between neurons of the input layer and the hidden layer, the hidden layers and the output layer and the threshold value of neurons in the hidden layer in the model. In addition to these data, the single value for the one output neuron was 0.7293. Having trained the ANN, it could be used to make prediction of possible futures. The data presented were the fixed values for the weights and thresholds in the ANN used in the next phase of this research.

The model after training is the quantitative manifestation of the inner laws in CSSD. It is almost impossible to give quantitative relationships between each of the simulated factors with certainty. However, through the process of training, the information of the system could be expressed by the weights and threshold values, and the model could be used for prediction.

4.5 Application: Assessing the Tenth FYP

The last step in the modeling process shown in Fig. 4 is the application of the model. The development targets set in the "Tenth FYP" of Shanghai for the six influential factors in 2005 were input into the ANN model to predict the IFWQI of 2005. After running the ANN, if the predicted IFWQI was over 1 it means that

Table 2 The interconnect weight (W_{ij}) between input layer neurons (i) and hidden layer neurons (j)

j (hidden layer neurons)	i (input layer neurons)					
	1	2	3	4	5	6
1	−1.3998	10.6125	−0.5501	−6.8552	4.0251	−2.3981
2	−1.3264	−8.9021	0.5491	8.6005	3.6808	−2.6206
3	1.7129	3.1290	0.6117	−6.2769	−2.4386	−3.9228
4	2.9561	−5.4328	−0.2358	5.0807	3.5352	−4.0497
5	−3.1730	−8.3153	0.6647	2.5808	1.8559	3.0065
6	−2.9441	4.8461	0.1633	−5.8684	−3.4640	−3.7965
7	−3.2089	1.3788	−0.3458	−10.3408	0.9966	3.6725
8	−3.1712	13.9568	0.2546	−5.1083	−1.0935	−1.6540

Table 3 The interconnect weight (V_{jt}) between hidden layer neurons (j) and ouput layer neurons (t)

j	1	2	3	4	5	6	7	8
V_{jt}	0.2123	−0.1055	−0.1415	0.5548	−0.0528	0.4393	−0.5061	−0.2059

Table 4 The threshold (θ_j) of hidden layer neurons (j)

j	1	2	3	4	5	6	7	8
θ_j	0.8172	3.2207	−0.8521	−3.1211	−1.6618	−2.0650	−1.8062	−2.7817

water quality exceeds the targeted water environmental protection criteria. After running the ANN the predicted IFWQI was found to be 0.5996. Thus indicating that the social and economic development objectives proposed in the Tenth FYP are reasonable, and will result in fair environmental conditions. However, it should be noted that water environment improvement has been an emphasis of the Shanghai government from 1992 when environmental rehabilitation started. The achievements on the water environment do not suggest that all the environmental factors would meet protection targets of 2005.

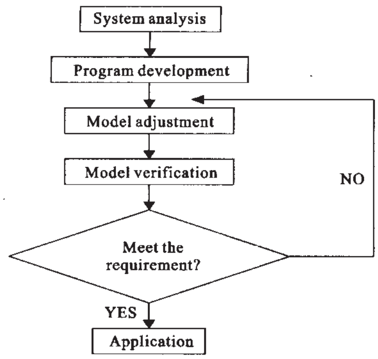

Fig. 4 The flow chart of model development

In order to test this prediction further we must wait for data of 2005. In the meantime work is progressing on the Eleventh FYP (2006–2010). The majority of this plan will be written in 2005 to 2006 using data up to and including 2005. It has been demonstrated here that ANN provides a tool which policy-makers may wish to consider in producing joined-up policies, and which could be used to test elements of the Eleventh FYP during its formulation.

5 CONCLUSIONS

Although only a trial model was set up in this research to study the complex social and environmental system, several conclusions could be obtained from this research.

The main finding is that the technology of ANN can be used for researching complex social and economic systems. The results presented in this paper show that an ANN can be used in solving nonlinear problems, and the development trend of the CSSD could be relatively precisely predicted in the model established by the ANN. One application of the technology can use sample training to simulate the basic laws in the system instead of finding out complicated quantitative relationships between each sub-systems or indicators. The research here demonstrates the feasibility of using ANN to research macroscopic adjustment issues of social and economic system as a system of policy analysis. Only a few indicators were used to establish the model in this research. This reflects the limited data in the public domain. There is no limit for the number of input factors which can be used in an ANN. If enough data could be obtained all the factors influencing the output factor could be used as input values. With more abundant data sources, a more mature model could be established and with this more precise prediction results.

The prediction results from the model could provide scientific foundation for regional development strategies and planning. Generally, the development objective of each sub-system has been set in terms of the development trend of its own or the ideal control value for the sub-system. The coupling relationships among each sub-system in CSSD have not been fully considered. Thus these targets may be suitable for each sub-system individually, but may not be very coordinated in the whole complex system. Using the model demonstrated in this research it is possible to set up more reasonable objectives by utilizing complex system thinking.

The ANN model could be used flexibly in different fields of decision-making. Each sub-system in the CSSD influences and restricts each other, thus each indicator could be used as an influential factors for each other and thus allow the model to be applied in different decision-making fields. In this research, IFWQI is used as the prediction factor to indicate if the social and economic development process of Shanghai is sustainable. This model could also be used to support decision-making in related sub-systems in CSSD, for example, in economic development planning, GDPPH could be set as the forecast factor to analyze economic growth in terms of environmental and social development objectives; and in social development planning, the social progress target could be predicted according to economic and environmental development objectives. There are a lot of application possibilities in the research on CSSD using the ANN. Sustainable development then could be managed, if not totally controlled, to a certain extent.

It should be emphasized that although ANN could be applied in many fields, however, for a complex system like sustainable development, it can not be expected to realize the forecast functions only by ANN. Other scientific analysis methods also should be applied together. The paper just proposed a possible research approach for the complex system of sustainable development.

ACKNOWLEDGEMENTS

The support of the British Council Office in Shanghai and all the conveniences provided by the Telford Institute of Environmental Systems (TIES), University of Salford are gratefully acknowledged.

REFERENCES

ANDERSON V, 1991. *Alternative Economic Indicators* [M]. London: Routledge, 1–128.

CONSTANZA R, WAINGER L, FOLKE C *et al*., 1993. Modeling complex ecological economic systems [J]. *BioScience*, 43: 545–555.

GREINER R, 1999. An integrated modeling system for investigating the benefits of catchment management [J]. *Environmental International*, 25(6/7): 725–734.

HAGAN M T, DEMUTH H, BEALE M, 1995. *Neural Network Design* [M]. Boston: PWS Publishing Company, 1–736.

HAYKIN S, 1999. *Neural Network—a Comprehensive Foundation* [M]. NJ Englewood Cliffs: Prentice-Hall, Inc., 1–842.

HOLLING C S, 1995. What barriers? What bridges? [A]. In: GUNDERSON L H, HOLLING C S, LIGHT S S (Eds.). *Barriers and Bridges to the Renewal of Ecosystems and Institutions* [C]. New York: Columbia University Press, 1–593.

HUANG W, FOO S, 2001. Neural network modeling of salinity variation in Apalachicola River [J]. *Water Research*, 36: 356–362.

HWANG S W,1996. The implications of the nonlinear paradigm for integrated environmental design and planning [J]. *Journal of Planning Literature*, 11: 167–180.

INNES E J, BOOHER D E, 1999. Metropolitan development as a complex system: a new approach to sustainability [J]. *Economic Development Quarterly*,13(2): 141–156.

KAUFFMAN S, 1995. *At Home in the Universe: The Search for the Laws of Self-organization and Complexity* [M]. London: Viking, 1–336.

KAY J J, REGIER H A, BOYLE M *et al*., 1999. Ecosystem approach for sustainability: addressing the challenge of complexity [J]. *Future*, 31: 721–742.

KELLY K, 1994. *Out of Control*: *The Rise of the Neobiological Civilization* [M]. MA Reading: Addison-Wesley, 1–214.

KIEL D, 1991. Lessons from the nonlinear paradigm: application of the theory of dissipative structures in the social sciences [J]. *Social Science Quarterly*, 72: 431–442.

LEWIN R, 1992. *Complexity*: *Life at the Edge of Chaos* [M]. New York: Macmillan, 1–288.

LOU Shun-tian, SHI Yang, 1998. *System Analysis and Design Based on MATLAB*: *Neural Network* [M]. Xi'an: Xi'an Electronics Science and Technology University Press, 1–205. (in Chinese)

NIJKAMP P, VREEKER R, 2000. Sustainable assessment of development scenarios: methodology and application to Thailand [J]. *Ecological Economics*, 33: 7–27.

PEZZEY J, 1989. Economic analysis of sustainable growth and sustainable development [R]. Washington D C: The World Bank.

Shanghai Statistic Bureau, 1999. Shanghai Statistical Yearbook 1999 [R]. Beijing: China Statistics Press. (in Chinese)

SHI Chun, 2001. Establishment of sustainable development adjusting and management model of the coastal zone [D]. Shanghai: East China Normal University. (in Chinese)

The National Environmental Protection Agency, 1993. Technology guideline of environmental impact assessment HJ/T 2.1-2.3 [R]. Beijing: The National Environmental Protection Agency. (in Chinese)

WALDROP M M, 1992. *Complexity*: *the Emerging Science at the Edge of Orders and Chaos* [M]. New York: Simon & Schuster, 1–384.

WESTOBY M, WALKER B, NOY-MEIR I, 1989. Opportunistic management for rangelands not at equilibrium [J]. *Journal of Range Management*, 42: 266–274.

WHEATLEY M, 1992. *Leadership and the New Science*: *Learning about Organization from an Orderly Universe* [M]. San Francisco: Berrett-Koehler, 1–164.

YANG Y K, 1999. The best point of current research on earth science system—the establishment of research framework of the coastal zone [J]. *Progress of Earth Science*, 17(1): 73–79.