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Chinese urbanization 2050: SD modeling and process simulation

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Abstract Is Chinese urbanization going to take a long time, or can its development goal be achieved by the government in a short time? What is the highest stable urbanization level that China can reach? When can China complete its urbanization? To answer these questions, this paper presents a system dynamic (SD) model of Chinese urbanization, and its validity and simulation are justified by a stock-flow test and a sensitivity analysis using real data from 1998 to 2013. Setting the initial conditions of the simulation by referring to the real data of 2013, the multi-scenario analysis from 2013 to 2050 reveals that Chinese urbanization will reach a level higher than 70% in 2035 and then proceed to a slow urbanization stage regardless of the population policy and GDP growth rate settings; in 2050, Chinese urbanization levels will reach approximately 75%, which is a stable and equilibrium level for China. Thus, it can be argued that Chinese urbanization is a long social development process that will require approximately 20 years to complete and that the ultimate urbanization level will be 75–80%, which means that in the distant future, 20–25% of China's population will still settle in rural regions of China.

Keywords Chinese urbanization, System dynamic (SD) model, Scenario simulation

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1. Introduction

Urbanization is a symbol of modernization and is a social transition process that can turn an agricultural country into an industrial and city-oriented country. Parallel to this process is the profound transformation of culture, social structure, employment structure, individual lifestyles, distribution of productivity, and changes in human settlement patterns. Chinese urbanization as a critical national process of social development, economic growth and environmental change, has undergone a rapid evolving pace, turning China's urbanization level from 18% in 1978 to 56.1% in 2015; however, urbanization has also created a series of problems, such as loss of agricultural land, reduction in biodiversity, unaffordable urban housing, problematic transportation, uneven regional economic development, political influences, etc. According to the reports presented at the 18th National Congress of the CPC and the thirteenth Five-Year Plan, urbanization has been set as the central task for China to be completely recognized as a well-developed society by 2020. However, is Chinese urbanization going to take a long time, or can its development goal be achieved by the government in a short time? What is the highest stable urbanization level that China can reach? When can China complete its urbanization? All of these questions cannot be answered without comprehensive and scientific exploration.

2. Review of relevant literature

Early research (Gu, 1992: 348–350) on Chinese urbanization by the Logistic model predicted that China's urbanization level would reach 61% in 2010, 65% in 2030, 69% in

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2040 and 73% in 2050. According to Chan and Hu (2003), in 2050 it is likely that the level will reach 60–66%. It is understandable that, using different approaches, the predicted urbanization levels in certain years can be different. For instance, by referring to the relationship between per capita GDP and the urbanization level in foreign countries, Chen et al. (2013) concluded that the urbanization level in China would be 59–60% in 2020 and approximately 68–70% in 2030. The Research Group of New Urbanization with Chinese Characteristics (Xu, 2013) applied a quantitative analysis of the transfer of the agricultural labor force to non-agricultural industries, the newborn population number, and the new rural labor force to the projection. They claimed that the urbanization level would reach 60% in 2020 and 65% in 2033. An integrated method, which combines curve fitting, economic modeling and growth rate of the ratio of the urban-rural population, led to the conclusion that in 2030 China's level of urbanization would be 68.38% and in 2050 it would be 81.63% (Gao and Wei, 2013).

In the "*National New Urbanization Plan (2014–2020)*", the goal for Chinese urbanization level in 2020 was set to 60%. However, the China Research Team at the Economist Intelligence Unit (2014) proposed that the urbanization level should be 61% in 2020 and 67% in 2030. By reviewing the literature at home and abroad, Hu (2013) concluded that China would have an urbanization rate of 58–63% in 2020 and 60–79% in 2050. In "*Urban China: Toward efficient, inclusive, and sustainable urbanization*" prepared by the World Bank and the Development Research Center of the State Council (China) (2014), in 2030 China's urbanization rate will be 66% without changing the current urbanization policies, and 70% in a reformation scenario. The differences between the predicted urbanization levels by different research agencies and scholars, as has been noted, is significant and, as a result, incurs the question of which conclusion to follow while formulating China's national policies of economic development agenda.

By referring to relevant theories and observed evidence, specialists in urbanization from all over the world have built a series of prediction models and simulation models for urbanization. Prior to the 1950s, the main prediction/modeling approach was time series analysis, which relied on trend extrapolation by methods such as arithmetic average, weighted average sequence, moving average, weighted moving average, trend forecasting and exponential smoothing based on historical time series data. In the 1960s and 1970s, static demographical analysis entered the analysis domain with demographical statistics and linear analysis at its core. Northam (1975), an American urban geographer, proposed "Northam's Curve" after exploring the development of urbanization levels in developed countries using a logistic regression. From the 1980s onwards, research on urbanization was fundamentally influenced and improved by systems science, operations research and metrology. Systems approaches such as synergy theory and self-organization theory were introduced to urbanization studies on topics such as population distribution, industry evolution, facility distribution, spatial patterns of traffic behavior and urban simulation models (Zeleny, 1980; Batten, 1982; Allen et al., 1984; Pumain et al., 1986).

In the 1990s, the means to acquire urbanization data was significantly improved, which further facilitated the advance of urbanization research. What was available not only included a multi-scale earth observation system and network capable of monitoring natural data but also databases of multiple types and agencies specializing in the acquisition and processing of socio-economic data. These developments, as a result, fundamentally improved the precision and scientific process of examining Chinese urbanization. In a book published in 2000, Portugali (2000) systematically explained the concept of the self-organizing city based on the principle of self-organization and synergy and proposed the framework of Free Agents in a Cellular Space (FACS). In a GIS modeling environment, Batty (2005) successfully applied fractal theory, cellular automata and agent-based modeling to the simulation, as well as visualization of the spatiotemporal dynamics of cities. SWARM, a modeling package developed by the Santa Fe Institute, is one of the most widely used modeling platforms for scholars to apply agent-based modeling to urban studies (Li, 2011). For instance, in China, Xue and Yang (2002), Xia et al. (2002), and Shen and Wu (2006) have presented models of urban spatial economics and urban transportation built up in SWARM. The most recently reported Multi-Agent System (MAS) integrated with GIS was developed by Li and Gu (2015): a dynamic geo-simulation model dealing with emergency response for urban public security. As a further step in this research stream, this paper probes the complex system of Chinese urbanization by system dynamic (SD) modeling expecting to generate more scientific, more precise and more reliable conclusions to serve as a reference for macro national policy making.

3. SD model for Chinese urbanization

System dynamics modeling provides the solution to practical problems by integrating qualitative and quantitative analysis (Wang, 1994), which reduces subjectivity in analysis and shifts modeling from static simulation to dynamic simulation (Jia and Ding, 2002). In addition, the structure of the system dynamics model is flexible rather than fixed, which enables combinations of dynamics of sub-systems as well as comparative analyses of different solutions (He et al., 2006). Forrester was the first to study the interactions between natural resources, technology and economic sectors (Meadows et al., 1972; Georgiadis and Besiou, 2008). In the 1970s, Forrester, together with the Club of Rome, published *World Dynamics* (Forrester, 1971) and *The limits to growth* (Meadows et al., 1972). Since then, SD modeling has been booming and is widely applied to the fields of earth science, economics, resource studies and urban and regional research. For example, it has been adopted to study urban systems and urban land-use expansion (Wolstenholme, 1983; Mohapatra et al., 1994; Guo et al., 2001; He et al., 2005; He et al., 2006; Liu et al., 2007; Shen et al., 2007; Chang et al., 2008), to explore the coupling of urbanization and the eco-system (Bockermann et al., 2005; Jin et al, 2009; Zhou and Mi, 2009; Egilmez and Tatari, 2012), to examine single-element systems (Cai, 2008; Armah et al., 2010; Venkatesan et al., 2011; Guan et al., 2011; Qiu et al, 2015) and large complex systems (Haghshenas et al., 2015; Xu and Coors, 2012; Tong and Dou, 2014; Ying et al., 2015) by SD modeling.

3.1 Model boundary and structure

The SD model needs to be built within a closed-system boundary, within which system interactions occur, giving the system its characteristic behavior (Forrester, 1969). Therefore, to build the SD model of Chinese urbanization, it is fundamental to define the model boundary.

The urbanization mechanism in China varies across different periods. From the start of the reform and opening policy at the end of 1970s to the middle of the 1990s, China's urbanization was predominantly driven by the growth of a surplus rural labor force, the rapid development of the urban tertiary industry, and the disparity between urban and rural education. Henceforth, the mechanism of Chinese urbanization diversified, with increasing driving forces emerging from the circulation system, foreign investment and trade, and construction of urban infrastructure. The circulation system referred to the movements of both goods and people; foreign investment deeply impacted China's production system, and foreign trade contributed to the total GDP China achieved. Construction of urban infrastructure mainly related to the building of urban water supply and transportation services.

The mechanism of China's urbanization, in fact, is far more complex than what has been recounted above. In rural China, there are thousands of township enterprises. These enterprises have contributed to the employment of the surplus rural labor force. Thus, these employed rural populations engaged not only in agricultural production but also in the production of goods and services subject to the secondary and tertiary industries. In this regard, we need to treat the production systems of the secondary and tertiary industries in rural China as one important part of the dynamic system of Chinese urbanization. Moreover, environmental problems caused by resource exploitation have deeply impacted people's lives, production activities, and migration behaviors. Therefore, the environmental system (water, air and solid waste) should be integrated into the SD model of Chinese urbanization as an indispensable part so that the urbanization mechanism can be well modeled and interpreted.

In addition, the sub-system of energy should also be considered, as without its support, the rural living system and the rural production system cannot operate properly. Moreover, the fossil fuel consumed by the energy production system can generate CO_2. This is a key factor contributing to global warming, climate change and the rising of sea levels, which in turn influence urbanization in coastal regions. Despite the importance of these aspects, the influence that comes from urban and rural sanitary conditions, food production, investment resources, land policies, fiscal policies, agricultural production policies and family plan policy should not be overlooked. These elements exert their power mainly upon two crucial sub-systems of the dynamics of Chinese urbanization: the population system and the production system. All of these elements constitute the basic sub-systems of the SD model of Chinese urbanization. The range of these sub-systems is what the boundary of the SD model refers to.

By synthesizing these sub-systems, including population, industry, capital, infrastructure, social facilities and environment, we have proposed the model framework as depicted by Figure 1. In addition, Table 1 lists all of the parameters of the SD model. As it is difficult to describe the industrial restructuring process and its influence upon urbanization directly, in the model we instead examine the change of the factors of production in the primary, secondary and tertiary industries. By considering the redistribution of capital and labor force, the two key production factors in the three industries, it is then possible to capture the overall structural change and value change of the three industries. These changes, in turn, exert an influence upon the urbanization process by transferring more people to the urban population, most of whom are engaged in the secondary and tertiary industries.

3.2 Variables and parameters of the SD model

By referring to the critical elements in all the sub-systems, the key performance indicators are depicted in Table 1. In SD modeling terms, these parameters can be classified into three types: stocks, flows, and auxiliaries. Table 1 gives details of the notation, meaning, type and unit of each of these parameters.

3.3 Causal-Loop diagram

The structure of a system in SD methodology is exhibited using a causal-loop diagram (CLD) (Georgiadis et al., 2005), which reflects the major feedback mechanisms in the system (Appendix 1 (available at http://earth.scichina.com)). Figure 1 shows the causal-loop diagram of the Chinese urbanization SD models, within which the cause and effect relationships among parameters are clarified.

Table 1 List of parameters of the Chinese urbanization SD model

Variable notation	Variable meaning	Variable unit	Variable notation	Variable meaning	Variable unit
CSRK	Urban population	10000	DYCYCZ	Output value of primary industry	100 million Yuan
NCSRKZC	Annual growth of urban population	10000/year	DYCYZDCZ	Maximum output value of primary industry	100 million Yuan
NCSRKDJ	Annual decrease of urban population	10000/year	DYCYCZZCL	Growth rate of the output value of primary industry	No unit
CSJKYXYZ	Influence factors of urban health	No unit	DYCYZCZ	Output value of primary industry	100 million Yuan
CSRKSWL	Urban population death rate	No unit	NCGD	Rural arable land	10000 ha
CSRKCSL	Urban population birth rate	No unit	DYCYZBCL	Capital stock of primary industry	100 million Yuan
CSJHSYYXYZ	Influence factor of urban family planning	No unit	DYCYZBCLBL	Percentage of the capital stock of primary industry	No unit
ZDRKCZL	Maximum population capacity	10000	CSSCZZ	Urban gross product	100 million Yuan
CSJYYZ	Urban education factor	No unit	GNSCZZ	GDP	100 million Yuan
CSZXXSZZCXS	Growth index of urban primary and secondary teachers	No unit	DECYCZ	Output value of secondary industry	100 million Yuan
CQCSJYSZSP	Initial level of teachers for urban education	1/10000	DECYZDCL	Maximum output value of secondary industry	100 million Yuan
CSZXXWMXS-YYJSS	Number of urban primary and secondary school teachers per 10000 students	1/10000	DECYCZZCL	Growth rate of the output value of secondary industry	No unit
CSZXXXSS	Number of urban primary and secondary school students	10000	CSDECYZBCL	capital stock of urban secondary industry	100 million Yuan
CSZXXJSS	Number of urban primary and secondary school teachers	10000	DECYZBCLBL	Percentage of capital stock of secondary industry	No unit
JYYZ	Education factor	No unit	NDECYZCZ	Annual value added of secondary industry	100 million Yuan /year
CSCYLDLXQ-ZCXS	Growth index of the demand of labor force in urban industries	No unit	DECYCYRYZCL	Growth rate of labor force of secondary industry	No unit
CSCYLDLXQYZ	Factor of the demand of labor force in urban industries	No unit	DECYLDLZJL	Increment of labor force of secondary industry	10000/year
CSCYLDLXQ	Demand of labor force in urban industries	10000	DECYLDL	labor force of secondary industry	10000
CQCSCYLDLXQ	Initial demand of labor force in urban industries	10000	DECYCYXS	Employment index of secondary industry	No unit
YLYZ	Medical factor	No unit	ZZBCL	Total capital stock	100 million Yuan
CQCSWRYYYSS	Initial number of doctors per 10000 citizens	1/10000	JLL	capital accumulation rate	No unit
CSYSS	Number of urban doctors	10000	ZZBCLNZJL	Annual increment of total capital stock	100 million Yuan /year
CSWRYYYSS	number of doctors per 10000 citizens	1/10000	SJDECYCZZCL	Real growth rate of the output value of secondary industry	No unit
CSWEYYYSS-ZCXS	Growth index of the number of doctors per 10000 citizens	No unit	DECYLD-SCLZCL	Growth rate of labor productivity of secondary industry	No unit
CSYLSP	Urban medical level	No unit	DECYLDLXQ	Labor demand of secondary industry	10000
DSCYLLDL	Labor force of tertiary industry	10000 person	DSCYCZ	Output value of tertiary industry	100 million Yuan
DSCYCYXS	Employment index of tertiary industry	No unit	DSCYZDCZ	Maximum output value of tertiary industry	100 million Yuan

(*To be continued on the next page*)

(*Continued*)

Variable notation	Variable meaning	Variable unit	Variable notation	Variable meaning	Variable unit
DSCYCYRYZCL	Growth rate of the number of employees in tertiary industry	No unit	CSDSCYZBCL	capital stock of urban tertiary industry	100 million Yuan
DSCYLDLZJZ	Increment of labor force in tertiary industry	10000/year	DSVCYZBCLBL	Percentage of capital stock of tertiary industry	No unit
NYLDSCL	Agricultural labor productivity	Yuan/person	NDSCYZC	Annual value added of tertiary industry	100 million Yuan/year
NYLDLXQ	Demand of agricultural labor force	10000 person	SJDSCYCZZCL	Real growth rate of the output value of tertiary industry	No unit
NYLDSCLZCSD	Growth rate of agricultural labor productivity	No unit	DSCYLDLXQ	Demand of labor force of tertiary industry	10000
NYLDLZCSD	Growth rate of the number of agricultural labor force	No unit	DSCYCZZCL	Growth rate of the output value of tertiary industry	No unit
NYLDLQYSD	Migration speed of agricultural labor force	No unit	DSCYLD-SCLZCL	Growth rate of the labor productivity of tertiary industry	No unit
NNYLDLZC	Annual growth of agricultural labor force	10000	NCRK	Rural population	10000
NYLDLXS	Index of agricultural labor force	No unit	NNCRKZC	Annual growth of rural population	10000/year
NYLDLTR	Input of agricultural labor force	10000	NNCRKDJ	Annual decrease of rural population	10000/year
CSHLYZ	Factor of urbanization	No unit	NCJHSYYXYZ	Influence factor of rural family planning	No unit
NCRKCSL	Birth rate of rural population	No unit	NCJKYXYZ	Influence factor of rural health	No unit
ZRK	Total population	10000	NCRKSWL	Death rate of rural population	No unit
CSHL	Urbanization rate	%			

3.4 Stock and flow diagrams

The causal-loop diagram of the sub-systems can be assembled into a stock and flow diagram, including main factors and subsystems such as industries, population, cities and towns, education, etc. (Figure 2). Stock variables reflect the results of accumulation, which illustrate the states of the system, while flow variables are adopted to capture the redistribution process of stocks, depicting the flows in the system. Supported by packages such as DYNAMO, iThink, Vensim® and Powersim®, it is possible that the theorized Chinese urbanization process illustrated by Figure 1 can be modeled using SD methodology.

3.5 Equations in the Chinese urbanization SD model

Economic growth is the foundation of economic development, and the advancement of labor productivity is the core of this process. Changes to both factors can fundamentally influence labor demand. To describe this relationship, the mathematical model proposed by Zhou (1994), which explores the interactions between economic growth rate, labor productivity, and labor force demand of different urban industrial sectors, is applied to this SD model. Moreover, with the development of agricultural labor productivity, the surplus agricultural labor will be turned into working force in urban sectors, such as industries, transportation, business, education, etc. The net labor force transferring rate in this process is closely related to the scale of agricultural production and the increase rate of agricultural labor productivity (Yuan et al., 1987). Considering these relationships, the equations in this Chinese urbanization SD model are formulated based on the Cobb-Douglas production function, and Table 2 gives details of the equations for each of three sub-systems: the economic sub-system, the population sub-system and the social service sub-system. Within the SD model, the dynamics of Chinese urbanization are described by the combination of both linear and nonlinear equations. Thus, the nonlinearity of Chinese urbanization is captured by and embedded in the SD model, which fundamentally improves the objectivity of the urbanization rate predicted by this model. In addition, the model's accuracy in simulating Chinese urbanization can be further enhanced by iterative parameter calibration and model validation against real collected data.

4. Validation of the Chinese SD model

Validation of a system dynamics model generally consists of two aspects: structural validation and a sensitivity test. Structural validation of the model seeks to determine whether it highly conforms to the real world. A sensitivity test, on the

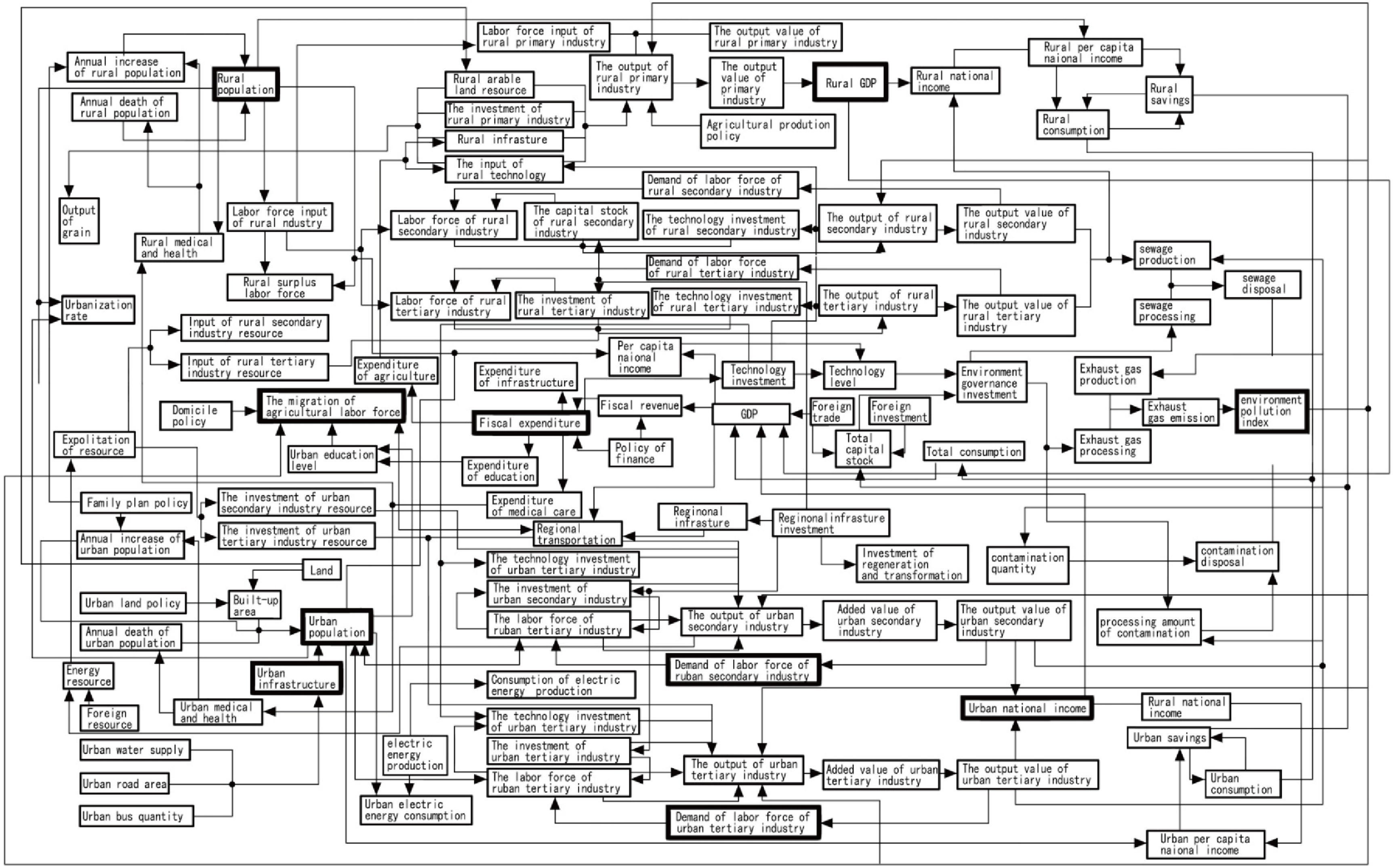

Figure 1 Causal loop diagram of the SD model of Chinese urbanization.

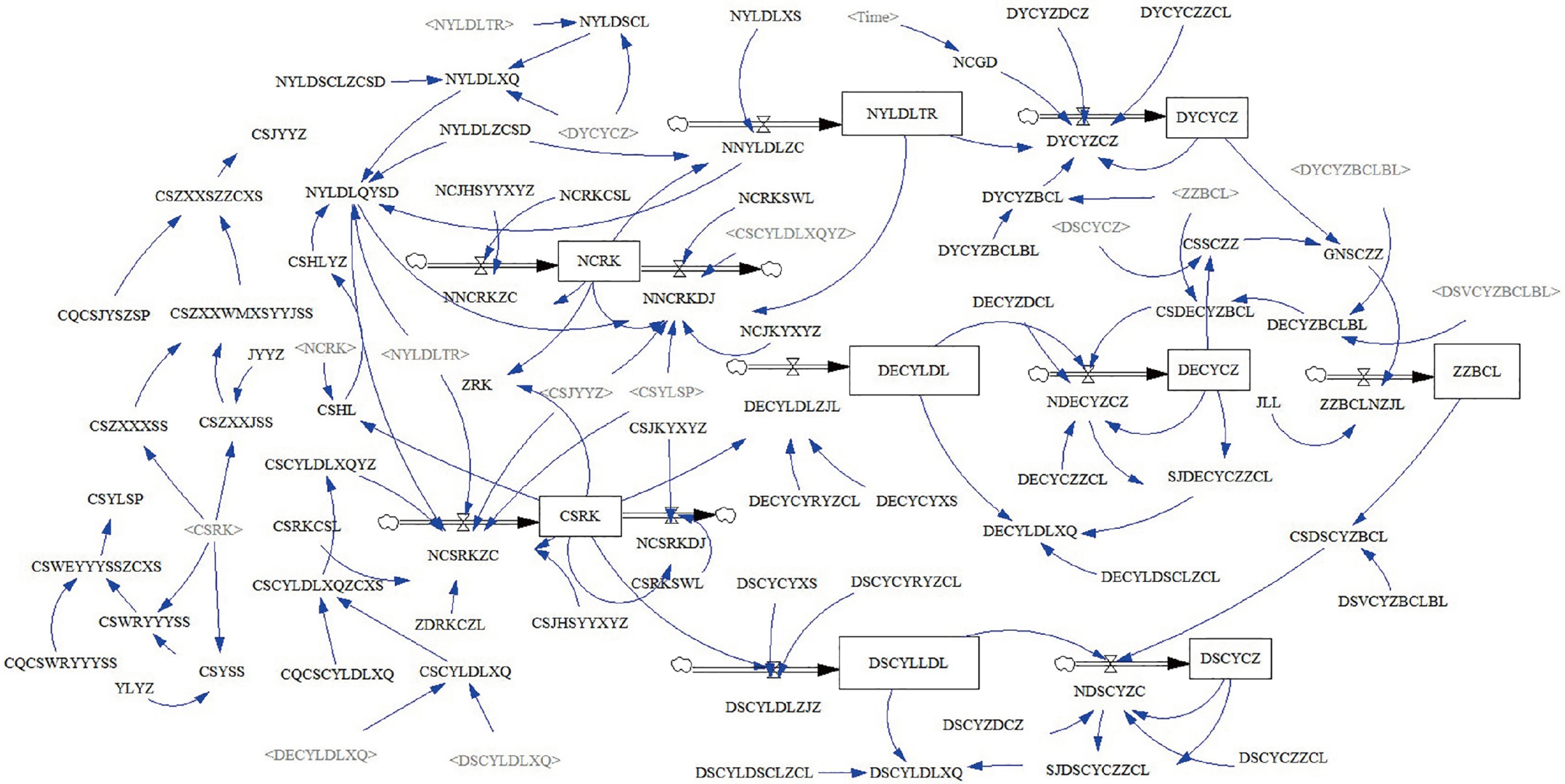

Figure 2 Stock and flow diagram of the SD model of Chinese urbanization.

Table 2 The groups of equations of the Chinese urbanization SD model

Sub-system	Main equation
1. The main equations of the economic sub-system	DYCYZCZ=DYCYCZZCL*(1−DYCYCZ/DYCYZDCZ)*EXP(10.5)*(NCGD^(0.4589))*(NYLDLTR^(−0.743)*DYCYZBCL^0.24) DYCYZBCL=ZZBCL*DYCYZBCLBL CSDECYZBCL=DECYZBCLBL*ZZBCL NDECYZCZ=DECYCZZCL*(1−DECYCZ/DECYZDCL)*EXP(1.003)*(DECYLDL^(−0.1958))*(CSDECYZBCL^0.967) ZZBCLNZJL=GNSCZZ*JLL CSDSCYZBCL=DSVCYZBCLBL*ZZBCL DECYLDLZJL=CSRK*DECYCYRYZCL*DECYCYXS DSCYLDLZJZ=CSRK*DSCYCYXS*DSCYCYRYZCL NDSCYZC=DSCYCZZCL*(1−DSCYCZ/DSCYZDCZ)*EXP(−8.76)*(DSCYLLDL^(1.095))*(CSDSCYZBCL^0.6766) DECYLDLXQ=DECYLDL*(1+SJDECYCZZCL−DECYLDSCLZCL) SJDECYCZZCL=NDECYZCZ/(DECYCZ−NDECYZCZ) DSCYLDLXQ=DSCYLLDL*(1+SJDSCYCZZCL−DSCYLDSCLZCL) SJDSCYCZZCL=NDSCYZC/(DSCYCZ−NDSCYZC) CSCYLDLXQZCXS=CSCYLDLXQ/CQCSCYLDLXQ GNSCZZ=DYCYCZ+CSSCZZ CSSCZZ=DECYCZ+DSCYCZ NNYLDLZC=NYLDLXS*NCRK*NYLDLZCSD
2. The main equations of the population sub-system	NNCRKZC=NCRKCSL*NCRK*NCJHSYYXYZ NNCRKDJ=NCRKSWL*NCJKYXYZ*NCRK+NYLDLTR*NYLDLQYSD*CSJYYZ*CSCYLDLXQYZ*CSYLSP NCRK=NNCRKZC−NNCRKDJ NNYLDLZC=NYLDLXS*NCRK*NYLDLZCSD NCSRKZC=(1−CSRK/ZDRKCZL)*(CSRKCSL*CSRK*CSJHSYYXYZ+CSCYLDLXQYZ*NYLDLQYSD*NYLDLTR*CSJYYZ*CSYLSP) NCSRKDJ=CSRKSWL*CSJKYXYZ*CSRK CSRK=NCSRKZC−NCSRKDJ CSHL=CSRK*100/(CSRK+NCRK) CSCYLDLXQZCXS=CSCYLDLXQ/CQCSCYLDLXQ
3. The main equations of the social service sub-system	CSZXXJSS=JYYZ*(0.00705*CSRK+105.995) CSZXXWMXSYYJSS=(CSZXXJSS*10000)/CSZXXXSS CSZXXSZZCXS=CSZXXWMXSYYJSS/CQCSJYSZSP CSZXXXSS=0.027943*CSRK+1976.11 CSYSS=YLYZ*(0.010885*CSRK−257.88) CSWRYYYSS=CSYSS*10000/CSRK CSWEYYYSSZCXS=CSWRYYYSS/CQCSWRYYYSS

other hand, aims to verify model stability and assesses its degree of confidence.

4.1 Structural validation

Prior to structural validation, the preliminary values of the model's variables were examined and defined by referring to real data. In addition, the dimensional consistency of all involved variables was tested to ensure the model's accuracy (Sterman, 2000). Then, through structural verification and extreme condition analysis, structural validity was examined by checking the simulated data against real historical data, to ascertain the reliability and accuracy of the model (Xu and Sun, 2008).

The complexity of China's urbanization requires the use of a series of variables to describe China's urbanization process. To illustrate the structural validity of the model, this paper focuses on the validation results of nine key variables by checking the simulated values against data from 1998 to 2013. These nine variables consist of the urbanization rate; total population; GDP; the output value of the primary, secondary, and tertiary industries (price in 1990); and the labor force of each of these three industries. Table 3 give details of the validation outcomes.

The average error rate of each of the nine variables, as depicted by Tables 3, does not exceed 10%. In addition, the average difference rate between the simulated urbanization level and the real urbanization level from 1998 to 2013 is only 0.774%. This indicates that what the model describes and simulates are congruent with China's urbanization process, which justifies the model's conformity, credibility and robustness. By visualizing the real data and the simulated data as shown in Figure 3, one observes that the simulated urbanization levels have a very close fitness to real levels, which means that this SD model is applicable to the simulation and forecasting of China's urbanization process.

4.2 Sensitivity analysis

The purpose of the sensitivity analysis is to verify the level of influence caused by the change of the model structure and/or values of model parameters (Jia and Ding, 2002). Generally,

Table 3 Model validation against historical data

Year	Urbanization rate (%)			Total population (10000)			GDP (price in 1990)		
	Simulated value	Real value	Error rate	Simulated value	Real value	Error rate	Simulated value	Real value	Error rate
1998	33.35	33.35	0.001	124761	124761	0.000	42876.6	42877.45	0.002
1999	34.37	34.78	1.191	125692	125786	0.075	46608.1	46144.64	1.004
2000	35.54	36.22	1.881	126590	126743	0.121	50810.3	50035.22	1.549
2001	36.89	37.66	2.033	127446	127627	0.142	55518.5	54188.31	2.455
2002	38.35	39.09	1.884	128267	128453	0.145	60772.9	59109.73	2.814
2003	39.82	40.53	1.744	129065	129227	0.125	66618.6	65035.7	2.434
2004	41.33	41.76	1.035	129834	129988	0.118	73105.8	71594.58	2.111
2005	42.83	42.99	0.370	130579	130756	0.135	80290.3	79691.95	0.751
2006	44.32	44.34	0.041	131302	131448	0.111	88233.5	89794.12	1.738
2007	45.8	45.89	0.205	132004	132129	0.095	97002.8	102511.1	5.373
2008	47.22	46.99	0.489	132692	132802	0.083	106672	112387.7	5.086
2009	48.59	48.34	0.507	133368	133450	0.061	117321	122743.4	4.418
2010	49.90	49.95	0.107	134035	134091	0.042	129038	135566.3	4.816
2011	51.15	51.27	0.230	134694	134735	0.030	141917	148173.9	4.223
2012	52.37	52.57	0.383	135340	135404	0.047	156060	159512.8	2.165
2013	53.55	53.70	0.283	135976	136072	0.071	171577	171749.3	0.100
Average error rate	–	–	0.774	–	–	0.088	–	–	2.565

Year	Output value of primary industry (100 million Yuan) (price in 1990)			Output value of secondary industry (100 million Yuan) (price in 1990)			Output value of tertiary industry (100 million Yuan) (price in 1990)		
	Simulated value	Real value	Error rate	Simulated value	Real value	Error rate	Simulated value	Real value	Error rate
1998	7527	7527.545	0.007	19814.6	19814.63	0.000	15535	15535.27	0.002
1999	7947.74	7600.134	4.574	21377	21114.43	1.244	17283.3	17430.08	0.842
2000	8388.59	7536.823	11.301	23161.9	22974.44	0.816	19259.8	19523.96	1.353
2001	8849.73	7798.631	13.478	25185.5	24467.49	2.935	21483.3	21922.18	2.002
2002	9331.45	8123.301	14.873	27466.2	26475.13	3.743	23975.3	24511.3	2.187
2003	9834.12	8322.848	18.158	30024.2	29896.24	0.428	26760.3	26816.61	0.210
2004	10358.2	9588.764	8.024	32881.8	33094.84	0.644	29865.8	28910.97	3.303
2005	10904.1	9661.073	12.866	36063.6	37747.17	4.460	33322.6	32283.7	3.218
2006	11472.4	9979.227	14.963	39596.4	43054.94	8.033	37164.7	36759.95	1.101
2007	12063.7	11040.15	9.271	43509.7	48527.52	10.340	41429.4	42943.46	3.526
2008	12678.6	12060.97	5.121	47835.2	53324	10.293	46158	47002.76	1.797
2009	13317.8	12683.26	5.003	52607.8	56758.44	7.313	51395.6	53301.66	3.576
2010	13981.9	13685.72	2.164	57864.8	63267.86	8.540	57191.1	58612.76	2.426
2011	14671.6	14872.45	1.350	63647	69032.21	7.801	63598	64269.2	1.044
2012	15387.8	16082.28	4.318	69998	72210.78	3.064	70673.7	71219.71	0.767
2013	16131.3	17196.81	6.196	76965.1	75386.28	2.094	78480.4	79166.2	0.866
Average error rate	–	–	8.229	–	–	4.484	–	–	1.764

Year	Input of agricultural labor force			Labor force of secondary industry			Labor force of tertiary industry		
	Simulated value	Real value	Error rate	Simulated value	Real value	Error rate	Simulated value	Real value	Error rate
1998	35177	35177	0.000	16600	16600	0.000	18860	18860	0.000
1999	34466.4	35768	3.639	16922.8	16421	3.056	19335.1	19205	0.677
2000	33761.4	36043	6.329	17258	16219	6.405	19828.3	19823	0.025
2001	33064.1	36399	9.161	17607	16234	8.459	20342	20165	0.879
2002	32376.8	36640	11.635	17971.9	15682	14.603	20878.9	20958	0.378
2003	31701.1	36204	12.438	18353.6	15927	15.236	21440.6	21605	0.759
2004	31037.4	34830	10.888	18752.4	16709	12.227	22027.4	22725	3.069
2005	30386.4	33442	9.137	19168.7	17766	7.896	22640.1	23439	3.409
2006	29748.5	31941	6.863	19602.6	18894	3.748	23278.7	24143	3.580
2007	29123.8	30731	5.230	20054.2	20186	0.653	23943.2	24404	1.888
2008	28512.3	29923	4.716	20523.2	20553	0.147	24633.5	25087	1.809
2009	27913.8	28890	3.381	21009.4	21080	0.336	25348.9	25857	1.966
2010	27327.8	27931	2.158	21512.1	21842	1.511	26088.8	26332	0.925
2011	26753.9	26594	0.601	22031	22544	2.276	26852.4	27282	1.575
2012	26191.7	25773	1.625	22565.6	23241	2.906	27639.1	27690	0.184
2013	25640.8	24171	6.081	23115.5	23170	0.235	28448.4	29636	4.007
Average error rate	–	–	5.868	–	–	4.981	–	–	1.571

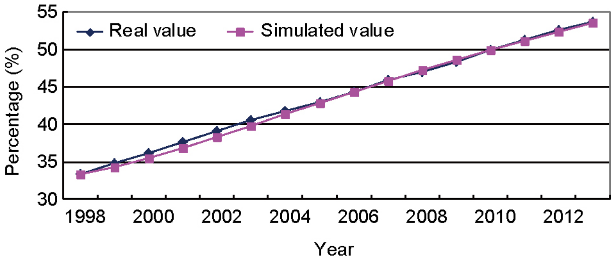

Figure 3 Simulated urbanization rate against real urbanization rate from 1998 to 2013.

the outputs of a robust model should have low sensitivity to most parameters. However, a model's robustness cannot ensure good performance regarding sensitivity, which is the basis for model improvement and optimization (Zhang et al., 2008). Formulas (1) and (2) are the general expressions of the measurement of the sensitivity level of a certain parameter.

$$S_Q = \left| \frac{\Delta Q_{(t)}}{Q_{(t)}} \cdot \frac{X_{(t)}}{\Delta X_{(t)}} \right|, \qquad (1)$$

$$S = \frac{1}{n}\sum_{i=1}^{n} S_{Q_i}, \qquad (2)$$

where t means time t, $Q_{(t)}$ is the value of Q at time t, $X_{(t)}$ is the value of X at time t, S_Q is the sensitivity level of status variable Q to parameter X, $\Delta Q_{(t)}$ and $\Delta X_{(t)}$ are the increments of variable Q and parameter X at time t, n is parameter for status variables, S_{Q_i} is the sensitivity level of variable Q_i, and S is the average sensitivity level of parameter X.

For sensitivity analysis, 22 variables are selected to confirm their influence levels towards the simulated urbanization rate (Table 3). The method is to check the resultant change in the urbanization level when the value of each of the 22 variables decreases or increases by 10% annually from 1998 to 2050 (Pei et al., 2010; Xue et al., 2011). According to eq. (1), each variable's sensitivity towards the urbanization rate for each annual variation can be calculated to express conditions of both an "increase by 10%" and a "decrease by 10%", thus producing 44 sensitivity values. Then, with eq. (2), it is possible to calculate the average sensitivity level of a certain variable, which can be regarded as its influence level upon the simulated urbanization rate (Table 4).

The results presented in Table 4 demonstrate that only four of the 22 variables have a sensitivity higher than 10%, which include birth rate of rural population, influence factor of rural family planning, education factor, and growth rate of agricultural labor productivity. This indicates that the simulated urbanization rate is insensitive to the majority of variables, and that the driving forces for China's urbanization in the next 35 years will mainly come from the transformation of agricul-

Table 4 The results of sensitivity analysis

Variable	Average sensitivity by increasing 10%	Average sensitivity by decreasing 10%	Variable	Average sensitivity by increasing 10%	Average sensitivity by decreasing 10%
Birth rate of rural population	11.49	10.98	Birth rate of urban population	3.78	3.83
Influence factor of rural family planning	11.49	10.98	Influence factor of urban family planning	3.78	3.83
Education factor	23.68	5.99	Medical factor	6.1	7.93
Influence factors of rural health	3.95	4.01	Influence factors of urban health	1.94	1.95
Growth rate of the output value of primary industry	0.004	0.004	Growth rate of the output value of secondary industry	0.86	0.87
Growth rate of the output value of tertiary industry	1.36	1.38	Growth rate of labor force of primary industry	8.35	8.07
Growth rate of labor force of secondary industry	0.35	0.36	Growth rate of labor force of tertiary industry	0.59	0.62
Growth rate of agricultural labor productivity	25.58	27.37	Growth rate of the labor productivity of secondary industry	0.66	0.67
Growth rate of the labor productivity of tertiary industry	0.97	0.96	Maximum urban population	2.57	3.11
Maximum output value of primary industry,	0	0	Maximum output value of secondary industry,	0.01	0.01
Maximum output value of tertiary industry	0.01	0.02	Accumulation rate	0.34	0.34

tural productivity, quality of education, and the development of the rural population, with the transformation of agricultural productivity as the most influential one.

The results of both structural validation and sensitivity analysis show that the SD model presented above is not only robust, accurate and credible but also stable and effective. Thus, it can be concluded that this SD model can be applied to the exploration of practical issues such as the prediction of China's urbanization rate and the assessment of China's urbanization policies.

5. Simulation and results

5.1 Data resources

Since the reform and opening its policy, China's economy has developed at an unprecedented rate. In 1978, China's GDP was 364.52 billion Yuan, while in 2012 it increased dramatically to 51.8942 trillion Yuan. During this same period, China's per capita GDP also increased tremendously from 381 Yuan per capita in 1978 to 38.4 thousand Yuan per capita in 2012. Parallel to this economic boom is China's rapid urbanization, with the urbanization rate increasing from 17.92% in 1978 to 52.57% in 2012. In recent years, the increase of the urbanization rate has been even higher at 1.4% per year, which means that China has already entered the stage of rapid urbanization as described by Northam's Curve.

The data required to build and validate the SD model was collected from "*China Compendium of Statistics 1949–2008*", and "*China Compilation of Historical Statistics of Provinces*, *Autonomous Regions and Municipalities 1949–1989*", as well as the "*China Statistical Yearbook*", the "*China City Statistical Yearbook*", "*China County Statistical Yearbook*", and "*Statistical Yearbook of the Chinese Investment in Fixed Assets*" for all examined years. Since the requisite data pertaining to Hong Kong, Macau, and Taiwan are unavailable, the geographical territory covered by the SD model only pertains to mainland China.

5.2 Data property and data type

In a period of socio-economic transformation, China's urbanization mechanism is influenced by many factors, including not only population and labor force but also China's economic scale, stage of development, available capital, education services, medical services, etc. Therefore, China's urbanization cannot be properly described and modeled without using a series of variables and data. In our research, we categorize all the collected data into three groups: demographical data, economic data, and social data. Since the socio-economic system is highly complex and non-linear, and China's urbanization is deeply engaged in economic development and social reform, the relationships among all the collected requisite data are characterized by high nonlinearity.

5.3 Parameter setting of the model

By referring to the readily processed data from 1998 to 2013, the values of the model's parameters are decided by the methods briefly outlined below.

(1) Values calculated using the arithmetic average of historical data include the following: birth rate of urban population (0.0111); birth rate of rural population (0.014); death rate of urban population (0.0052); death rate of rural population (0.006); index of agricultural labor force (0.436); employment index of secondary industry (0.333); employment index of tertiary industry (0.4137); capital accumulation rate (0.49); growth rate of the output value of the primary industry (0.0552); growth rate of the output value of the secondary industry (0.094); growth rate of the output value of the tertiary industry (0.117); growth rate of the agricultural labor force (–0.0196); growth rate of the number of employees in the tertiary industry (0.0233); and growth rate of the number of employees in the tertiary industry (0.0276).

(2) Values of five parameters are set by extrapolation of development trends: influence factor of rural family planning (1.15); influence factor of urban family planning (1.05); influence factor of rural health (0.95); influence factor of urban health (0.92); and medical factor (0.98).

(3) Variables whose values are determined by table function include the following: factor of the demand of labor force in urban industries; urban education factor; and urban medical factor.

(4) Variables whose values are calculated through regression analysis are the following: number of urban doctors; number of urban primary and secondary school students; and number of urban primary and secondary school teachers.

(5) Capital stock and labor elasticity index of primary, secondary, and tertiary industries are calculated by Cobb-Douglas production function (CD function).

(6) The value of arable land is calculated by the GM (1, 1) model. As the difference between the predicted value by this GM (1, 1) model and the real value can be exaggerated gradually towards the future, we designate 1.8 billion acres of arable land (one acre equals approximately 667 m^2) as the threshold value for the model. That is, when the predicted arable land reaches 1.8 billion acres, it will not change afterwards.

5.3.1 GDP growth rate

According to an article titled "Asian economic center: prediction on China" published in the "*Frankfurter Rundschau*" by Robert W. Fogel, by 2030, China's per capita GDP is set to reach 85 thousand dollars and by 2040 its GDP is scheduled to reach 123 trillion dollars. Many Chinese specialists view this prediction as unattainable, since its actualization would depend on an annual GDP growth rate of approximately 10%, as well as an appreciation in the RMB rate of exchange. Since China's economy is now at a "New Normal" stage and a lagging in GDP growth is predicted, it is unlikely that China's annual GDP growth rate will exceed 8% in the future. Moreover, since 2013 China's industrial structure has transformed from a pattern of "secondary, tertiary and primary" to one of "tertiary, secondary and primary". This means that the tertiary industry will overtake the secondary industry and become the leading industry in China (Liu and Cai, 2015). In addition, now China's economy is stepping into a stage of structural economic slowdown (Han et al., 2016). By taking into account these new developments and the fact that the average growth rate of China's primary industry was only 4% from 1996 to 2013, we predict the urbanization level towards 2050 in three scenarios. In the high-growth scenario, the growth rate of the primary industry, the secondary industry and the tertiary industry is set to 4%, 7% and 8%, respectively. In the medium-growth scenario, for each of the industries the corresponding growth rate is assumed to be 3.5%, 6.5% and 7.5%; and in the low-growth scenario the respective rate is assumed to be 3%, 6% and 7%.

5.3.2 *Family planning policy*

In 2007, the China Population Development Strategy Research Group launched the "*Research report of China's population development strategy*" and stated that China's population will reach 1.45 billion in 2020, reaching its peak value of 1.5 billion in 2033. However, by reviewing the current social issues caused by the one-child policy, such as a shortage in the labor force and an aging population, the central government is preparing to adjust its current family planning policy. By referring to the population data (1998–2013) from the "*China Population Statistics Yearbook*", "*China Population and Employment Statistics Yearbook*" and the Fifth Census Data (2000), we can obtain the child-bearing status of urban and rural women in China (See Appendix 2 for details).

The one-child policy in China experienced no adjustment between 1998 and 2013. Therefore, if the central government modifies the one-child policy to a 1.5-child policy or even a two-child policy, the consequential impact on the variable of "influence factor of urban/rural family planning" could be significant. The effects on the "influence factor of family planning" resulting from a two-child policy and a 1.5-child policy are calculated using eqs. (3) and (4).

$$\text{Effect on "influence factor of family planning"(two-child policy)}=1+(\text{number of child one} - \text{number of child two})/\text{number of child one}, \tag{3}$$

$$\text{Effect on "influence factor of family planning"(1.5-child policy)}=1+(\text{number of child one}/2 - \text{number of child two})/\text{number of child one}. \tag{4}$$

Table 5 provides a detailed account of the "influence factor of family planning" resulting from a 1.5- and two-child policy from 1998 to 2013. It shows that in urban areas the average effect is 1.81 for a two-child policy and 1.31 for a 1.5-child policy. By contrast, in the rural area the effect on the "influence factor of rural family planning" is 1.44 for a two-child policy and 0.94 for a 1.5-child policy. Therefore, it can be inferred that turning the "one couple, one child" to a "1.5-child" family planning policy will have no significant influence upon Chinese urbanization but with a "two-child" policy the influence will be evident.

Table 5 Influence factor of family planning on Chinese urbanization (1998–2013)

Year	Urban area		Rural area	
	Two-child policy	1.5-child policy	Two-child policy	1.5-child policy
1998	1.84	1.34	1.54	1.04
1999	1.86	1.36	1.48	0.98
2000	1.84	1.34	1.50	1.00
2001	1.88	1.38	1.47	0.97
2002	1.86	1.36	1.45	0.95
2003	1.87	1.37	1.47	0.97
2004	1.85	1.35	1.46	0.96
2005	1.75	1.25	1.33	0.83
2006	1.80	1.30	1.42	0.92
2007	1.83	1.33	1.41	0.91
2008	1.83	1.33	1.44	0.94
2009	1.82	1.32	1.44	0.94
2010	1.72	1.22	1.36	0.86
2011	1.77	1.27	1.45	0.95
2012	1.75	1.25	1.42	0.92
2013	1.69	1.19	1.42	0.92
Average	1.81	1.31	1.44	0.94

5.4 Scenario analysis

The SD model of Chinese urbanization was developed using Vensim1 PLE, a fully functional system dynamics software package from Ventana Systems, Inc. (Harvard, MA, USA). The unit time frame is one year and the model was run over a period of 35 years, representing a medium-term security planning horizon. Attempting to conduct a meaningful scenario analysis for a longer period would be fruitless, since uncertainty embedded in the model can reduce the prediction accuracy and create further difficulties when interpreting the results when the simulation spans too long of a period of time. For the purposes of scenario analysis, 2013 is set as the base year. Therefore, all of the parameter's initial values are copies of the corresponding values in 2013. Using scenario analysis, this section seeks to explore the possible urbanization rates between 2013 and 2050 under different population policies and GDP growth rates. It is expected these conclusions can serve as the scientific underpinning of the macro decision-making of the urbanization agenda in China.

5.4.1 Scenario 1. High GDP growth rate and the one-child policy

If we suppose the one-child policy does not change and the GDP growth rate is set high, then the current influence factor of both urban and rural family planning will be maintained, and the growth rates of the primary, secondary, and tertiary industries will be 4%, 7% and 8%, respectively. Under these conditions, we can see that after 2035, China's urbanization rate will increase to 70% or higher and to 77.08% in 2050 (Figure 4; Table 6).

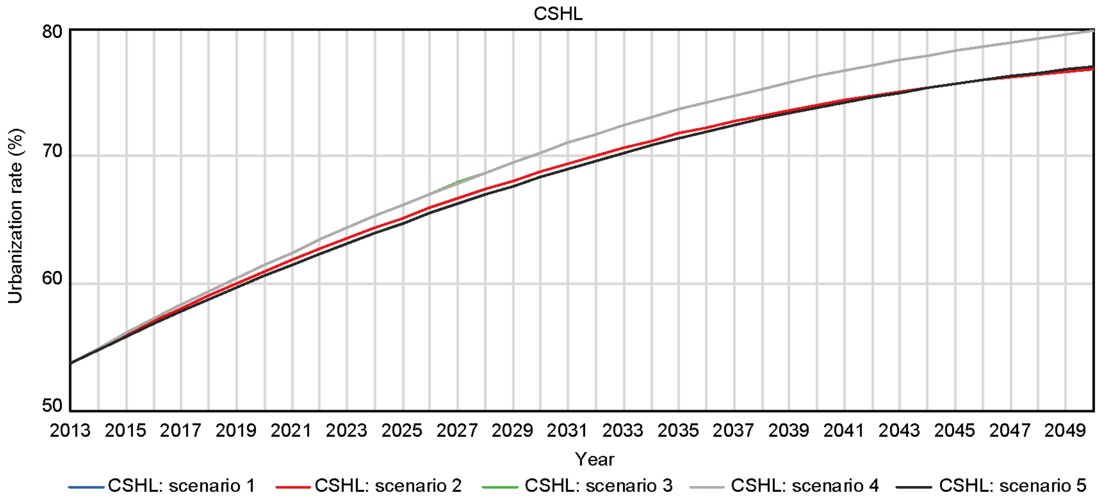

Figure 4 China's urbanization rate in five different scenarios (2013–2050).

Table 6 The projected urbanization rate in different scenarios (2015–2050)

No.	Scenario	2015	2020	2025	2030	2035	2040	2045	2050
1	High GDP growth rate, one-child policy	55.8625	60.613	64.7493	68.3447	71.4142	73.8208	75.6662	77.0765
2	Low GDP growth rate, two-child policy	55.9801	60.9496	65.1846	68.7679	71.773	74.0341	75.6839	76.8673
3	Medium GDP growth rate, 1.5-child policy	56.121	61.4804	66.1899	70.3022	73.6693	76.2679	78.2901	79.8624
4	Low GDP growth rate, 1.5-child policy	56.1207	61.4799	66.1885	70.3009	73.6681	76.2668	78.289	79.8614
5	Low GDP growth rate, one-child policy	55.8621	60.6123	64.747	68.3424	71.4119	73.8186	75.6641	77.0745
6	High GDP growth rate, 1.5-child policy	56.121	61.4806	66.1908	70.3032	73.6701	76.2687	78.2908	79.8631
7	High GDP growth rate, two-child policy	55.9804	60.9503	65.1866	68.7699	71.7749	74.036	75.6857	76.869
8	Medium GDP growth rate, one-child policy	55.8625	60.6128	64.7483	68.3437	71.4132	73.8199	75.6653	77.0756
9	Medium GDP growth rate, two-child policy	55.9804	60.9501	65.1858	68.7691	71.7741	74.0352	75.685	76.8683

5.4.2 Scenario 2. Low GDP growth rate and a two-child policy

If the population policy changes from a one-child to a two-child policy, and the growth rate of the three industries is set low, then the resulting “influence factor of family planning” for the city will be 1.44 times the current urban value and 1.81 times the current rural value for country-side areas, with growth rates of 3%, 6% and 7% for the primary, secondary, and tertiary industries, respectively. As depicted by Figure 4, under these conditions, after 2035 the urbanization rate will be higher than 70%. In 2050, this value can be expected to reach 76.8673%.

5.4.3 Scenario 3. Medium GDP growth rate and a 1.5-child policy

If the central government implements a 1.5-child policy, and the GDP growth rate is maintained at a medium level, the “influence factor of rural family planning” will not change, but its urban counterpart will be multiplied by 1.31; correspondingly, the growth rates of the primary, secondary, and tertiary industries will be 3.5%, 6.5% and 7.5%, respectively. Under these conditions, the simulated urbanization rate after 2035 will exceed 70% and reach 79.864% in 2050, as seen from Figure 4.

5.4.4 Scenario 4. Low GDP growth rate and a 1.5-child policy

Given the assumption of 1.5-child policy and low GDP growth rate, the “influence factor of rural family planning” will not change, but its urban counterpart will be 1.31 times its original value, and the growth rates of the primary, secondary, and tertiary industries will be 3%, 6% and 7%, respectively. With these configurations, China’s urbanization rate, as demonstrated by Figure 4, will exceed 72% after 2035 and reach 79.8614% in 2050.

5.4.5 Scenario 5. Low GDP growth rate and the one-child policy

Scenario 5 assumes that the GDP growth rate is low and the family planning policy is one-child. Then, the “influence factor of rural/urban family planning” is equal to its original value, and the primary, secondary, and tertiary industries have growth rates of 3%, 6% and 7%, respectively. Under these initial conditions, China’s urbanization rate will be higher than 70% after 2035 and by 2050 it will increase to a value of 77.0745% (Figure 4).

5.5 The simulation results

In addition to these five scenarios, another four scenarios with very low likelihood of occurrence are also simulated. The results of all nine scenarios illustrate that China’s urbanization rate will be higher than 70% in 2035 and reach 75% or an even higher level in 2050, regardless of what combination of GDP growth rate (low, medium and high) and family planning policy (one-child, 1.5-child and two-child) is enacted. This outcome coincides with the urbanization process experienced by foreign developed countries. As has been justified theoretically and testified in practice in foreign countries, the development trajectory of the urbanization rate can be described by an “S” curve. When the rate reaches 70%, urbanization will enter a stable stage, which is the general trend and law of urbanization. In fact, most foreign developed countries have already reached this stage.

Compared with the GDP growth rate, we found that change in family planning policy has a more evident impact on China’s urbanization. Moreover, among the three different family planning policies, the 1.5-child policy makes a more significant contribution to increasing China’s urbanization rate than the currently implemented one-child policy. Interestingly, the impact resulting from the two-child policy, compared with the other two policies, is less significant.

6. Conclusions

This paper presents a Chinese urbanization SD model to explore China’s future urbanization rate towards 2050 in different scenarios. It generates four key conclusions, discussed below.

(1) Structural validation and sensitivity analysis using real data from 1998 to 2013 justifies that this Chinese urbanization SD model is robust, with high credibility, validity and simulation practicality. According to the simulated results, it is found that more than 20 years are still needed for the completion of Chinese urbanization. Therefore, we can conclude that urbanization as a goal in China cannot be realized in a short time, but must undergo a long social transformation process.

(2) Scenario analysis (2013–2050) through the SD model reveals that China’s urbanization rate will be approximately 70.0–72.0% in 2035, regardless of the settings of the GDP growth rate (6.5%, 7.0% or 7.5%) and the family planning policy (one-child policy, 1.5-child policy or two-child policy).

(3) Sensitivity analysis indicates that, compared with the GDP growth rate, a change in family planning policy has a more significant impact on China’s urbanization. In addition, regarding family planning policy itself, a 1.5-child policy will impact China’s urbanization more fundamentally than a two-child policy will.

(4) In 2050, the urbanization rate will be approximately 75%, an equilibrium level for China in the long run.

Thus, it can be summarized that Chinese urbanization entails a long social development process requiring approximately 20 years to complete. The ultimate equilibrium urbanization level will be 75–80%, which means that in a foreseeable long future, 20–25% of China's population will continue to live in the countryside of China.

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References

Allen P M, Boon F, Engelen G, Sanglier M. 1984. Modeling evolving spatial choice patterns. Appl Math Comput, 14: 97–129

Armah F A, Yawson D O, Pappoe A A N M. 2010. A systems dynamics approach to explore traffic congestion and air pollution link in the city of Accra, Ghana. Sustainability, 2: 252–265

Batten D. 1982. On the dynamics of industrial evolution. Region Sci Urban Econ, 12: 449–462

Batty M. 2005. Agents, cells, and cities: New representational models for simulating multiscale urban dynamics. Environ Planning A, 37: 1373–1394

Bockermann A, Meyer B, Omann I, Spangenberg J H. 2005. Modelling sustainability. J Policy Model, 27: 189–210

Cai L. 2008. The Application of System Dynamics in the Research of Sustainable Development (in Chinese). Beijing: China Environmental Science Press

Chan K W, Hu Y. 2003. Urbanization in China in the 1990s: New definition, different series, and revised trends. China Review 3: 49–71

Chang Y C, Hong F W, Lee M T. 2008. A system dynamic based DSS for sustainable coral reef management in Kenting coastal zone, Taiwan. Ecol Model, 211: 153–168

Chen M, Liu W, Tao X. 2013. Evolution and assessment on China's urbanization 1960–2010: Under-urbanization or over-urbanization? Habitat Int, 38: 25–33

Egilmez G, Tatari O. 2012. A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact. Transport Res A-Pol, 46: 1086–1096

Forrester J W. 1969. Urban Dynamics. Cambridge: MIT Press

Forrester J W. 1971. World Dynamics. Lawrence: Wright-Allen Press

Gao C L, Wei H K. 2013. Study on the prediction of Chinese urbanization trend (in Chinese). Mod Econ Sci, 35: 85–90

Georgiadis P, Besiou M. 2008. Sustainability in electrical and electronic equipment closed-loop supply chains: A system dynamics approach. J Cleaner Prod, 16: 1665–1678

Georgiadis P, Vlachos D, Iakovou E. 2005. A system dynamics modeling framework for the strategic supply chain management of food chains. J Food Eng, 70: 351–364

Gu C L. 1992. Chinese Urban Hierarchy: History, Status Quo and Prospect. Beijing: Commercial Press. 334–350, 340, 348–350

Guan D, Gao W, Su W, Li H, Hokao K. 2011. Modeling and dynamic assessment of urban economy-resource-environment system with a coupled system dynamics—Geographic information system model. Ecol Indicators, 11: 1333–1344

Guo H C, Liu L, Huang G H, Fuller G A, Zou R, Yin Y Y. 2001. A system dynamics approach for regional environmental planning and management: A study for the Lake Erhai Basin. J Environ Manage, 61: 93–111

Haghshenas H, Vaziri M, Gholamialam A. 2015. Evaluation of sustainable policy in urban transportation using system dynamics and world cities data: A case study in Isfahan. Cities, 45: 104–115

Han Y H, Huang L X, Zou J H. 2016. The advent of the era of China's economic structural slowdown (in Chinese). Stat Res, 33: 23–33

He C Y, Shi P J, Chen J, Pan Y Z, Li X B, Li J, Li Y C, Li J G. 2005. Developing land use scenario dynamics model by the integration of system dynamics model and cellular automata model. Sci China Ser D-Earth Sci, 48: 1979–1989

He H B, Pan Y G, Chen L H. 2006. Tentative study on prediction model of regional energy demand (in Chinese). Prediction Analysis, (23): 3–5

Hu X L. 2013. Urbanization and low-carbon transformation. In: Wang W G, Zheng G G, eds. Report on Climate Change (2013): Low-Carbon Urbanization (in Chinese). Beijing: Social Sciences Academic Press

Jia R A, Ding R H. 2002. System dynamics: Analysis of feeback dynamic complexity (in Chinese). Beijing: Higher Education Press

Jin W, Xu L, Yang Z. 2009. Modeling a policy making framework for urban sustainability: Incorporating system dynamics into the Ecological Footprint. Ecol Econ, 68: 2938–2949

Li Q. 2011. Research on dynamic simulation model of urban public safety emergency response based on multi-agent. Dissertation for Doctoral Degree. Beijing: Tsinghua University

Li Q, Gu C L. 2015. A dynamic simulation approach to support emergency decision making on urban public safety (in Chinese). Sci China Ser D-Earth Sci, 45: 290–304

Liu W, Cai Z Z. 2015. The upgradation of industrial structure in the process of China's industrialization and its economic growth under the new normal. J Peking Univ-Philos Soc Sci, 52: 5–19

Liu Y, Lv X, Qin X, Guo H, Yu Y, Wang J, Mao G. 2007. An integrated GIS-based analysis system for land-use management of lake areas in urban fringe. Landscape Urban Plan, 82: 233–246

Meadows D H, Meadows D L, Randers J, Behrens W. 1972. The Limits to Growth: A Report to the Club of Rome. New York: Universe Books

Mohapatra P. Mandal P, Bora M. 1994. Introduction to System Dynamics Modeling. Hyderabad: Orient Longman Ltd

Northam R M. 1975. Urban Geography. New York: John Wiley & Sons

Pei T Y, Zhang H W, Zhang X H, Lei M. 2010. Logistic analysis in eco-compus based on system dynamic and sensitivity model (in Chinese). Sikuan Enviroment, 29: 64–67

Portugali J. 2000. Self-Organization and the City. Berlin: Springer-Verlag

Pumain D, Saint-Julien T, Sanders L. 1986. Urban dynamics of some French cities. Eur J Oper Res, 25: 3–10

Qiu Y, Shi X L, Shi C H. 2015. A system dynamics model for simulating the logistics demand dynamics of metropolitans: A case study of Beijing, China. J Ind Eng Manage, 8: 783–803

Shen T Y, Wu B. 2006. China urban future simulation: An integrated framework of CGE and GIS (in Chinese). Adv Earth Sci, 21: 1153–1163

Shen T Y, Wang W D, Hou M, Guo Z C, Xue L, Yang K Z. 2007. Study on spatio-temporal system dynamic models of urban growth. Syst Eng-Theor Practice, 27: 10–17

Sterman J. 2000. Business Dynamics: Systems Thinking and Modeling for a Complex World. Boston: McGraw-Hill. 982

The World Bank and the Development Research Center of the State Council (China). 2014. Urban China: Toward Efficient, Inclusive, and Sustainable Urbanization. Beijing: China Development Press. 121

The Economist Intelligence Unit. 2014. China's Urbanization in 2030. China Economic Report, (7): 93–98

Tong L, Dou Y. 2014. Simulation study of coal mine safety investment based on system dynamics. Int J Mining Sci Tech, 24: 201–205

Venkatesan A K, Ahmad S, Johnson W, Batista J R. 2011. Systems dynamic model to forecast salinity load to the Colorado River due to urbanization within the Las Vegas Valley. Sci Total Environ, 409: 2616–2625

Wang Q F. 1994. System Dynamics (in Chinese). Beijing: Tsinghua University Press

Wolstenholme E F. 1983. Modeling national development program—An exercise in system description and qualitative analysis using system dynamics. J Oper Res Soc, 34: 1133–1148

Xia B, Hu J M, Zhang Z, Yao Y D. 2002. Visualized simulation of urban traffic guidance system based on PARAMICS (in Chinese). Systems Engineering, 20: 72–78

Xu K D. 2013. Study on the Development Strategy of New Urbanization with Chinese Characteristics (Comprehensive volume) (in Chinese). Beijing: China Building Industry Press

Xu Y, Sun C Z. 2008. Simulation of water resources carrying capacity based on a system dynamic model in Dalian (in Chinese). J Saf Environ, 8: 71–74

Xu Z, Coors V. 2012. Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development. Build Environ, 47: 272–287

Xue B, Song X S, Yan D H. 2011. Simulation and prediction of water resources carrying capacity based on a system dynamic model in Tianjin (in Chinese). South-to-North Water Diversion Water Sci Technol, 9: 43–47

Xue L, Yang K Z. 2002. Sciences of complexity and studies of evolution simulation of regional spatial structure. Geogr Res, 21: 79–88

Ying Q, Shi X L, Shi C H. 2015. A system dynamics model for simulating the logistics demand dynamics of metropolitans: A case study of Beijing, China. J Ind Eng Manage, 8: 783–803

Yuan J X, Wang R Q, Yin C X, Qiu Z F. 1987. Application of Systems Theory in Regional Planning (in Chinese). Beijing: Social Sciences Academic Press

Zeleny M. 1980. Autopoiesis, Dissipative Structures and Spontaneous Social Orders. Boulder: Westview Press

Zhang X H, Zhang H W, Zhang B A. 2008. Application of system dynamics approach to urban water demand forecasting and water resources planning (in Chinese). China Water Waste Water, 24: 42–46

Zhou T Y. 1994. Labor and Economic Growth (in Chinese). Shanghai: Sanlian Press

Zhou W, Mi H. 2009. Systems dynamics of future urbanization and energy-related CO_2 emissions in China. Wseas Transactions Systems, 8: 1145–1154