*Title Page

https://doi.org/10.1016/j.jclepro.2018.07.154

A system dynamics model for simulating urban sustainability performance: A China case study

Yongtao Tan[a*], Liudan Jiao[b] , Chenyang Shuai[a], and Liyin Shen[c]

[a] Department of Building & Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong.
[b] School of Economics and Management, Chongqing Jiaotong University, Chongqing 400045, China.
[c] School of Construction Management & Real Estate, Chongqing University, Chongqing 400045, China.

*Corresponding author. Tel: + 852 2766 5828 Fax: +852 2764 5131.
E-mail addresses: bstan@polyu.edu.hk (Yongtao Tan), jld0617@126.com (Liudan Jiao), 1391843874@qq.com (Chenyang Shuai), shenliyin@cqu.edu.cn (Liyin Shen)

Highlights

- An urban sustainability system dynamics model for Chinese cities is established.
- The sustainability performance of Beijing from 2005 to 2030 is simulated based on three scenarios.
- Under high speed scenario, Beijing’s sustainability performance would decline in future.
- A low speed of urbanization policy should be adopted by Beijing for a sustainable development.

A system dynamics model for simulating urban sustainability performance: A China case study

Abstract

China has been experiencing a rapid urbanization process. Various relevant policies and strategies have been implemented for sustainable urbanization. For a better understanding of sustainable urbanization, many research efforts have been made on urban sustainability assessment. The traditional indicator index is normally used to evaluate the urban sustainability performance. However, the urban development is a complex system, and the existing methods cannot reflect the systemic interactions among variables. Therefore, this paper aims to develop a system dynamics model for simulating urban sustainability performance. The system dynamics model comprises four sub-systems, namely, the economic sector, social sector, environment sector and resource sector. Then, the system dynamics model is used to simulate the sustainability performance of the city, Beijing, with three scenarios. The results indicate that the system dynamics modelling is a useful tool for simulating urban sustainability performance and can help policy makers formulate relevant strategies for a better sustainable development of cities.

Keywords: Sustainable development, System dynamics, Urban sustainability performance, China

1 Introduction

Urbanization has been widely appreciated as one of the most important national development strategies, especially for the developing countries (Shen and Zhou, 2014). For example, as the biggest developing country in the world, China experienced a rapid urbanization process over the past 30 years. According to statistics, the urbanization level of China increased dramatically from 17.9% in 1978 to 54.8% in 2014 and nearly 600 million people migrated from rural to urban areas (Huang et al., 2016). This movement has been appreciated as a momentous event and attracted wide international attention (Yang, 2013). Many researchers have recognized that urbanization plays a positive role in promoting economic development, improving the living and medical environment, upgrading industrial structure and per capita income (Zhou et al., 2015a；Madlener and Sunak，2011; Spence and Buckley, 2009). However, the rapid speed of urbanization could also result in a myriad of environmental problems and social inequities, such as air pollution, acid rain, water and land pollution and solid wastes (Vafa-Arani et al., 2014, Lin et al., 2014; Shen and Zhou, 2014).

Based on this background, much attention has been paid to the sustainable development of cities. It has been well appreciated that the sustainable development principles need be adopted to guide the urbanization practices by organizations and governments throughout the world because sustainable urbanization is an effective way to promote the sustainable development of urban areas (Tan et al., 2017; Shen et al., 2016a ; Wang et al., 2015). Moreover, it is predicted that the developing countries will still have rapid urbanization over the next several years, and thus have to deal with the sustainable urbanization issues. For example, the urbanization level of China is projected to be 77.5% in 2050, a further increase of 22.7% compared with the urbanization rate in 2014 (Wu et al., 2014). The Chinese government is aware of the importance of sustainable urbanization and is putting efforts in a New-type urbanization path. The most notable aspect of New-type urbanization is the transfer from land-centered urbanization to people-oriented urbanization(Chen et al., 2015). Therefore, an accurate assessment of urban sustainability has become necessary, which not only provides decision makers a better understanding of sustainable urbanization, but also provides useful references for developing relevant sustainable urban development strategies (Han et al., 2009; Uwasu and Yabar, 2011; Zhou, et al., 2015).

Numerous indicators and assessment tools have been developed by previous researchers for assessing the performance of sustainable urbanization from different perspectives. These indicators and tools have been widely used in academia and practice to assess and monitor the urbanization process (Huang et al., 1998, Zhao and Chai, 2015; Huang, et al., 2016, Shen, et al., 2011；Zhou, et al., 2015b; Michael, et al., 2014; Charan and Venkataraman, 2017). Nevertheless, there are some limitations by using indicators to assess urban sustainability. Huang et al. (2009) pointed out that as urban development is a complex system including various variables, the indicators cannot reflect the systemic interactions among these variables, and so cannot provide normative indications of future directions of urban development. It is echoed by Uwasu and Yabar (2011) that the existing sustainable indicators and tools may ignore some important features of sustainability and do not explicitly address the relations between environmental aspects and socio-economic aspects.

Based on above discussion, there is a need to introduce a method to evaluate urban sustainability performance by considering the interactions among the indicators. Therefore, this study aims to (1) develop a simulation model to assess the level of sustainable urbanization based on the principle of System dynamics; (2) demonstrate the application of the SD model through the case study of the city Beijing in China; (3) analyze the simulation results based on different scenarios.

2. Literature review

System Dynamics (SD) was firstly proposed by Forrester in 1956 for investigating the information-feedback character of industrial systems and improving the organizational form (Thompson and Bank, 2010). It is well appreciated that SD is an effective tool to analyze the relationships and interactions among the variables in a system. It can help to understand the impact of various factors on the objectives defined in a system and provide useful information for decision-makers (Guan et al., 2011；Yao et al., 2011). It is a typical simulation technique for evaluating the decision-making performance. It can analyze the complex and inter-dependent relationships between the variables in a system and improve the accuracy of the evaluation results.

The system dynamics method has been used in various fields, such as transportation (Egilmez and Tatari, 2012; Shepherd, 2014), land use (Yu et al., 2011; Shen et al., 2009), waste management (Yuan et al., 2012), environment management (Chen et al., 2006; Güneralp and Seto, 2008), and project management (Zhang et al., 2014; Yao et al., 2011). For example, Fong et al. (2009) adopted System Dynamics Model to forecast the CO_2 emission trends with the case of Iskandar Development Region of Malaysia. Shen et al. (2009) applied a system dynamics model for the sustainable land use and urban development in Hong Kong. Guan et al. (2011) developed an integrated evaluation model to assess the urban environment development level of the city Chongqing in China by integrating system dynamics with Geographic Information System (GIS). Yuan et al. (2012) used a System Dynamics method to assess the effects of management strategies on the reduction of construction and demolition waste. Rehan et al. (2012) developed causal loop diagrams and a system dynamics model for financial sustainable management of urban water distribution networks and simulated a series of policy levers between financial sustainability and household affordability.

However, there are a few existing studies that have used the System Dynamic for simulating and evaluating urban sustainability performance. Huang and Chen (1999) developed a dynamic urban system model, which includes six subsystems: land use, population, transportation, water resource, solid waste and waste water treatment, to simulate the performance of the urban sustainability of the city Taipei. This model cannot be used for evaluating the cities in China directly because China has different characteristics of urban development. Han et al. (2009) presented an integrated system dynamics and cellular automata model for assessing the speed of urban growth. He selected the city, Shanghai, in China as a case study, which is not for sustainable urbanization. Mavrommati et al. (2013) proposed a System Dynamics approach for Ecologically Sustainable Development (ESD) in urban coastal systems, which mainly focused on the relationship between environmental and economic dimensions, without the variables of social dimensions.

Based on above literature review, it can be summarized that the System Dynamics method has been used by many researchers in various fields. However, there are few studies on applying System Dynamics to sustainable urbanization. The existing studies can provide useful references for simulating urban sustainability performance in this study. This research will apply System Dynamics to simulate the performance of sustainable urbanization in China.

3 Methodology

In this study, the method of System Dynamics was used for simulating urban sustainability performance. There are three main elements of System Dynamics, including feedback loops, variables, and equations (Vafa-Arani et al., 2014). The feedback loop is defined as a closed chain of causes and effects. Figure 1(a) is an example of the feedback loop of population change (Trappey et al., 2011). The population is influenced by two variables, Birth Rate and Death Rate. When the birth rate increases, the population will increase. When the death rate increases, the population will decrease. Therefore, the left of the diagram shows a positive feedback loop and the right shows a negative feedback loop.

<Please insert Figure 1 here>

There are three main kinds of variables in a feedback loop, including the stock variable, the rate variable, and the auxiliary variable. The stock variable accumulates a flow over continuous time periods; the rate variable represents a flow during a time period; and the auxiliary variable identifies rate variables. The three kinds of variables are linked by equations with the form of integral, differential, or other types. Figure 1(b) shows a simple system dynamics model for simulating the population growth of a city (Trappey et al., 2011). In Figure 1(b), the variable—Population will change with time, and is defined as stock variable. The variables— Birth and Death are defined as rate variables. The rates of birth and death are the auxiliary variables.

System dynamics has three general steps: articulation of the problem or conceptualization, dynamic hypothesis formulation, and then testing and analysis, as shown in Figure 2 (Espinoza et al., 2017). Therefore, in this study, the first step, identifying the key variables of the SD model will be based on the review of the existing urban sustainability assessment indicators, such as the urban sustainable development index issued by McKinsey Company and Tsinghua University in China

(Urban Sustainability Index, 2014), Shen et al. (2011), Uwasu and Yabar (2011), Shen and Zhou (2014), Zhang (2015) and Tan et al. (2016). The availability of data is also considered when identifying the key variables. Finally, 19 basic indicators under four dimensions are identified, as shown in Table 1, and will be used as key variables for the SD model.

<Please insert Figure 2 here>

<Please insert Table 1 here>

After identifying the key variables, the next step is to establish the stock-flow diagram among the variables. A stock-flow diagram is to depict the relationships between the variables in the system through the above two kinds of flows. The existing SD models related to sustainable urbanization, such as Shen et al. (2009), Han et al. (2009), Guan et al. (2011) and Mavrommati et al. (2013), are used as references to analyze the relationships between the variables in this study.

4. SD model development

Based on the 19 indicators selected in Table 1, and through the stock-flow diagram analysis of the variables, a system dynamics model of urban sustainability is established in this study, as shown in Figure 3. The software Vensim PLE 5.1 was used for developing the diagrams. The SD model consists of four sub-systems, economic sector, social sector, environment sector and resource sector. The stock-flow diagrams of the four sub- systems will be presented in each sector, respectively.

<Please insert Figure 3 here>

<u>Economic sector</u>

The economic sector plays an important role during the urbanization process of a city. Previous study suggests that good economic sustainability during urbanization is characterized by several indicators such as a high GDP level and stable economic condition (Shen et al., 2016a). Therefore, the total economic index is mainly determined by three key variables, GDP from service industry, Government investment in R&D per capita and Disposable income per urban capita in this study. The stock-flow diagram of the economic sector is shown in Figure 34. In Figure 4, stock variables describe the cumulative effect of the system, which can react to the accumulation of material, energy and information over time. There are three stock variables, Total population, Urbanization rate and GDP in economic sector. Rate variable describes the speed of the system's cumulative effect and reflects the changes of stock variables over time, representing the speed of change in the system or the amplitude of a decision. Four rate variables, Annual GDP growth, Population growth (natural increase), Population growth (migratory increase), Annual urbanization rate growth are introduced. Auxiliary variables are the intermediate variables, which run through the entire decision-making process and 13 auxiliary variables are in the economic sector. Figure 4 also shows the relationships among interacting variables. For example, the key auxiliary variable, GDP from service industry, is mainly influenced by three auxiliary variables: Total population, Urbanization rate and GDP

(Han et al., 2009). The Government investment in R&D is mainly from the local government annual fiscal revenue. The variable of Disposable income per urban capita is highly related to the GDP per capita. The higher GDP per capita, the higher Disposable income per urban capita is. The stock variable, Total population, is determined by two rate variables: Population growth (natural increase) and Population growth (migratory increase), (Shen et al., 2009).

<Please insert Figure 4 here>

Social sector

It has been pointed out that urbanization should bring social benefits in the areas of medical treatment, education, health and others (Dye, 2008; Zhou et al., 2015). Therefore, the social index was determined by five key variables: Urban unemployment rate, Number of doctors per 10,000 urban population, Number of elementary school students per 10,000 urban population, Pension security coverage and Health care security coverage. The stock-flow diagram of the social sector is shown in Figure 5. Similar to the economic sector, there are also three stock variables, Total population, Urbanization rate, GDP; four rate variables, Annual GDP growth, Population growth (natural increase), Population growth (migratory increase), Annual urbanization rate growth in this sector and 23 auxiliary variables. Furthermore, in the social sub-system, the variables of Local government annual fiscal revenue and Disposable income per urban capita are defined as two core variables because they have influence on other variables. For example, the auxiliary variable Number of elementary school students is in high correlation with the two auxiliary variables: Disposable income per urban capita and financial education investment (Gao and Shi, 2008).

<Please insert Figure 5 here>

Environment sector

The Chinese government has been putting more attention on environmental issues in recent years. The ecological degradation and environmental pollution due to fast economic development are two major problems in China. Moreover, the environment sector is influenced by the economic sector and social sector. The whole environment sub-system includes five stock variables, six rate variables and 42 auxiliary variables, as shown in Figure 6. The stock-flow diagram shows the relationships among the variables. For example, the auxiliary variable of Urban green area is directly influenced by the variable of local government annual fiscal revenue (Han et al., 2009) and the Annual waste water emissions is determined by two auxiliary variables: Annual domestic waste water emissions and Annual industrial waste water emissions (Guan et al. 2011).

<Please insert Figure 6 here>

Resource sector

Rapid urbanization consumes a lot of resources including land, water and fossil energy (Tan et al., 2016; Han et al., 2017). The stock-flow diagram of the resource sector is shown in Figure 7. There are four stock variables, Total population, Urbanization rate, GDP and Urban area; five rate variables, Annual GDP growth, Population growth (natural increase), Population growth (migratory increase), Annual urbanization rate growth, Annual urban area growth, and 15 auxiliary variables, in this sector. For example, the auxiliary variable of Annual total water consumption is considered from three aspects: Annual domestic water consumption, annual industrial water consumption and annual agricultural water consumption (He et al., 2011).

<Please insert Figure 7 here>

5 Model simulation and results analysis

The application of the established SD model was demonstrated by a case study of the city, Beijing in China. Beijing, as the capital of China, is one of the largest cities in China. It's population reached 21.7 million and the total GDP was nearly 23 thousand billion Yuan by the end of 2015 (National Bureau of Statistics, 2016). However, the rapid urbanization process has caused some environmental and social problems, especially the air pollution, hazy weather and traffic congestion, that have become serious in Beijing and have raised dramatic attention in China. In order to solve these problems, relevant measures for prompting sustainable development in Beijing have been implemented, such as developing an urban public transportation system, and reducing carbon emissions (Beijing Municipal Commission of Development & Reform, 2016). Therefore, Beijing is a good case for studying sustainable urban development in China.

5.1 Model validation

Firstly, it is imperative to test the accuracy and feasibility of the SD model. This can be fulfilled by obtaining a match between the simulated results (SR) and historical data (HD) of the variables in the system. The data for Beijing were collected from the website of the National Bureau of Statistics in China. To validate the SD model, the time horizon for the variables was set as 10 years, from 2005-2014. Matching results were obtained through the software Vensim PLE 5.1 and the matching results of the five variables, Total population, Service industry output value, Number of health workers, Annual total water consumption and Farmland area, were selected for demonstration of the SD model validation. The matching results are shown in Table 2. It can be seen that the simulated values of variables are very close to the real values, with very low relative errors. This indicates the high validity of the SD model. Therefore, the established SD model is reliable to represent the causal feedback relationships among the variables, and simulate the urban sustainability performance.

<Please insert Table 2 here>

5.2 Simulation scenarios

Scenario analysis is useful for assuming a possible range of futures, based upon which effective strategies and actions are to be sought (Kishita et al., 2016). The values of variables and parameters in the SD model can be adjusted based on different scenarios, and the simulation results will be different. Subsequently, relevant sustainable development strategies can be developed based on different simulation results. These developing strategies and their influence on cities' future sustainability performance can be further examined by re-using the SD model.

In this study, three different development scenarios were assumed for SD model simulation. The first scenario is that the current economic development speed is maintained, with all parameters and variables at their current growth rate. The investment on sustainable development is still at the current rate. Secondly, a faster urbanization process with higher economic and population growth rate was assumed. Under this scenario, the values of the variables, Annual GDP growth, Population growth, Annual urbanization rate growth were higher than the current growth rate. The investment on sustainable development was held still at the current rate. Thirdly, as a contrast, a slower urbanization process with slower economic and population growth rate was assumed. Under this scenario, the values of the variables, Annual GDP growth, Population growth, Annual urbanization rate growth were lower than the current growth rate, but the investment on sustainable development was set higher than the current rate. The simulation time horizon of the SD model for the three simulation scenarios is 25 years, from 2005 to 2030.

5.3 Simulation results

The software Vensim PLE 5.1 was used simulate the urban sustainability performance of Beijing, based on the three scenarios. The stock-flow diagrams developed above were used for scenario analysis. The equations were developed based on the relevant studies and regression analyses among the variables (Shen et al., 2009; Han et al., 2009; Guan et al., 2011). Due to the limitation of the paper length, eight equations in the SD model were selected for demonstration and are illustrated as follows：

1) Total sustainable urbanization performance=Economic index*0.17+ Environment index*0.33+Social index*0.33+Resource index*0.17
2) Annual household waste emissions= Domestic solids waste emissions per capita*Total population (Unit：ten thousand tons)
3) Annual Industrial waste water emissions=Secondary industry output value*Waste water emission of per 10,000 secondary output value (Unit: ten thousand tons)
4) Annual total water consumption=Annual agricultural water consumption+ Annual industrial water consumption+ Annual domestic water consumption (Unit: hundred million m^3)
5) Annual waste water emissions= Annual Industrial waste water emissions+ Annual domestic waste water emissions (Unit: ten thousand tons)
6) Financial Education Investment=Proportion of educational funds expenditure in fiscal revenue*Local government annual fiscal revenue (Unit: hundred million Yuan/RMB)
7) Public transport journeys per capita=Total number of public transport journeys/Total population (Unit: number of public transport journeys per person)
8) Urban green area=16,525*LN (Local government annual fiscal revenue)-74,153 (Unit: square kilometer)

Simulation results of the economic sector

The simulation result of the economic sector of the city, Beijing, from 2005 to 2030, is shown in Figure 8. It can be seen that the difference between the three scenarios is small, and the economic sector will keep a steady growth in future. According to the results of UCI (2012), the economic index of Beijing is ranked 1st among the surveyed 185 cities in China from 2005 and 2011. Moreover, the urbanization rate of Beijing was 86.5% by the end of 2015 and Beijing has reached to a terminal stage of urbanization, according to Northam's theory of urbanization stage division (Northam,1975). From the past experience of the urbanization process in China, economic development is the primary work in the initial urbanization stage. Through the past 30 years' rapid development, the economic level of Beijing has already reached to a steady stage. Therefore, there are minor differences between the three scenarios of Beijing's economic development.

<Please insert Figure 8 here>

Simulation of social sector

Figure 9 presents the simulation performance of the social sector of Beijing from 2005 to 2030. Under the low speed scenario, the performance of the social sector of Beijing will keep a steady growth in future. Under the current speed, the social performance will have a slow growth until 2021, with no changes after that. Under the high speed scenario, the performance of the social sector of Beijing has a declining trend during the period of 2021 to 2030.

A comparison of these three results indicates that a low speed of urbanization process should be adopted by Beijing to maintain a sustainable social development. Previous studies appreciated that the social development is also a main purpose of urbanization, and urbanization should have positive effects on social aspects, including social mobilization, literacy, political participation, education, and health, especially at the initial stage of urbanization (Dye, 2008). Now, Beijing is the educational, cultural and healthcare centre of China. High quality services in education, social welfare and healthcare are provided in Beijing. According to the calculated results of UCI (2012), the social index of Beijing is ranked 4th among the surveyed 185 cities in China in 2011. It also indicates that the social development level of Beijing has reached a high level.

<Please insert Figure 9 here>

Simulation results of the environment sector

The simulation results under the three simulation scenarios are quite different in the environment sector, as shown in Fig. 10. This shows that, under the low speed development, the environment sector performs much better than the other two scenarios. Under the low speed scenario, the environmental performance will reach the peak value in 2016-17, and decline until 2021, then gain another growth until 2027. Under the current speed scenario, the environmental performance also has some fluctuations, which will reach the peak value in 2016, and decline until 2020, then gain another low growth until 2025. Under high speed scenario, the environmental performance will decline during the period of 2016 to 2030. It can be seen that the lower speed economic development and higher investment on environment protection are very effective for improve Beijing's environmental performance. The government needs to balance the economic development and environment protection (Shen et al., 2017). Air pollution is considered as a major environmental problem in Beijing and its environmental performance was just ranked 27th among 185 cities in China according to the ranked results of UCI in 2005. However, many efforts have been put in by the Beijing government to improve the environmental condition in recent years, such as the “Clean Air Action Plan” and “Air Pollution Prevention and Control regulations” (Zhang, et al., 2016) and it has achieved a good level of progress. It is also reported by the United Nations Environment Programme (2015) that the air quality of Chinese cities is improving notably, such as Beijing, Shanghai, and the air management experiences in these cities are a good reference for other cities in the world.

<Please insert Figure 10 here>

Simulation results of the resource sector

The simulation results are shown in Fig. 11. The differences between the three scenarios are obvious. Under the current and high speed scenarios, the resource sector performance will decline. Under the low speed scenario, the performance will keep a low steady growth. Water resource shortage is a major problem in Beijing. According to statistics, the average shortage volume of water in Beijing from 2005 and 2014 is 0.6 billion m^3 (Beijing Municipal Commission of Development & Reform, 2016). Farmland shortage is another major problem in Beijing. It was reported that, from 1996 to 2009, the loss of farmland in Beijing is around 87 square kilometres per year (Ministry of Land Resource of the People’s Republic of China, 2016).

<Please insert Figure 11 here>

Simulation results of total performance

By integrating the four sectors, the total sustainable urbanization performance of Beijing was simulated and the result is shown in Fig. 12. It can be seen that the total sustainable urbanization performance of Beijing is high. According the ranking of UCI, the sustainability performance of Beijing was ranked within the top 10 among 185 surveyed cities in China from 2005 -2011. As shown in Fig. 10, under the high speed scenario, the sustainability performance of Beijing would be declining. Under the low speed scenario, there would be a steady growth until 2030. Under the current scenario, the total sustainability performance would have a low growth from 2016 to 2024, then decline. It indicates that a low speed of urbanization policy should be adopted by Beijing for achieving a sustainable development. The relationship between urban sustainability and urbanization depicted by Shen et al. (2012) is that in the initial urbanization stage, the impact of urbanization on economic and social development is low, and therefore, the sustainable urbanization performance is low. When urbanization continues, its effect on the economy, society, and environment increases; thus, the urbanization sustainability increases. But, the improvement of sustainability will be slow in the terminal stage of urbanization and the sustainability will maintain a certain level.

<Please insert Figure 12 here>

5.4 Policy suggestions

Based on the above scenario analysis, it can be summarized that that the urbanization speed has an impact on Beijing's sustainable development. The low speed development pattern will contribute to a higher urban sustainability performance than other two scenarios. The total performance will keep declining even at the current urbanization speed. Therefore, the imperative task of Beijing is to improve the quality of urbanization rather than the speed of urbanization (Jiao et al., 2016). The economic and social sectors of Beijing perform better than the environment and resource sectors. In order to improve the total urban sustainability performance of Beijing, the government should put more efforts on the environment and resource sectors, and improve the balance between sectors. With the above analysis, relevant policy suggestions can be proposed for the four sectors.

Economic sector

Economic development is still the primary task of urbanization in China. However, those mega cities, such as Beijing, and Shanghai, are already the leaders in economic development in China, and are already at the terminal stage of urbanization, according to Northam's urbanization development theory (Shen et al., 2017). Berry (1973) suggested that the positive relationship exists between GDP per capita and urbanization, which is obvious at the initial stage of urbanization. However, Shen et al. (2012) assumed that the economies will grow slowly and even stop growing at a certain level in the later stage of urbanization because the impact of urbanization to economic development will decreased in the later stages. Therefore, in order to promote the economic development, other patterns need to be considered. For example, the National New-type Urbanization Plan (2014-2020) issued by the Chinese government places emphasis on people (Wang et al., 2015) and it defined three main tasks in the future urbanization:- (1) gradually settle the former agricultural population who have migrated to the cities; (2) optimize urbanization; , and (3) increase the sustainability of cities to eventually achieve unified urban and rural development. With the increasing level of urbanization in China, the economic development will keep growing. Yet, there is a need for government to balance the development of different sectors. Perhaps surprisingly, a lower economic development speed may be a better choice for those cities with a high level of urbanization.

Social sector

Similar with the economic sector, the effect of urbanization on the social sector would be decreased when at the mature stage of urbanization, and even become negative if urbanization goes beyond the carrying capacity of a city (Shen et al., 2012). The simulation performance of the social sector of Beijing is good, but the performance presents a tendency of decline under the high speed simulation scenario. It also pointed out by Cao et al. (2014) that in most large cities in China, the social welfare resources such as education, healthcare and insurance, are only provided to their registered residents. Therefore, it is imperative to promote equitable and universal public services for all residents, including social security, medical treatment, education, and culture in Beijing.

Environment sector

The performance of the environment sector of Beijing is the lowest of the other three sectors. Alberti and Marzluff (2004) pointed out that the rapid urbanization will induce environmental degradation and decrease the city environment quality. If without external intervention, the deterioration would continue, which will result in the city's demolition or abandonment. Based on the research result of Alberti and Marzluff (2004), Shen et al. (2012) argued that the environmental deterioration can be avoided and the environment quality can be improved and maintained at a certain level through proper policy intervention. The simulation results under the low speed scenario in this study show that proper policy intervention can help improve the environment performance of cities. It has been well appreciated that financial support by government is an effective tool for improving the environment management quality and energy saving by arousing the public and business awareness and enthusiasm of implementing environment management policies (Shen et al., 2016b; He et al., 2012; Kanada et al., 2013). Therefore, with the prosperous economic development, the Beijing government should provide financial support and relevant public policies to improve the city environment condition.

Resource sector

Similar with environment sector, the resource sector also presents a declining tendency under the current and high urbanization speed. Many previous studies have examined the relationship between urbanization and total energy consumption and it is well appreciated that urbanization and energy consumption are positively related. (Ni and Thomas, 2004; Zhou et al., 2012; Lenzen et al., 2006; Sun et al., 2014; Yang et al., 2015; Martínez-Zarzoso, and Maruotti, 2011). For example, Zhou et al. (2012) reported that urbanization has profoundly affected on the energy consumption of residential households, transportation, and the building materials industry. Lenzen et al. (2006) found that as the process of urbanization develops further, the per capita energy consumption is generally higher in areas of high urbanization than that in areas of low urbanization, and the energy consumption structure is more advanced in the high urbanization areas, which is echoed by Sun et al. (2014). Therefore, it is suggested that the government should consider how to use resources more efficiently, such as new technologies for energy saving, green products, and low-carbon emission technologies (Ni and Thomas, 2004； Li et al., 2016; Wang et al., 2016).

6 Summary and Conclusions

Many developing countries will still experience the rapid development of urbanization in the future. Accurate assessment results of the sustainable urbanization are imperative for understanding the urbanization process and providing support to the implementation of urban development strategy. In this study, a System Dynamics model that comprises an integrated economic-social-environmental–resource subsystem is established to assist simulating the performance of sustainable urbanization. The case study of Beijing in China demonstrates that the SD model is helpful to simulate the performance of sustainable urbanization. The SD model has a number of advantages. First, the method provides a new angle in assessing the sustainable urbanization performance. Second, this method can improve the accuracy of the assessment results by considering the complex and inter-dependent relationships between the variables in the process of urbanization. Third, through the results analyses under different simulation scenarios, different policies and strategies can be implemented to guide the development of urbanization.

It is also appreciated that different cities may have had different main tasks in the urbanization process. For the city of Beijing, its major task is improving the urbanization quality, especially the environment condition and resource protection and utilization, since Beijing has already reached to the terminal stage of urbanization. For other cities in the central and west regions in China with a low urbanization rate, their major mission is coordinate between the speed of the urbanization and environment protection. It is the further research agenda of this research team to examine the sustainable urbanization performance of other cities in China by using the established SD model.

Acknowledgements

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 25223215).The authors would also like to acknowledge the editing by Dr. Paul W. Fox of an earlier draft of this paper.

References

Alberti, M., Marzluff, J. M. (2004). Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. *Urban ecosystems*, *7*(3), 241-265.

Berry, B. J. L. (1973). *The human consequences of urbanization: Divergent paths in the urban experience of the twentieth century*. St. Martin’s Press, New York, America.

Beijing Municipal Commission of Development & Reform .(2016) .Retrieved from www.bjpc.gov.cn/English/201512/t9802512.htm

Cao, S., Lv, Y., Zheng, H., Wang, X. (2014). Challenges facing China's unbalanced urbanization strategy. *Land Use Policy*, 39, 412-415.

Charan, A. S., Venkataraman, H. (2017). Greening the Economy: A Review of Urban Sustainability Measures for Developing New Cities. *Sustainable Cities and Society*, 32,1-8

Chen, M. C., Ho, T. P., Jan, C. G. (2006). A system dynamics model of sustainable urban development: Assessing air purification policies at Taipei City. *Asian Pacific Planning Review*, 4(1), 29-52.

Chen, M., Liu, W., Lu, D. (2015). Challenges and the way forward in China’s new-type urbanization. *Land Use Policy*, 55, 334-339.

Dye, C. (2008). Health and urban living. *Science*, 319(5864), 766-769.

Egilmez, G., Tatari, O. (2012). A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact. *Transportation Research Part A: Policy and Practice*, 46(7), 1086-1096.

Espinoza, A., Bautista, S., Narváez, P. C., Alfaro, M., Camargo, M. (2017). Sustainability assessment to support governmental biodiesel policy in Colombia: A system dynamics model. *Journal of Cleaner Production*, 141, 1145-1163.

Fong, W. K., Matsumoto, H., Lun, Y. F. (2009). Application of System Dynamics model as decision making tool in urban planning process toward stabilizing carbon dioxide emissions from cities. *Building and Environment*, 44 (7), 1528-1537.

Gao, L., Shi, X. Y. (2008). An Analysis of the Systematic Dynamics in the Interaction between Education and Economy and Its Enlightenment. *Journal of Shaanxi Normal University (Philosophy and Social Sciences Edition)*, 37(2), 96-101.

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. *Ecological Indicators*, 11(5), 1333-1344.

Güneralp, B., Seto, K. C. (2008). Environmental impacts of urban growth from an integrated dynamic perspective: A case study of Shenzhen, South China. *Global Environmental Change*, 18(4), 720-735.

Han, J., Hayashi, Y., Cao, X., Imura, H. (2009). Application of an integrated system dynamics and cellular automata model for urban growth assessment: A case study of Shanghai, China. *Landscape and Urban Planning*, 91(3), 133-141.

Han, J., Meng, X., Zhou, X., Yi, B., Liu, M., Xiang, W. N. (2017). A long-term analysis of urbanization process, landscape change, and carbon sources and sinks: A case study in China's Yangtze River Delta region. *Journal of Cleaner Production*, 141, 1040-1050.

He, G., Lu, Y., Mol, A. P., Beckers, T. (2012). Changes and challenges: China's environmental management in transition. *Environmental Development*, 3, 25-38.

He, R. W., Liu, S. Q., Liu, Y. W. (2011). Application of System Dynamics in Analyzing the Carrying Capacity of Water Resources in Karst Region of Southwest China--A Case Study in Bijie Region, Guizhou Province. *Scientia Geographica Sinica*, 31(11), 1376-1382.

Huang, S. L., Chen, C. W. (1999). A system dynamics approach to the simulation of urban sustainability. Ecosystems and Sustainable Development II, WIT Press, Southampton, England.

Huang, L., Yan, L., Wu, J. (2016). Assessing urban sustainability of Chinese megacities: 35 years after the economic reform and open-door policy. *Landscape and Urban Planning*, 145, 57-70.

Huang, S. L., Wong, J. H., Chen, T. C. (1998). A framework of indicator system for measuring Taipei's urban sustainability. *Landscape and urban planning*, 42(1), 15-27.

Huang, S. L., Yeh, C. T., Budd, W. W., Chen, L. L. (2009). A Sensitivity Model (SM) approach to analyze urban development in Taiwan based on sustainability indicators. *Environmental impact assessment review*, 29(2), 116-125.

Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. *Transportation Research Part D: Transport and Environment*, 31, 21-36.

Jiao, L., Shen, L., Shuai, C., He, B. (2016). A Novel Approach for Assessing the

Performance of Sustainable Urbanization Based on Structural Equation Modeling: A China Case Study. *Sustainability*, 8(9), 910.

Kanada, M., Dong, L., Fujita, T., Fujii, M., Inoue, T., Hirano, Y., ... Geng, Y. (2013). Regional disparity and cost-effective SO 2 pollution control in China: A case study in 5 mega-cities. *Energy Policy*, 61, 1322-1331.

Kishita, Y., Nakatsuka, N., Akamatsu, F. (2017). Scenario analysis for sustainable woody biomass energy businesses: The case study of a Japanese rural community. *Journal of Cleaner Production*, 142, 1471-1485

Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., Schaeffer, R. (2006). A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy*, *31*(2), 181-207.

Li, H., Zhao, X., Yu, Y., Wu, T., Qi, Y. (2016). China's numerical management system for reducing national energy intensity. *Energy Policy*, 94, 64-76.

Lin, T., Gibson, V., Cui, S., Yu, C. P., Chen, S., Ye, Z., Zhu, Y. G. (2014). Managing urban nutrient biogeochemistry for sustainable urbanization. *Environmental Pollution*, 192, 244-250.

Liu, X., Ma, S., Tian, J., Jia, N., Li, G. (2015). A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO 2 emissions: A case study of Beijing. *Energy Policy*, 85, 253-270.

Madlener, R., Sunak, Y. (2011). Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management?. *Sustainable Cities and Society*, 1(1), 45-53.

Martínez-Zarzoso, I., Maruotti, A. (2011). The impact of urbanization on CO 2 emissions: evidence from developing countries. *Ecological Economics*, *70*(7), 1344-1353.

Mavrommati, G., Bithas, K., Panayiotidis, P. (2013). Operationalizing sustainability in urban coastal systems: A system dynamics analysis. *Water research*, 47(20), 7235-7250.

Michael, F. L., Noor, Z. Z., Figueroa, M. J. (2014). Review of urban sustainability indicators assessment–Case study between Asian countries. *Habitat International*, 44, 491-500.

Ministry of Land Resource of the People's Republic of China. (2016)..Retrieved from www.mlr.gov.cn/mlrenglish/

National Bureau of Statistics.(2016). Retrieved from *data.stats.gov.cn*

Ni, W., Thomas, B. J. (2004). Energy for sustainable development in China. *Energy Policy*, 32(10), 1225–1229

Northam, R. M. (1975). Urban geography. John Wiley & Sons, New York, America.

Rehan, R., Knight, M. A., Unger, A. J. A., Haas, C. T. (2013). Development of a system dynamics model for financially sustainable management of municipal watermain networks. *Water research*, 47(20), 7184-7205.

Shen, L., He, B., Jiao, L., Song, X., Zhang, X. (2016b). Research on the development of main policy instruments for improving building energy-efficiency. *Journal of Cleaner Production*, *112*, 1789-1803.

Shen, L., Peng, Y., Zhang, X., Wu, Y. (2012). An alternative model for evaluating sustainable urbanization. *Cities*, 29(1), 32-39.

Shen, L. Y., Ochoa, J. J., Shah, M. N., Zhang, X. (2011). The application of urban sustainability indicators–A comparison between various practices. *Habitat International*, 35(1), 17-29.

Shen, L., Shuai, C., Jiao, L., Tan, Y., Song, X. (2017). Dynamic sustainability performance during urbanization process between BRICS countries. *Habitat International*, 60, 19-33.

Shen, L., Shuai, C., Jiao, L., Tan, Y., Song, X. (2016a). A global perspective on the sustainable performance of urbanization. *Sustainability*, 8(8), 783.

Shen, L., Zhou, J. (2014). Examining the effectiveness of indicators for guiding sustainable urbanization in China. *Habitat International*, 44, 111-120.

Shen, Q., Chen, Q., Tang, B. S., Yeung, S., Hu, Y., Cheung, G. (2009). A system dynamics model for the sustainable land use planning and development. *Habitat International*, 33(1), 15-25.

Shepherd, S. P. (2014). A review of system dynamics models applied in transportation. *Transportmetrica B: Transport Dynamics*, 2(2), 83-105.

Spence, M., Annez, P. C., Buckley, R. M. (2009). Urbanization and growth. World Bank Publications.

Sun, C., Ouyang, X., Cai, H., Luo, Z., Li, A. (2014). Household pathway selection of energy consumption during urbanization process in China. *Energy Conversion and Management*, *84*, 295-304.

Tan, Y., Xu, H., Jiao, L., Ochoa, J. J., Shen, L. (2017). A study of best practices in promoting sustainable urbanization in China. *Journal of Environmental Management*, 193, 8-18.

Tan, Y., Xu, H., Zhang, X. (2016). Sustainable urbanization in China: A comprehensive literature review. *Cities*, 55, 82-93.

Thompson, B. P., Bank, L. C. (2010). Use of system dynamics as a decision-making tool in building design and operation. *Building and Environment*, 45(4), 1006-1015.

Trappey, A. J., Trappey, C. V., Hsiao, C. T., Ou, J. J., Chang, C. T. (2012). System dynamics modelling of product carbon footprint life cycles for collaborative green supply chains. *International Journal of Computer Integrated Manufacturing*, 25(10), 934-945.

United Nations Environment Programme. (2015). Retrieved from www.unep.org/chinese/

Urban Sustainability Index. (2014). Retrieved from www.urbanchinainitiative.org/zh/resources/dev_page.html

Uwasu, M., Yabar, H. (2011). Assessment of sustainable development based on the capital approach. *Ecological indicators*, 11(2), 348-352.

Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. *Transportation Research Part D: Transport and Environment*, 31, 21-36.

Wang, S., Zhou, C., Li, G., Feng, K. (2016). CO 2, economic growth, and energy consumption in China's provinces: Investigating the spatiotemporal and econometric characteristics of China's CO 2 emissions. *Ecological Indicators*, *69*, 184-195.

Wang, X. R., Hui, E. C. M., Choguill, C., Jia, S. H. (2015). The new urbanization policy in China: which way forward?. *Habitat International*, 47, 279-284.

Wu, J., Xiang, W. N., Zhao, J. (2014). Urban ecology in China: Historical developments and future directions. *Landscape and Urban Planning*, 125, 222-233.

Xu, Z., Coors, V. (2012). Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development. *Building and Environment*, *47*, 272-287.

Yang, J., Zhang, W., Zhang, Z. (2015). Impacts of urbanization on renewable energy consumption in China. *Journal of Cleaner Production*, 114, 443-451.

Yang, X.J., 2013. China's rapid urbanization. *Science,* 342(6156), 310-310. Yao, H., Shen, L., Tan, Y., Hao, J. (2011). Simulating the impacts of policy scenarios on the sustainability performance of infrastructure projects. *Automation in Construction*, 20(8), 1060-1069.

Yuan, H., Chini, A. R., Lu, Y., Shen, L. (2012). A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. *Waste management*, 32(3), 521-531.

Yu, C. H., Chen, C. H., Lin, C. F., Liaw, S. L. (2003). Development of a system dynamics model for sustainable land use management. *Journal of the Chinese Institute of Engineers*, 26(5), 607-618.

Zhang, X. (2015). Sustainable urbanization: a bi-dimensional matrix model. *Journal of Cleaner Production*, 134, 425-433.

Zhang, X., Wu, Y., Shen, L., Skitmore, M. (2014). A prototype system dynamic model for assessing the sustainability of construction projects. *International Journal of Project Management*, 32(1), 66-76.

Zhao, J., Chai, L. (2015). A novel approach for urbanization level evaluation based on information entropy principle: A case of Beijing. *Physica A: Statistical Mechanics and its Applications*, 430, 114-125.

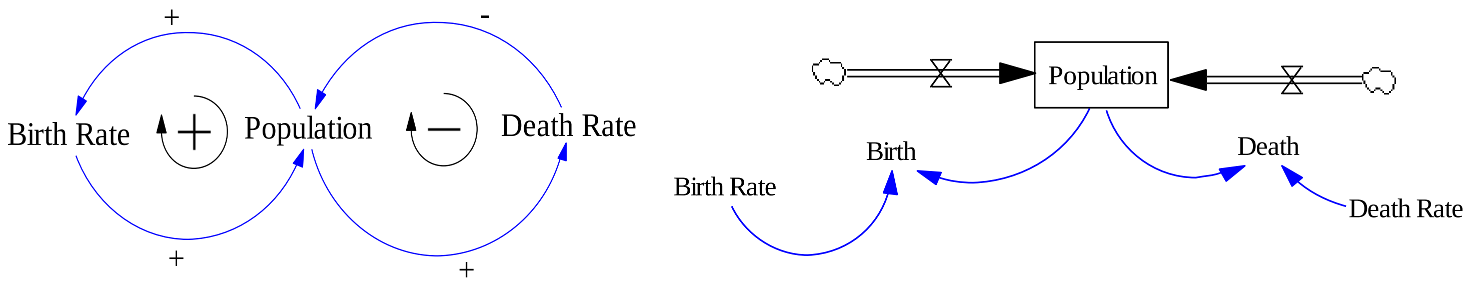
Zhou, D., Xu, J., Wang, L., Lin, Z. (2015). Assessing urbanization quality using structure and function analyses: A case study of the urban agglomeration around Hangzhou Bay (UAHB), China. *Habitat International*, 49, 165-176.

Zhou, J., Shen, L., Song, X., Zhang, X. (2015b). Selection and modeling sustainable urbanization indicators: A responsibility-based method. *Ecological Indicators*, 56, 87-95.

Zhou, J., Zhang, X., Shen, L. (2015a). Urbanization bubble: Four quadrants measurement model. *Cities*, 46, 8-15.

Zhou, W., Zhu, B., Chen, D., Griffy-Brown, C., Ma, Y., Fei, W. (2012). Energy consumption patterns in the process of China's urbanization. *Population and Environment*, 33(2-3), 202-220.

Figure



(a) (b)

Figure 1(a) A population causal feedback loop (Trappey et al., 2011) (b) A population System dynamics model (Trappey et al., 2011)

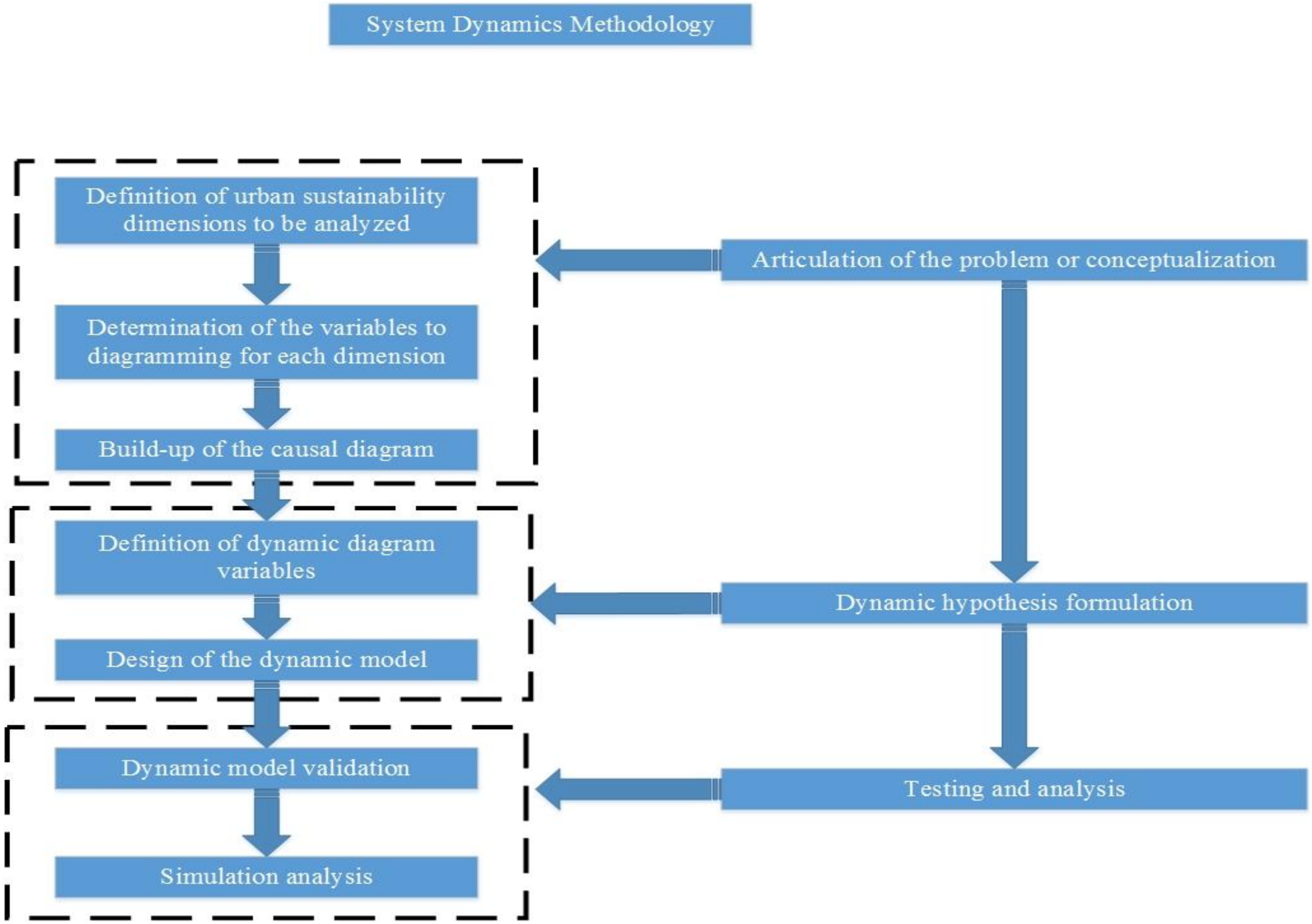


Figure 2 The four steps of System dynamics method

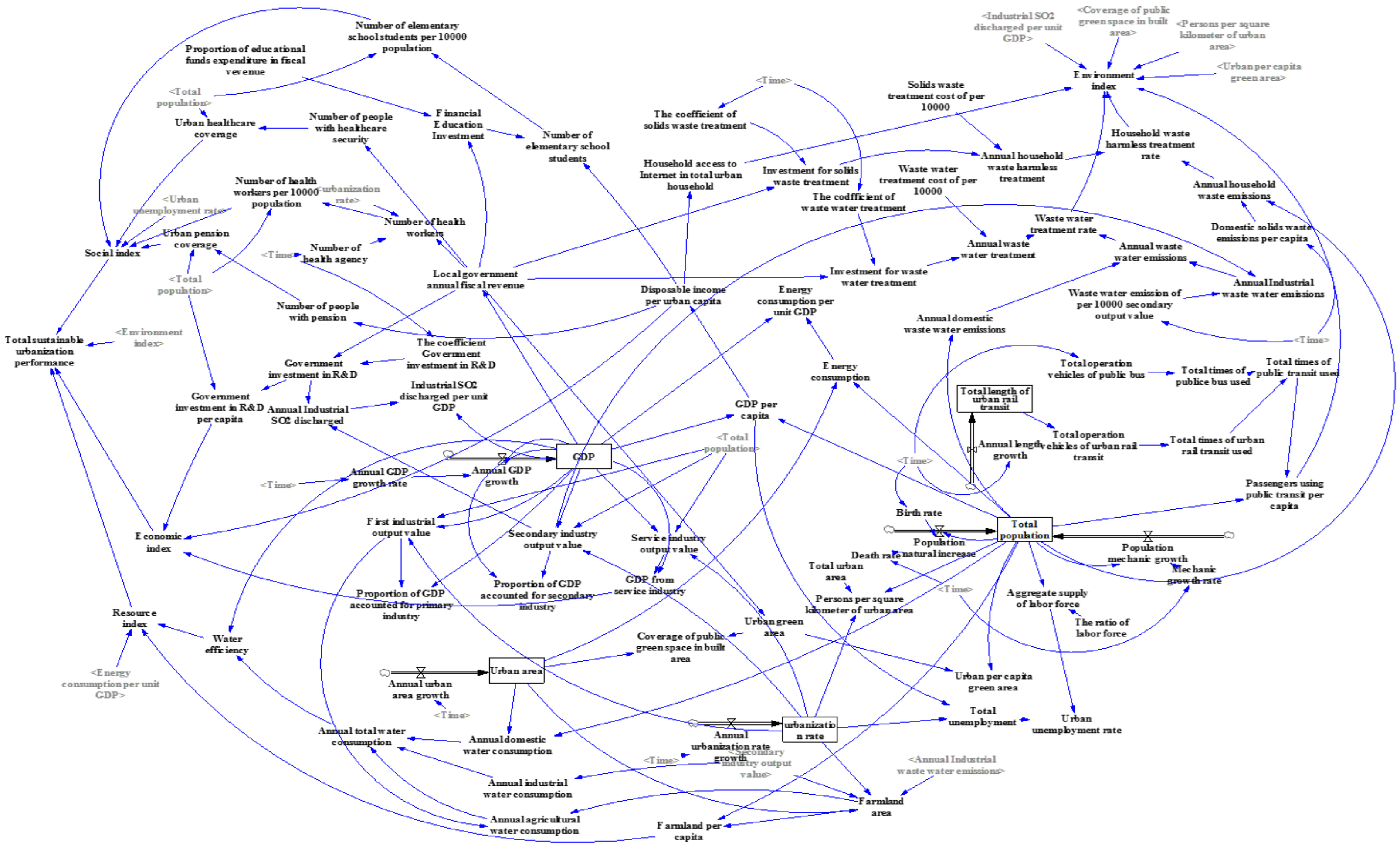


Figure 3 Stock-flow diagram of urban sustainability system dynamics model

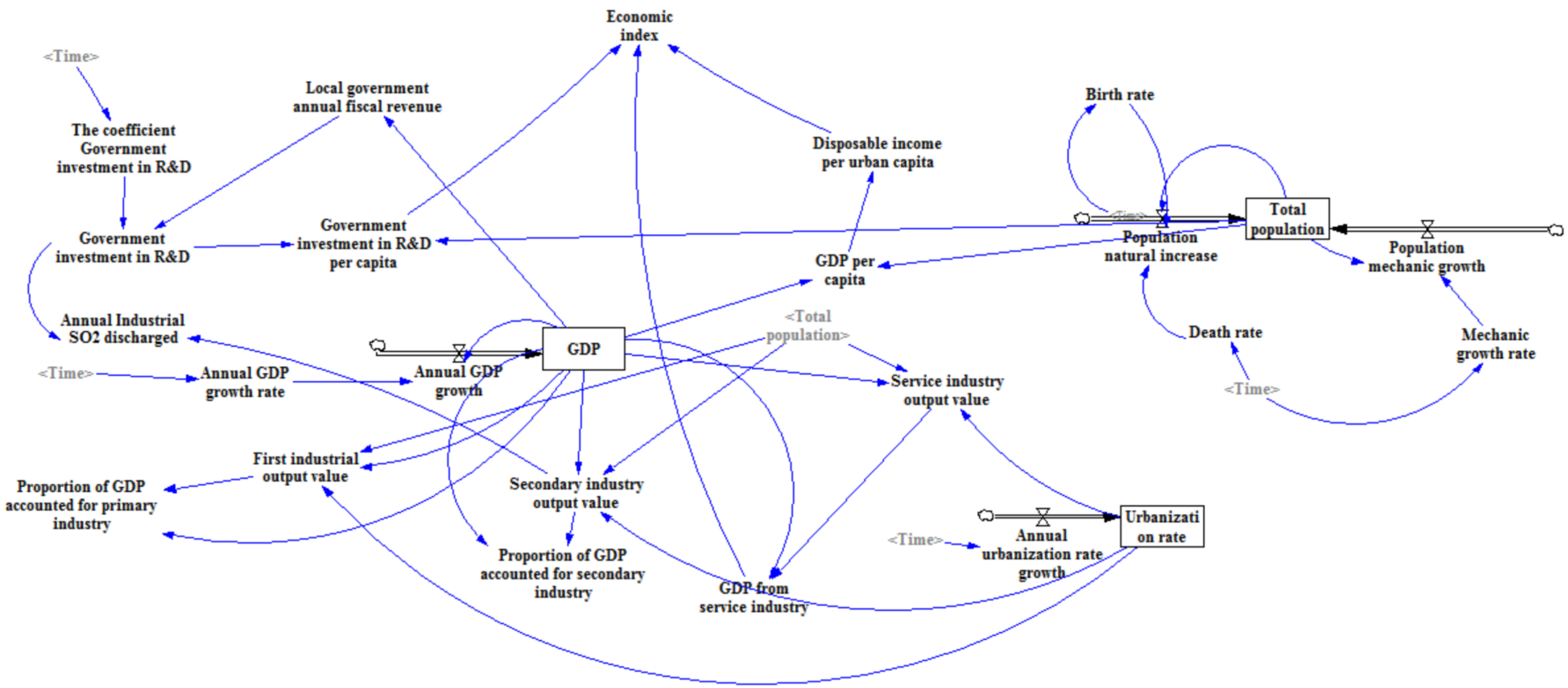


Figure 4 Stock-flow diagram of the economic sector

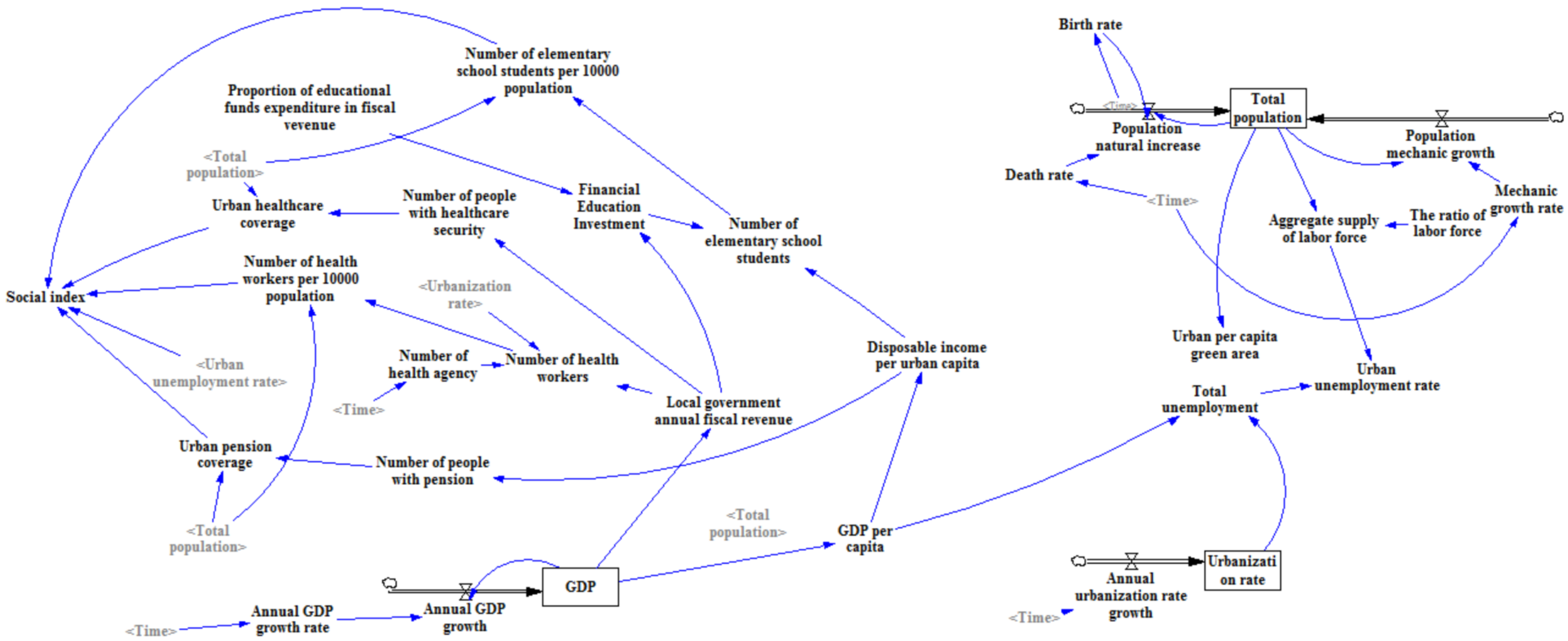


Figure 5 Stock-flow diagram of the social sector

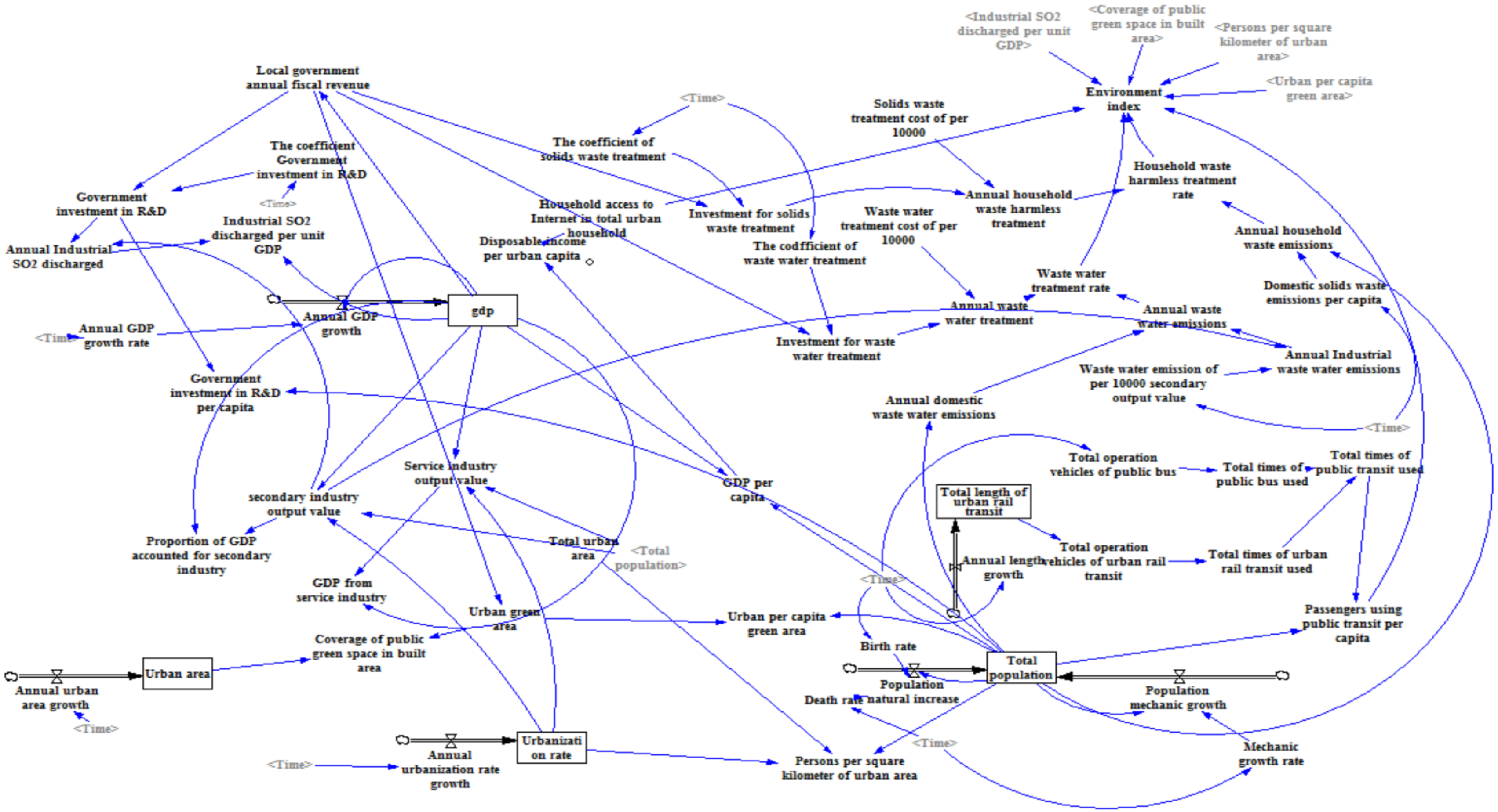


Figure 6 Stock-flow diagram of the environment sector

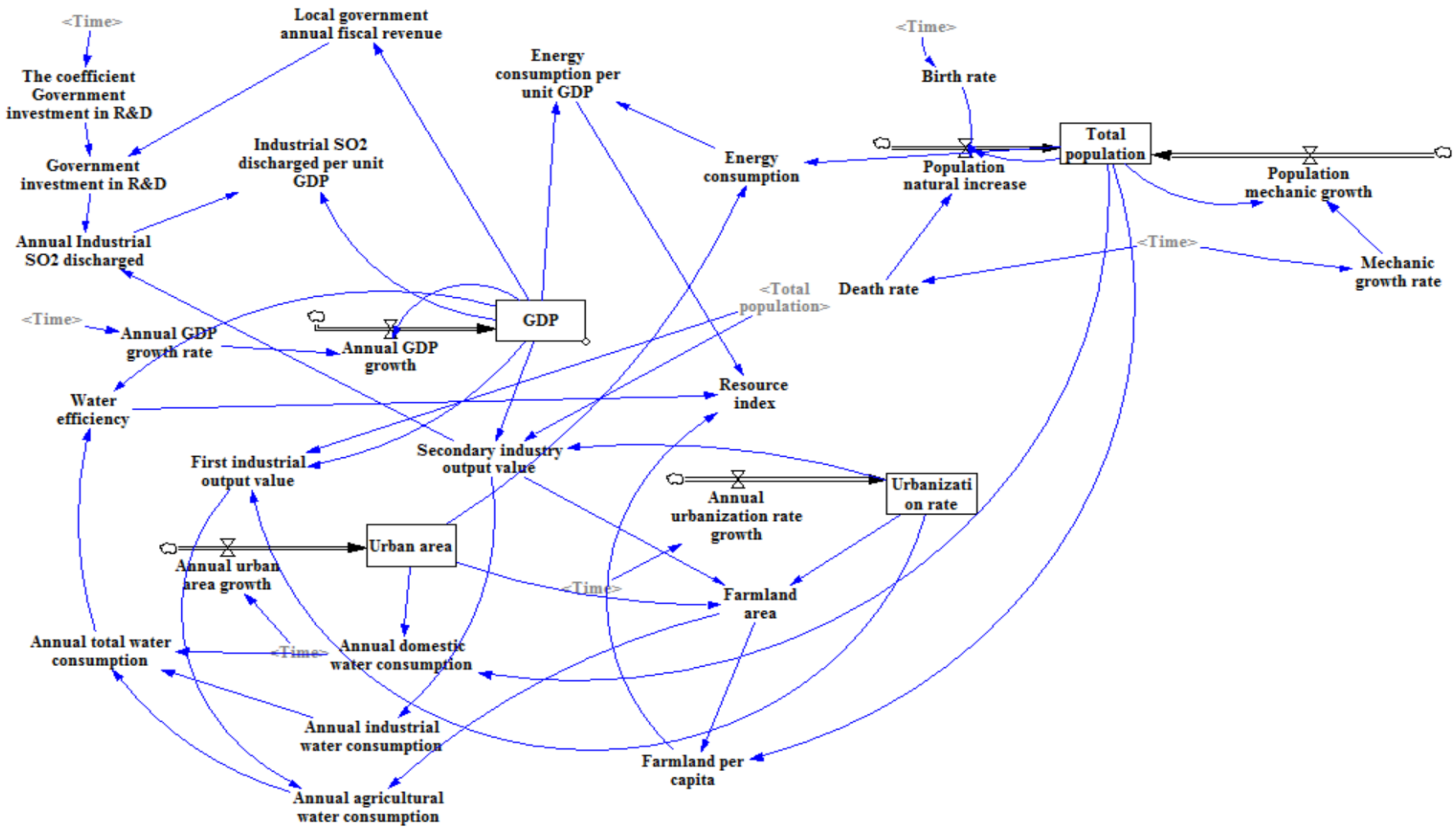


Figure 7 Stock-flow diagram of the resource sector

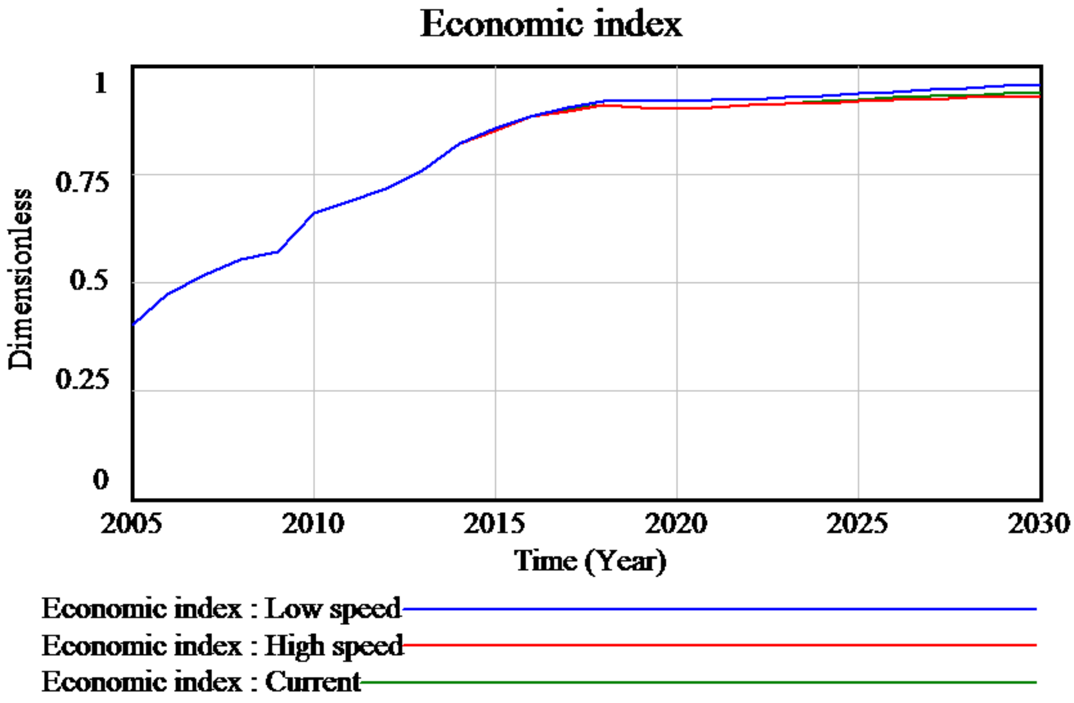


Figure 8 Simulation result of the economic sector

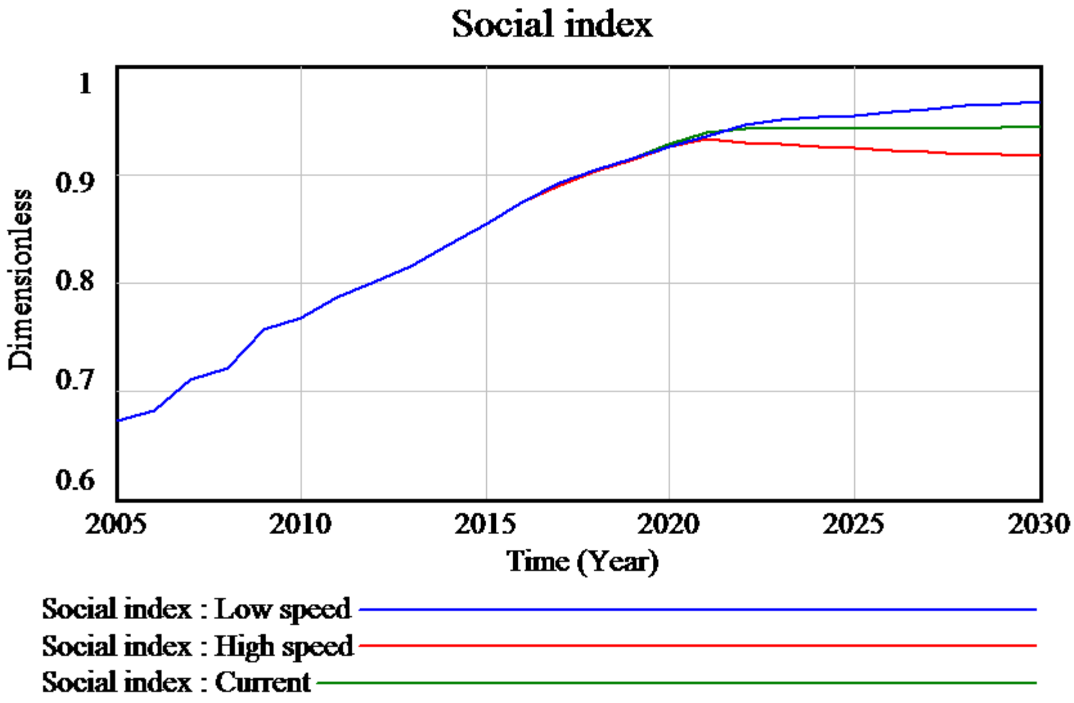


Figure 9 Simulation result of the social sector

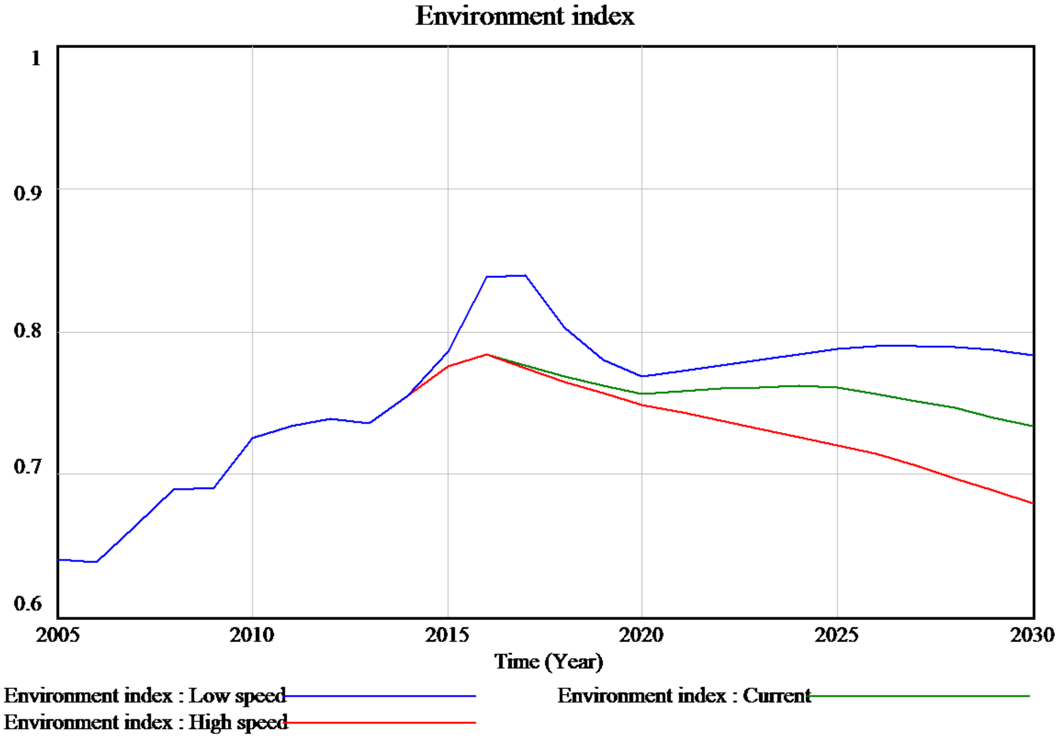


Figure 10 Simulation result of the environment sector

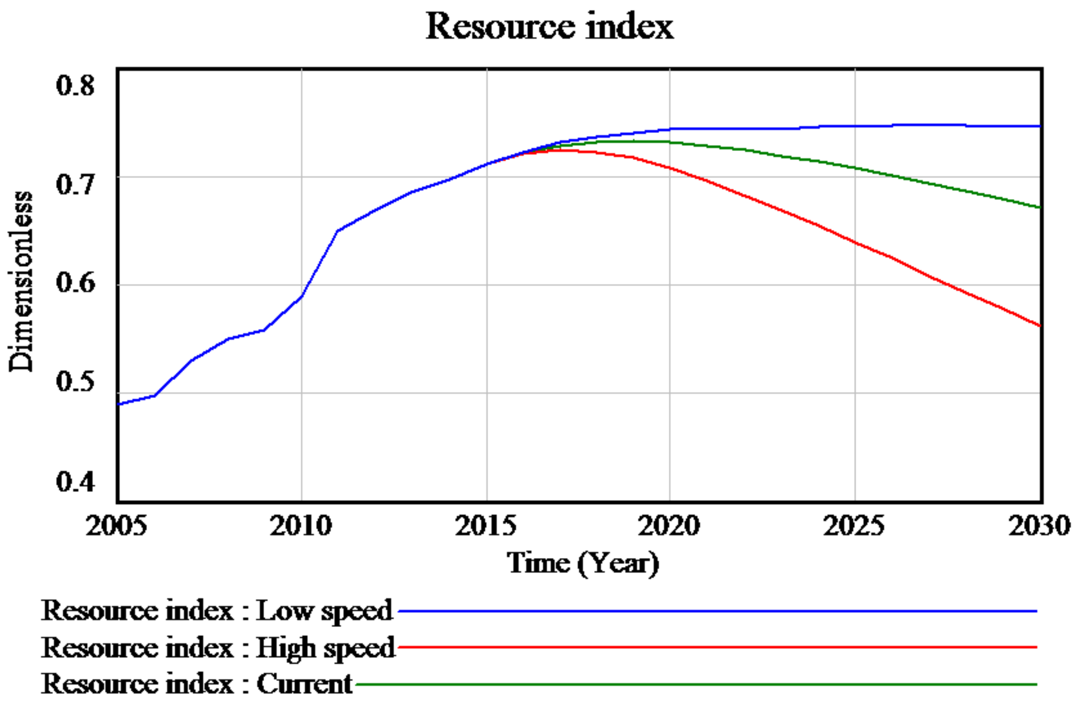


Figure 11 Simulation result of the resource sector

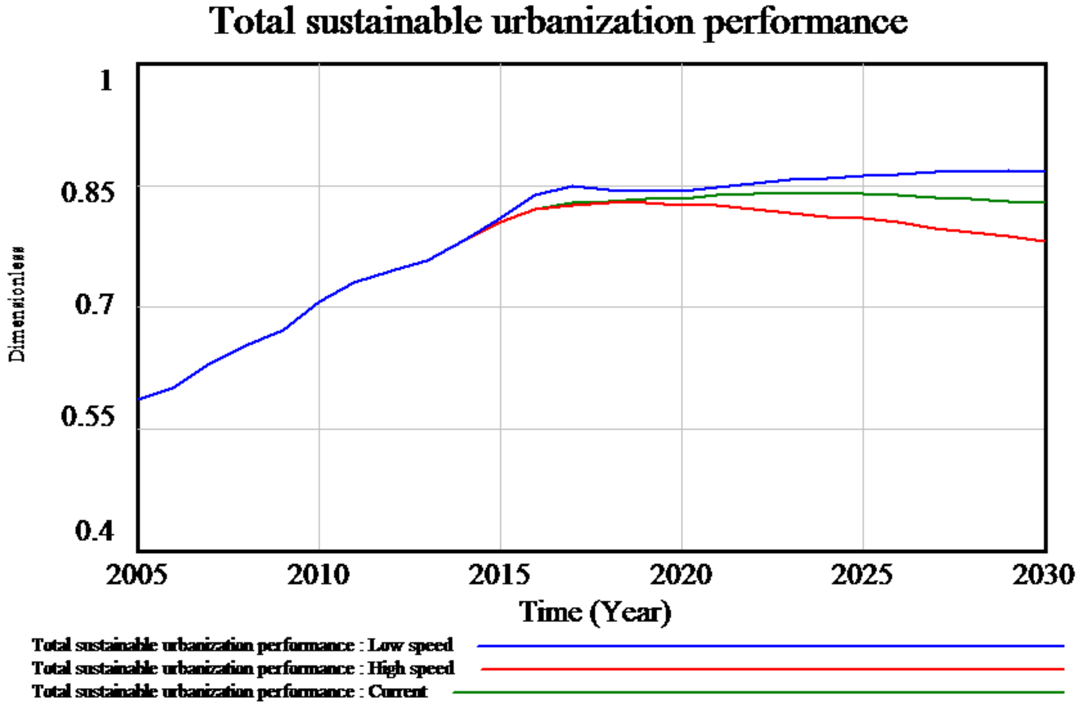


Figure 12 Simulation result of total sustainable urbanization performance

Table

Table 1 Evaluation indicators for sustainable urbanization

Dimensions	Indicators
Economic	Disposable income per urban capita
	Government investment in R&D per urban capita
	GDP from service industry
Social	Urban unemployment rate
	Number of doctors per10,000 urban population
	Number of elementary school students per10,000 urban population
	Pension security coverage
	Health care security coverage
Environment	Persons per square kilometer of urban area
	Passengers using public transit per capita
	Coverage of public green space in built area
	Household access to Internet in total urban household
	Urban per capita green area
	Industrial SO2 discharged per unit GDP
	Wastewater treatment rate
	Domestic waste treated
Resource	Total energy consumption per unit GDP
	Water efficiency
	Farmland per capita

Table 2 Verification with historical data

Year	Total population (Unit: ten thousand)			Service industry output value (Unit: hundred million Yuan)			Number of health workers (Unit: ten thousand)			Annual total water consumption (Unit: hundred million m^3)			Farmland area (Unit: hectare)		
	HD	SR	error %	HD	SR	error %	HD	SR	error %	HD	SR	error %	HD	SR	error %
2005	1,538	1,538	0.00	4,854.33	4,971.13	0.02	15.7	15.94	0.02	33.4	33.56	0.00	2,334	2,433	0.04
2006	1,601	1,570	-0.02	5,837.55	5,921.25	0.01	16.63	16.31	-0.02	32.68	32.53	0.00	2,330	2,343	0.01
2007	1,633	1,607	-0.02	7,236.15	7,351.01	0.02	18.31	18.25	0.00	32.08	31.72	-0.01	2,330	2,325	0.00
2008	1,695	1,651	-0.03	8,375.76	8,372.55	0.00	19.43	19.03	-0.02	31.88	31.33	-0.02	2,320	2,319	0.00
2009	1,755	1,700	-0.03	9,179.19	9,188.89	0.00	21.17	22.69	0.07	31.91	31.10	-0.03	2,317	2,298	-0.01
2010	1,962	1,753	-0.10	10,600.84	10,877.8	0.03	22.36	22.81	0.02	31.19	29.94	-0.04	2,317	2,208	-0.05
2011	2,019	1,811	-0.10	12,363.18	12,667.5	0.02	23.57	23.77	0.01	31.49	30.14	-0.04	2,317	2,343	0.01
2012	2,069	1,873	-0.09	13,669.93	13,999.9	0.02	25.32	24.63	-0.03	30.21	30.00	-0.01	2,210	2,309	0.04
2013	2,115	1,938	-0.08	15,348.61	15,328	0.00	15.7	15.94	0.02	33.4	33.56	0.00	2,334	2,433	0.04
2014	2,152	2,004	-0.07	16,627.04	16,834.9	0.01	16.63	16.31	-0.02	32.68	32.53	0.00	2,330	2,343	0.01

A system dynamics model for simulating urban sustainability performance: A China case study

Abstract

China has been experiencing a rapid urbanization process. Various relevant policies and strategies have been implemented for sustainable urbanization. For a better understanding of sustainable urbanization, many research efforts have been made on urban sustainability assessment. The traditional indicator index is normally used to evaluate the urban sustainability performance. However, the urban development is a complex system, and the existing methods cannot reflect the systemic interactions among variables. Therefore, this paper aims to develop a system dynamics model for simulating urban sustainability performance. The system dynamics model comprises four sub-systems, namely, the economic sector, social sector, environment sector and resource sector. Then, the system dynamics model is used to simulate the sustainability performance of the city, Beijing, with three scenarios. The results indicate that the system dynamics modelling is a useful tool for simulating urban sustainability performance and can help policy makers formulate relevant strategies for a better sustainable development of cities.

Keywords: Sustainable development, System dynamics, Urban sustainability performance, China

1 Introduction

Urbanization has been widely appreciated as one of the most important national development strategies, especially for the developing countries (Shen ~~&~~ and Zhou, 2014). For example, as the biggest developing country in the world, China experienced a rapid urbanization process over the past 30 years. According to statistics, the urbanization level of China increased dramatically from 17.9% in 1978 to 54.8% in 2014 and nearly 600 million people migrated from rural to urban areas (Huang et al., 2016). This movement has been appreciated as a momentous event and attracted wide international attention (Yang, 2013). Many researchers have recognized that urbanization plays a positive role in promoting economic development, improving the living and medical environment, upgrading industrial structure and per capita income (Zhou et al., 2015a；Madlener ~~&~~ and Sunak，2011; Spence ~~&~~ and Buckley, 2009). However, the rapid speed of urbanization could also result in a myriad of environmental problems and social inequities, such as air pollution, acid rain, water and land pollution and solid wastes (Vafa-Arani et al., 2014, Lin et al., 2014; Shen ~~&~~ and Zhou, 2014).

Based on this background, much attention has been paid to the sustainable development of cities. It has been well appreciated that the sustainable development principles need be adopted to guide the urbanization practices by organizations and governments throughout the world because sustainable urbanization is an effective way to promote the sustainable development of urban areas (Tan et al., 2017; Shen et al., 2016a ; Wang et al., 2015). Moreover, it is predicted that the developing countries will still have rapid urbanization over the next several years, and thus have to deal with the sustainable urbanization issues. For example, the urbanization level of China is projected to be 77.5% in 2050, a further increase of 22.7% compared with the urbanization rate in 2014 (Wu et al., 2014). The Chinese government is aware of the importance of sustainable urbanization and is putting efforts in a New-type urbanization path. The most notable aspect of New-type urbanization is the transfer from land-centered urbanization to people-oriented urbanization(Chen et al., 2015). Therefore, an accurate assessment of urban sustainability has become necessary, which not only provides decision makers a better understanding of sustainable urbanization, but also provides useful references for developing relevant sustainable urban development strategies (Han et al., 2009; Uwasu ~~&~~ and Yabar, 2011; Zhou, et al., 2015).

Numerous indicators and assessment tools have been developed by previous researchers for assessing the performance of sustainable urbanization from different perspectives. These indicators and tools have been widely used in academia and practice to assess and monitor the urbanization process (Huang et al., 1998, Zhao ~~&~~ and Chai, 2015; Huang, et al., 2016, Shen, et al., 2011; Zhou, et al., 2015b; Michael, et al., 2014; Charan ~~&~~ and Venkataraman, 2017). Nevertheless, there are some limitations by using indicators to assess urban sustainability. Huang et al. (2009) pointed out that as urban development is a complex system including various variables, the indicators cannot reflect the systemic interactions among these variables, and so cannot provide normative indications of future directions of urban development. It is echoed by Uwasu ~~&~~ and Yabar (2011) that the existing sustainable indicators and tools may ignore some important features of sustainability and do not explicitly address the relations between environmental aspects and socio-economic aspects.

Based on above discussion, there is a need to introduce a method to evaluate urban sustainability performance by considering the interactions among the indicators. Therefore, this study aims to (1) develop a simulation model to assess the level of sustainable urbanization based on the principle of System dynamics; (2) demonstrate the application of the SD model through the case study of the city Beijing in China; (3) analyze the simulation results based on different scenarios.

2. Literature review

System Dynamics (SD) was firstly proposed by Forrester in 1956 for investigating the information-feedback character of industrial systems and improving the organizational form (Thompson ~~&~~ and Bank, 2010). It is well appreciated that SD is an effective tool to analyze the relationships and interactions among the variables in a system. It can help to understand the impact of various factors on the objectives defined in a system and provide useful information for decision-makers (Guan et al., 2011；Yao et al., 2011). It is a typical simulation technique for evaluating the decision-making performance. It can analyze the complex and inter-dependent relationships between the variables in a system and improve the accuracy of the evaluation results.

The system dynamics method has been used in various fields, –such as transportation (Egilmez & and Tatari, 2012; Shepherd, 2014), land use (Yu et al., 2011; Shen et al., 2009), waste management (Yuan et al., 2012), environment management (Chen et al., 2006; Güneralp & and Seto, 2008), and project management (Zhang et al., 2014; Yao et al., 2011). For example, Fong et al. (2009) adopted System Dynamics Model to forecast the CO_2 emission trends with the case of Iskandar Development Region of Malaysia. Shen et al. (2009) applied a system dynamics model for the sustainable land use and urban development in Hong Kong. Guan et al. (2011) developed an integrated evaluation model to assess the urban environment development level of the city Chongqing in China by integrating system dynamics with Geographic Information System (GIS). Yuan et al. (2012) used a System Dynamics method to assess the effects of management strategies on the reduction of construction and demolition waste. Rehan et al. (2012) developed causal loop diagrams and a system dynamics model for financial sustainable management of urban water distribution networks and simulated a series of policy levers between financial sustainability and household affordability.

However, there are a few existing studies that have used the System Dynamic for simulating and evaluating urban sustainability performance. Huang and Chen (1999) developed a dynamic urban system model, which includes six subsystems: land use, population, transportation, water resource, solid waste and waste water treatment, to simulate the performance of the urban sustainability of the city Taipei. This model cannot be used for evaluating the cities in China directly because China has different characteristics of urban development. Han et al. (2009) presented an integrated system dynamics and cellular automata model for assessing the speed of urban growth. He selected the city, Shanghai, in China as a case study, which is not for sustainable urbanization. Mavrommati et al. (2013) proposed a System Dynamics approach for Ecologically Sustainable Development (ESD) in urban coastal systems, which mainly focused on the relationship between environmental and economic dimensions, without the variables of social dimensions.

Based on above literature review, it can be summarized that the System Dynamics method has been used by many researchers in various fields. However, there are few studies on applying System Dynamics to sustainable urbanization. The existing studies can provide useful references for simulating urban sustainability performance in this study. This research will apply System Dynamics to simulate the performance of sustainable urbanization in China.

3 Methodology

In this study, the method of System Dynamics was used for simulating urban sustainability performance. There are three main elements of System Dynamics, including feedback loops, variables, and equations (Vafa-Arani et al., 2014). The feedback loop is defined as a closed chain of causes and effects. Figure 1(a) is an example of the feedback loop of population change (Trappey et al., 2011). The population is influenced by two variables, Birth Rate and Death Rate. When the birth rate increases, the population will increase. When the death rate increases, the population will decrease. Therefore, the left of the diagram shows a positive feedback loop and the right shows a negative feedback loop.

<Please insert Figure 1 here>

There are three main kinds of variables in a feedback loop, including the stock variable, the rate variable, and the auxiliary variable. The stock variable accumulates a flow over continuous time periods; the rate variable represents a flow during a time period; and the auxiliary variable identifies rate variables. The three kinds of variables are linked by equations with the form of integral, differential, or other types. Figure 1(b) shows a simple system dynamics model for simulating the population growth of a city (Trappey et al., 2011). In Figure 1(b), the variable—Population will change with time, and is defined as stock variable. The variables— Birth and Death are defined as rate variables. The rates of birth and death are the auxiliary variables.

System dynamics has three general steps: articulation of the problem or conceptualization, dynamic hypothesis formulation, and then testing and analysis, as shown in Figure 2 (Espinoza et al., 2017). Therefore, in this study, the first step, identifying the key variables of the SD model will be based on the review of the existing urban sustainability assessment indicators, such as the urban sustainable development index issued by McKinsey Company and Tsinghua University in China (Urban Sustainability Index~~UCI~~, 2014)~~ (http://www.urbanchinainitiative.org/en/)~~, Shen et al. (2011), Uwasu ~~&~~ and Yabar (2011), Shen ~~&~~ and Zhou (2014), Zhang (2015) and Tan et al. (2016). The availability of data is also considered when identifying the key variables. Finally, 19 basic indicators under four dimensions are identified, as shown in Table 1, and will be used as key variables for the SD model.

<Please insert Figure 2 here>

<Please insert Table 1 here>

After identifying the key variables, the next step is to establish the stock-flow diagram among the variables. A stock-flow diagram is to depict the relationships between the variables in the system through the above two kinds of flows. The existing SD models related to sustainable urbanization, such as Shen et al. (2009), Han et al. (2009), Guan et al. (2011) and Mavrommati et al. (2013), are used as references to analyze the relationships between the variables in this study.

4. SD model development

Based on the 19 indicators selected in Table 1, and through the stock-flow diagram analysis of the variables, a system dynamics model of urban sustainability is established in this study, as shown in Figure 3. The software Vensim PLE 5.1 was used for developing the diagrams. The SD model consists of four sub-systems, economic sector, social sector, environment sector and resource sector. The stock-flow diagrams of the four sub- systems will be presented in each sector, respectively.

<Please insert Figure 3 here>

Economic sector

The economic sector plays an important role during the urbanization process of a city. Previous study suggests that good economic sustainability during urbanization is characterized by several indicators such as a high GDP level and stable economic condition (Shen et al., 2016a). Therefore, the total economic index is mainly determined by three key variables, GDP from service industry, Government investment in R&D per capita and Disposable income per urban capita in this study. The stock-flow diagram of the economic sector is shown in Figure 34. In Figure 4, stock variables describe the cumulative effect of the system, which can react to the accumulation of material, energy and information over time. There are three stock variables, Total population, Urbanization rate and GDP in economic sector. Rate variable describes the speed of the system's cumulative effect and reflects the changes of stock variables over time, representing the speed of change in the system or the amplitude of a decision. Four rate variables, Annual GDP growth, Population growth (natural increase), Population growth (migratory increase), Annual urbanization rate growth are introduced. Auxiliary variables are the intermediate variables, which run through the entire decision-making process and 13 auxiliary variables are in the economic sector. Figure 4 also shows the relationships among interacting variables. For example, the key auxiliary variable, GDP from service industry, is mainly influenced by three auxiliary variables: Total population, Urbanization rate and GDP (Han et al., 2009). The Government investment in R&D is mainly from the local government annual fiscal revenue. The variable of Disposable income per urban capita is highly related to the GDP per capita. The higher GDP per capita, the higher Disposable income per urban capita is. The stock variable, Total population, is determined by two rate variables: Population growth (natural increase) and Population growth (migratory increase), (Shen et al., 2009).

<Please insert Figure 4 here>

Social sector

It has been pointed out that urbanization should bring social benefits in the areas of medical treatment, education, health and others (Dye, 2008; Zhou et al., 2015). Therefore, the social index was determined by five key variables: Urban unemployment rate, Number of doctors per 10,000 urban population, Number of elementary school students per 10,000 urban population, Pension security coverage and Health care security coverage. The stock-flow diagram of the social sector is shown in Figure 5. Similar to the economic sector, there are also three stock variables, Total population, Urbanization rate, GDP; four rate variables, Annual GDP growth, Population growth (natural increase), Population growth (migratory increase), Annual urbanization rate growth in this sector and 23 auxiliary variables. Furthermore, in the social sub-system, the variables of Local government annual fiscal revenue and Disposable income per urban capita are defined as two core variables because they have influence on other variables. For example, the auxiliary variable Number of elementary school students is in high correlation with the two auxiliary variables: Disposable income per urban capita and financial education investment (Gao ~~&~~ and Shi, 2008).

<Please insert Figure 5 here>

Environment sector

The Chinese government has been putting more attention on environmental issues in recent years. The ecological degradation and environmental pollution due to fast economic development are two major problems in China. Moreover, the environment sector is influenced by the economic sector and social sector. The whole environment sub-system includes five stock variables, six rate variables and 42 auxiliary variables, as shown in Figure 6. The stock-flow diagram shows the relationships among the variables. For example, the auxiliary variable of Urban green area is directly influenced by the variable of local government annual fiscal revenue (Han et al., 2009) and the Annual waste water emissions is determined by two auxiliary variables: Annual domestic waste water emissions and Annual industrial waste water emissions (Guan et al. 2011).

<Please insert Figure 6 here>

Resource sector

Rapid urbanization consumes a lot of resources including land, water and fossil energy (Tan et al., 2016; Han et al., 2017). The stock-flow diagram of the resource sector is shown in Figure 7. There are four stock variables, Total population, Urbanization rate, GDP and Urban area; five rate variables, Annual GDP growth, Population growth (natural increase), Population growth (migratory increase), Annual urbanization rate growth, Annual urban area growth, and 15 auxiliary variables, in this sector. For example, the auxiliary variable of Annual total water consumption is considered from three aspects: Annual domestic water consumption, annual industrial water consumption and annual agricultural water consumption (He et al., 2011).

<Please insert Figure 7 here>

5 Model simulation and results analysis

The application of the established SD model was demonstrated by a case study of the city, Beijing in China. Beijing, as the capital of China, is one of the largest cities in China. It's population reached 21.7 million and the total GDP was nearly 23 thousand billion Yuan by the end of 2015 (National Bureau of Statistics, 2016). However, the rapid urbanization process has caused some environmental and social problems, especially the air pollution, hazy weather and traffic congestion, that have become serious in Beijing and have raised dramatic attention in China. In order to solve these problems, relevant measures for prompting sustainable development in Beijing have been implemented, such as developing an urban public transportation system, and reducing carbon emissions (Beijing Municipal Commission of Development & Reform, 2016). Therefore, Beijing is a good case for studying sustainable urban development in China.

5.1 Model validation

Firstly, it is imperative to test the accuracy and feasibility of the SD model. This can be fulfilled by obtaining a match between the simulated results (SR) and historical data (HD) of the variables in the system. The data for Beijing were collected from the website of the National Bureau of Statistics in China. To validate the SD model, the time horizon for the variables was set as 10 years, from 2005-2014. Matching results were obtained through the software Vensim PLE 5.1 and the matching results of the five variables, Total population, Service industry output value, Number of health workers, Annual total water consumption and Farmland area, were selected for demonstration of the SD model validation. The matching results are shown in Table 2. It can be seen that the simulated values of variables are very close to the real values, with very low relative errors. This indicates the high validity of the SD model. Therefore, the established SD model is reliable to represent the causal feedback relationships among the variables, and simulate the urban sustainability performance.

<*Please insert Table 2 here*>

5.2 Simulation scenarios

Scenario analysis is useful for assuming a possible range of futures, based upon which effective strategies and actions are to be sought (Kishita et al., 2016). The values of variables and parameters in the SD model can be adjusted based on different scenarios, and the simulation results will be different. Subsequently, relevant sustainable development strategies can be developed based on different simulation results. These developing strategies and their influence on cities' future sustainability performance can be further examined by re-using the SD model.

In this study, three different development scenarios were assumed for SD model simulation. The first scenario is that the current economic development speed is maintained, with all parameters and variables at their current growth rate. The investment on sustainable development is still at the current rate. Secondly, a faster urbanization process with higher economic and population growth rate was assumed. Under this scenario, the values of the variables, Annual GDP growth, Population growth, Annual urbanization rate growth were higher than the current growth rate. The investment on sustainable development was held still at the current rate. Thirdly, as a contrast, a slower urbanization process with slower economic and population growth rate was assumed. Under this scenario, the values of the variables, Annual GDP growth, Population growth, Annual urbanization rate growth were lower than the current growth rate, but the investment on sustainable development was set higher than the current rate. The simulation time horizon of the SD model for the three simulation scenarios is 25 years, from 2005 to 2030.

5.3 Simulation results

The software Vensim PLE 5.1 was used simulate the urban sustainability performance of Beijing, based on the three scenarios. The stock-flow diagrams developed above were used for scenario analysis. The equations were developed based on the relevant studies and regression analyses among the variables (Shen et al., 2009; Han et al., 2009; Guan et al., 2011). Due to the limitation of the paper length, eight equations in the SD model were selected for demonstration and are illustrated as follows：

1) Total sustainable urbanization performance=Economic index*0.17+ Environment index*0.33+Social index*0.33+Resource index*0.17
2) Annual household waste emissions= Domestic solids waste emissions per capita*Total population (Unit： ten thousand tons)
3) Annual Industrial waste water emissions=Secondary industry output value*Waste water emission of per 10,000 secondary output value (Unit: ten thousand tons)
4) Annual total water consumption=Annual agricultural water consumption+ Annual industrial water consumption+ Annual domestic water consumption (Unit: hundred million m^3)
5) Annual waste water emissions= Annual Industrial waste water emissions+ Annual domestic waste water emissions (Unit: ten thousand tons)
6) Financial Education Investment=Proportion of educational funds expenditure in fiscal revenue*Local government annual fiscal revenue (Unit: hundred million Yuan/RMB)
7) Public transport journeys per capita=Total number of public transport journeys/Total population (Unit: number of public transport journeys per person)
8) Urban green area=16,525*LN (Local government annual fiscal revenue)-74,153 (Unit: square kilometer)

Simulation results of the economic sector

The simulation result of the economic sector of the city, Beijing, from 2005 to 2030, is shown in Figure 8. It can be seen that the difference between the three scenarios is small, and the economic sector will keep a steady growth in future. According to the results of UCI (2012), the economic index of Beijing is ranked 1st among the surveyed 185 cities in China from 2005 and 2011. Moreover, the urbanization rate of Beijing was 86.5% by the end of 2015 and Beijing has reached to a terminal stage of urbanization, according to Northam's theory of urbanization stage division

(Northam,1975). From the past experience of the urbanization process in China, economic development is the primary work in the initial urbanization stage. Through the past 30 years' rapid development, the economic level of Beijing has already reached to a steady stage. Therefore, there are minor differences between the three scenarios of Beijing's economic development.

<Please insert Figure 8 here>

Simulation of social sector

Figure 9 presents the simulation performance of the social sector of Beijing from 2005 to 2030. Under the low speed scenario, the performance of the social sector of Beijing will keep a steady growth in future. Under the current speed, the social performance will have a slow growth until 2021, with no changes after that. Under the high speed scenario, the performance of the social sector of Beijing has a declining trend during the period of 2021 to 2030.

A comparison of these three results indicates that a low speed of urbanization process should be adopted by Beijing to maintain a sustainable social development. Previous studies appreciated that the social development is also a main purpose of urbanization, and urbanization should have positive effects on social aspects, including social mobilization, literacy, political participation, education, and health, especially at the initial stage of urbanization (Dye, 2008). Now, Beijing is the educational, cultural and healthcare centre of China. High quality services in education, social welfare and healthcare are provided in Beijing. According to the calculated results of UCI (2012), the social index of Beijing is ranked 4th among the surveyed 185 cities in China in 2011. It also indicates that the social development level of Beijing has reached a high level.

<Please insert Figure 9 here>

Simulation results of the environment sector

The simulation results under the three simulation scenarios are quite different in the environment sector, as shown in Fig. 10. This shows that, under the low speed development, the environment sector performs much better than the other two scenarios. Under the low speed scenario, the environmental performance will reach the peak value in 2016-17, and decline until 2021, then gain another growth until 2027. Under the current speed scenario, the environmental performance also has some fluctuations, which will reach the peak value in 2016, and decline until 2020, then gain another low growth until 2025. Under high speed scenario, the environmental performance will decline during the period of 2016 to 2030. It can be seen that the lower speed economic development and higher investment on environment protection are very effective for improve Beijing's environmental performance. The government needs to balance the economic development and environment protection (Shen et al., 2017). Air pollution is considered as a major environmental problem in Beijing and its environmental performance was just ranked 27th among 185 cities in China according to the ranked results of UCI in 2005. However, many efforts have been put in by the

Beijing government to improve the environmental condition in recent years, such as the "Clean Air Action Plan" and "Air Pollution Prevention and Control regulations" (Zhang, et al., 2016) and it has achieved a good level of progress. It is also reported by the United Nations Environment Programme (2015) that the air quality of Chinese cities is improving notably, such as Beijing, Shanghai, and the air management experiences in these cities are a good reference for other cities in the world.

<Please insert Figure 10 here>

Simulation results of the resource sector

The simulation results are shown in Fig. 11. The differences between the three scenarios are obvious. Under the current and high speed scenarios, the resource sector performance will decline. Under the low speed scenario, the performance will keep a low steady growth. Water resource shortage is a major problem in Beijing. According to statistics, the average shortage volume of water in Beijing from 2005 and 2014 is 0.6 billion m^3 (Beijing Municipal Commission of Development & Reform, 2016). Farmland shortage is another major problem in Beijing. It was reported that, from 1996 to 2009, the loss of farmland in Beijing is around 87 square kilometres per year (Ministry of Land Resource of the People's Republic of China, 2016).

<Please insert Figure 11 here>

Simulation results of total performance

By integrating the four sectors, the total sustainable urbanization performance of

Beijing was simulated and the result is shown in Fig. 12. It can be seen that the total sustainable urbanization performance of Beijing is high. According the ranking of UCI, the sustainability performance of Beijing was ranked within the top 10 among 185 surveyed cities in China from 2005 -2011. As shown in Fig. 10, under the high speed scenario, the sustainability performance of Beijing would be declining. Under the low speed scenario, there would be a steady growth until 2030. Under the current scenario, the total sustainability performance would have a low growth from 2016 to 2024, then decline. It indicates that a low speed of urbanization policy should be adopted by Beijing for achieving a sustainable development. The relationship between urban sustainability and urbanization depicted by Shen et al. (2012) is that in the initial urbanization stage, the impact of urbanization on economic and social development is low, and therefore, the sustainable urbanization performance is low. When urbanization continues, its effect on the economy, society, and environment increases; thus, the urbanization sustainability increases. But, the improvement of sustainability will be slow in the terminal stage of urbanization and the sustainability will maintain a certain level.

<Please insert Figure 12 here>

5.4 Policy suggestions

Based on the above scenario analysis, it can be summarized that that the urbanization speed has an impact on Beijing's sustainable development. The low speed development pattern will contribute to a higher urban sustainability performance than other two scenarios. The total performance will keep declining even at the current urbanization speed. Therefore, the imperative task of Beijing is to improve the quality of urbanization rather than the speed of urbanization (Jiao et al., 2016). The economic and social sectors of Beijing perform better than the environment and resource sectors. In order to improve the total urban sustainability performance of Beijing, the government should put more efforts on the environment and resource sectors, and improve the balance between sectors. With the above analysis, relevant policy suggestions can be proposed for the four sectors.

Economic sector

Economic development is still the primary task of urbanization in China. However, those mega cities, such as Beijing, and Shanghai, are already the leaders in economic development in China, and are already at the terminal stage of urbanization, according to Northam's urbanization development theory (Shen et al., 2017). Berry (1973) suggested that the positive relationship exists between GDP per capita and urbanization, which is obvious at the initial stage of urbanization. However, Shen et al. (2012) assumed that the economies will grow slowly and even stop growing at a certain level in the later stage of urbanization because the impact of urbanization to economic development will decreased in the later stages. Therefore, in order to promote the economic development, other patterns need to be considered. For example, the National New-type Urbanization Plan (2014-2020) issued by the Chinese government places emphasis on people (Wang et al., 2015) and it defined three main tasks in the future urbanization:- (1) gradually settle the former agricultural population who have migrated to the cities; (2) optimize urbanization; , and (3) increase the sustainability of cities to eventually achieve unified urban and rural development. With the increasing level of urbanization in China, the economic development will keep growing. Yet, there is a need for government to balance the development of different sectors. Perhaps surprisingly, a lower economic development speed may be a better choice for those cities with a high level of urbanization.

Social sector

Similar with the economic sector, the effect of urbanization on the social sector would be decreased when at the mature stage of urbanization, and even become negative if urbanization goes beyond the carrying capacity of a city (Shen et al., 2012). The simulation performance of the social sector of Beijing is good, but the performance presents a tendency of decline under the high speed simulation scenario. It also pointed out by Cao et al. (2014) that in most large cities in China, the social welfare resources such as education, healthcare and insurance, are only provided to their registered residents. Therefore, it is imperative to promote equitable and universal public services for all residents, including social security, medical treatment, education, and culture in Beijing.

Environment sector

The performance of the environment sector of Beijing is the lowest of the other three sectors. Alberti and Marzluff (2004) pointed out that the rapid urbanization will induce environmental degradation and decrease the city environment quality. If without external intervention, the deterioration would continue, which will result in the city's demolition or abandonment. Based on the research result of Alberti and Marzluff (2004), Shen et al. (2012) argued that the environmental deterioration can be avoided and the environment quality can be improved and maintained at a certain level through proper policy intervention. The simulation results under the low speed scenario in this study show that proper policy intervention can help improve the environment performance of cities. It has been well appreciated that financial support by government is an effective tool for improving the environment management quality and energy saving by arousing the public and business awareness and enthusiasm of implementing environment management policies (Shen et al., 2016b; He et al., 2012; Kanada et al., 2013). Therefore, with the prosperous economic development, the Beijing government should provide financial support and relevant public policies to improve the city environment condition.

Resource sector

Similar with environment sector, the resource sector also presents a declining tendency under the current and high urbanization speed. Many previous studies have examined the relationship between urbanization and total energy consumption and it is well appreciated that urbanization and energy consumption are positively related.

(Ni ~~&~~ and Thomas, 2004; Zhou et al., 2012; Lenzen et al., 2006; Sun et al., 2014; Yang et al., 2015; Martínez-Zarzoso, ~~&~~ and Maruotti, 2011). For example, Zhou et al. (2012) reported that urbanization has profoundly affected on the energy consumption of residential households, transportation, and the building materials industry. Lenzen et al. (2006) found that as the process of urbanization develops further, the per capita energy consumption is generally higher in areas of high urbanization than that in areas of low urbanization, and the energy consumption structure is more advanced in the high urbanization areas, which is echoed by Sun et al. (2014). Therefore, it is suggested that the government should consider how to use resources more efficiently, such as new technologies for energy saving, green products, and low-carbon emission technologies (Ni ~~&~~ and Thomas, 2004； Li et al., 2016; Wang et al., 2016).

6 Summary and Conclusions

Many developing countries will still experience the rapid development of urbanization in the future. Accurate assessment results of the sustainable urbanization are imperative for understanding the urbanization process and providing support to the implementation of urban development strategy. In this study, a System Dynamics model that comprises an integrated economic-social-environmental–resource subsystem is established to assist simulating the performance of sustainable urbanization. The case study of Beijing in China demonstrates that the SD model is helpful to simulate the performance of sustainable urbanization. The SD model has a number of advantages. First, the method provides a new angle in assessing the sustainable urbanization performance. Second, this method can improve the accuracy of the assessment results by considering the complex and inter-dependent relationships between the variables in the process of urbanization. Third, through the results analyses under different simulation scenarios, different policies and strategies can be implemented to guide the development of urbanization.

It is also appreciated that different cities may have had different main tasks in the urbanization process. For the city of Beijing, its major task is improving the urbanization quality, especially the environment condition and resource protection and utilization, since Beijing has already reached to the terminal stage of urbanization. For other cities in the central and west regions in China with a low urbanization rate, their major mission is coordinate between the speed of the urbanization and environment protection. It is the further research agenda of this research team to examine the sustainable urbanization performance of other cities in China by using the established SD model.

Acknowledgements

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 25223215).The authors would also like to acknowledge the editing by Dr. Paul W. Fox of an earlier draft of this paper.

References

Alberti, M., & Marzluff, J. M. (2004). Ecological resilience in urban ecosystems: linking urban patterns to human and ecological functions. *Urban ecosystems*, *7*(3), 241-265.

Berry, B. J. L. (1973). *The human consequences of urbanization: Divergent paths in the urban experience of the twentieth century*. St. Martin's Press, New York, America.

Beijing Municipal Commission of Development & Reform .(2016) .Retrieved from http://www.bjpc.gov.cn/English/201512/t9802512.htm

Cao, S., Lv, Y., Zheng, H., & Wang, X. (2014). Challenges facing China's unbalanced urbanization strategy. *Land Use Policy*, 39, 412-415.

Charan, A. S., & Venkataraman, H. (2017). Greening the Economy: A Review of Urban Sustainability Measures for Developing New Cities. *Sustainable Cities and Society*, 32,1-8

Chen, M. C., Ho, T. P., & Jan, C. G. (2006). A system dynamics model of sustainable urban development: Assessing air purification policies at Taipei City. *Asian Pacific Planning Review*, 4(1), 29-52.

Chen, M., Liu, W., & Lu, D. (2015). Challenges and the way forward in China's new-type urbanization. *Land Use Policy*, 55, 334-339.

Dye, C. (2008). Health and urban living. *Science*, 319(5864), 766-769.

Egilmez, G., & Tatari, O. (2012). A dynamic modeling approach to highway sustainability: Strategies to reduce overall impact. *Transportation Research Part A:*

Formatted: Font: Not Italic

Formatted: Font: (Default) Times New Roman, 12 pt, Not Italic, Font color: Auto, Pattern: Clear

Policy and Practice, 46(7), 1086-1096.

Espinoza, A., Bautista, S., Narváez, P. C., Alfaro, M., & Camargo, M. (2017). Sustainability assessment to support governmental biodiesel policy in Colombia: A system dynamics model. *Journal of Cleaner Production*, 141, 1145-1163.

Fong, W. K., Matsumoto, H., & Lun, Y. F. (2009). Application of System Dynamics model as decision making tool in urban planning process toward stabilizing carbon dioxide emissions from cities. *Building and Environment*, 44 (7), 1528-1537.

Gao, L., & Shi, X. Y. (2008). An Analysis of the Systematic Dynamics in the Interaction between Education and Economy and Its Enlightenment. *Journal of Shaanxi Normal University (Philosophy and Social Sciences Edition)*, 37(2), 96-101.

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. *Ecological Indicators*, 11(5), 1333-1344.

Güneralp, B., & Seto, K. C. (2008). Environmental impacts of urban growth from an integrated dynamic perspective: A case study of Shenzhen, South China. *Global Environmental Change*, 18(4), 720-735.

Han, J., Hayashi, Y., Cao, X., & Imura, H. (2009). Application of an integrated system dynamics and cellular automata model for urban growth assessment: A case study of Shanghai, China. *Landscape and Urban Planning*, 91(3), 133-141.

Han, J., Meng, X., Zhou, X., Yi, B., Liu, M., & Xiang, W. N. (2017). A long-term analysis of urbanization process, landscape change, and carbon sources and sinks: A case study in China's Yangtze River Delta region. *Journal of Cleaner Production*, 141, 1040-1050.

He, G., Lu, Y., Mol, A. P., & Beckers, T. (2012). Changes and challenges: China's environmental management in transition. *Environmental Development*, 3, 25-38.

He, R. W., Liu, S. Q., & Liu, Y. W. (2011). Application of System Dynamics in Analyzing the Carrying Capacity of Water Resources in Karst Region of Southwest China--A Case Study in Bijie Region, Guizhou Province. *Scientia Geographica Sinica*, 31(11), 1376-1382.

Huang, S. L., & Chen, C. W. (1999). A system dynamics approach to the simulation of urban sustainability. Ecosystems and Sustainable Development II, WIT Press, Southampton, England.

Huang, L., Yan, L., & Wu, J. (2016). Assessing urban sustainability of Chinese megacities: 35 years after the economic reform and open-door policy. *Landscape and Urban Planning*, 145, 57-70.

Huang, S. L., Wong, J. H., & Chen, T. C. (1998). A framework of indicator system for measuring Taipei's urban sustainability. *Landscape and urban planning*, 42(1), 15-27.

Huang, S. L., Yeh, C. T., Budd, W. W., & Chen, L. L. (2009). A Sensitivity Model (SM) approach to analyze urban development in Taiwan based on sustainability indicators. *Environmental impact assessment review*, 29(2), 116-125.

Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., & Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran. *Transportation Research Part D: Transport and Environment*, 31, 21-36.

Jiao, L., Shen, L., Shuai, C., & He, B. (2016). A Novel Approach for Assessing the Performance of Sustainable Urbanization Based on Structural Equation Modeling: A China Case Study. *Sustainability*, 8(9), 910.

Kanada, M., Dong, L., Fujita, T., Fujii, M., Inoue, T., Hirano, Y., ... & Geng, Y. (2013). Regional disparity and cost-effective SO 2 pollution control in China: A case study in 5 mega-cities. *Energy Policy*, 61, 1322-1331.

Kishita, Y., Nakatsuka, N., & Akamatsu, F. (20176). Scenario analysis for sustainable woody biomass energy businesses: The case study of a Japanese rural community. *Journal of Cleaner Production*, 142, 1471-1485.

Lenzen, M., Wier, M., Cohen, C., Hayami, H., Pachauri, S., & Schaeffer, R. (2006). A comparative multivariate analysis of household energy requirements in Australia, Brazil, Denmark, India and Japan. *Energy*, *31*(2), 181-207.

Li, H., Zhao, X., Yu, Y., Wu, T., & Qi, Y. (2016). China's numerical management system for reducing national energy intensity. *Energy Policy*, 94, 64-76.

Lin, T., Gibson, V., Cui, S., Yu, C. P., Chen, S., Ye, Z., & Zhu, Y. G. (2014). Managing urban nutrient biogeochemistry for sustainable urbanization. *Environmental Pollution*, 192, 244-250.

Liu, X., Ma, S., Tian, J., Jia, N., & Li, G. (2015). A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO 2 emissions: A case study of Beijing. *Energy Policy*, 85, 253-270.

Madlener, R., & Sunak, Y. (2011). Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management?. *Sustainable Cities and Society*, 1(1), 45-53.

Martínez-Zarzoso, I., ~~&~~ Maruotti, A. (2011). The impact of urbanization on CO 2 emissions: evidence from developing countries. *Ecological Economics*, *70*(7), 1344-1353.

Mavrommati, G., Bithas, K., ~~&~~ Panayiotidis, P. (2013). Operationalizing sustainability in urban coastal systems: A system dynamics analysis. *Water research*, 47(20), 7235-7250.

Michael, F. L., Noor, Z. Z., ~~&~~ Figueroa, M. J. (2014). Review of urban sustainability indicators assessment–Case study between Asian countries. *Habitat International*, 44, 491-500.

Ministry of Land Resource of the People's Republic of China. (2016).~~-~~.Retrieved from ~~http://~~www.mlr.gov.cn/mlrenglish/

National Bureau of Statistics~~,~~.(2016) ~~（ 2016 ）~~ ~~2016~~. Retrieved from ~~http://~~*data.stats.gov.cn*

Ni, W., ~~&~~ Thomas, B. J. (2004). Energy for sustainable development in China. *Energy Policy*, 32(10), 1225–1229

Northam, R. M. (1975). Urban geography. John Wiley & Sons, New York, America~~NY~~.

Rehan, R., Knight, M. A., Unger, A. J. A., ~~&~~ Haas, C. T. (2013). Development of a system dynamics model for financially sustainable management of municipal watermain networks. *Water research*, 47(20), 7184-7205.

Shen, L., He, B., Jiao, L., Song, X., ~~&~~ Zhang, X. (2016b). Research on the development of main policy instruments for improving building energy-efficiency. *Journal of Cleaner Production*, *112*, 1789-1803.

Shen, L., Peng, Y., Zhang, X., ~~&~~ Wu, Y. (2012). An alternative model for evaluating sustainable urbanization. *Cities*, 29(1), 32-39.

Shen, L. Y., Ochoa, J. J., Shah, M. N., ~~&~~ Zhang, X. (2011). The application of urban sustainability indicators–A comparison between various practices. *Habitat International*, 35(1), 17-29.

Shen, L., Shuai, C., Jiao, L., Tan, Y., ~~&~~ Song, X. (2017). Dynamic sustainability performance during urbanization process between BRICS countries. *Habitat International*, 60, 19-33.

Shen, L., Shuai, C., Jiao, L., Tan, Y., ~~&~~ Song, X. (2016a). A global perspective on the sustainable performance of urbanization. *Sustainability*, 8(8), 783.

Shen, L., ~~&~~ Zhou, J. (2014). Examining the effectiveness of indicators for guiding sustainable urbanization in China. *Habitat International*, 44, 111-120.

Shen, Q., Chen, Q., Tang, B. S., Yeung, S., Hu, Y., ~~&~~ Cheung, G. (2009). A system dynamics model for the sustainable land use planning and development. *Habitat International*, 33(1), 15-25.

Shepherd, S. P. (2014). A review of system dynamics models applied in transportation. *Transportmetrica B: Transport Dynamics*, 2(2), 83-105.

Spence, M., Annez, P. C., ~~&~~ Buckley, R. M. (2009). Urbanization and growth. World Bank Publications.

Sun, C., Ouyang, X., Cai, H., Luo, Z., ~~&~~ Li, A. (2014). Household pathway selection of energy consumption during urbanization process in China. *Energy Conversion and Management*, *84*, 295-304.

Tan, Y., Xu, H., Jiao, L., Ochoa, J. J., & Shen, L. (2017). A study of best practices in promoting sustainable urbanization in China. *Journal of Environmental Management*, 193, 8-18.

Tan, Y., Xu, H., & Zhang, X. (2016). Sustainable urbanization in China: A comprehensive literature review. *Cities*, 55, 82-93.

Thompson, B. P., & Bank, L. C. (2010). Use of system dynamics as a decision-making tool in building design and operation. *Building and Environment*, 45(4), 1006-1015.

Trappey, A. J., Trappey, C. V., Hsiao, C. T., Ou, J. J., & Chang, C. T. (2012). System dynamics modelling of product carbon footprint life cycles for collaborative green supply chains. *International Journal of Computer Integrated Manufacturing*, 25(10), 934-945.

United Nations Environment Programme. (2015). Retrieved from http://www.unep.org/chinese/

Urban Sustainability Index. (2014). Retrieved from http://www.urbanchinainitiative.org/zh/resources/dev_page.html

Uwasu, M., & Yabar, H. (2011). Assessment of sustainable development based on the capital approach. *Ecological indicators*, 11(2), 348-352.

Vafa-Arani, H., Jahani, S., Dashti, H., Heydari, J., & Moazen, S. (2014). A system dynamics modeling for urban air pollution: A case study of Tehran, Iran.

Formatted: Left

Transportation Research Part D: Transport and Environment, 31, 21-36.

Wang, S., Zhou, C., Li, G., & Feng, K. (2016). CO 2, economic growth, and energy consumption in China's provinces: Investigating the spatiotemporal and econometric characteristics of China's CO 2 emissions. *Ecological Indicators*, *69*, 184-195.

Wang, X. R., Hui, E. C. M., Choguill, C., & Jia, S. H. (2015). The new urbanization policy in China: which way forward?. *Habitat International*, 47, 279-284.

Wu, J., Xiang, W. N., & Zhao, J. (2014). Urban ecology in China: Historical developments and future directions. *Landscape and Urban Planning*, 125, 222-233.

Xu, Z., & Coors, V. (2012). Combining system dynamics model, GIS and 3D visualization in sustainability assessment of urban residential development. *Building and Environment*, *47*, 272-287.

Yang, J., Zhang, W., & Zhang, Z. (2015). Impacts of urbanization on renewable energy consumption in China. *Journal of Cleaner Production*, 114, 443-451..

Yang, X.J., 2013. China's rapid urbanization. *Science*, 342(6156), 310-310 342, 310.

Yao, H., Shen, L., Tan, Y., & Hao, J. (2011). Simulating the impacts of policy scenarios on the sustainability performance of infrastructure projects. *Automation in Construction*, 20(8), 1060-1069.

Yuan, H., Chini, A. R., Lu, Y., & Shen, L. (2012). A dynamic model for assessing the effects of management strategies on the reduction of construction and demolition waste. *Waste management*, 32(3), 521-531.

Yu, C. H., Chen, C. H., Lin, C. F., & Liaw, S. L. (2003). Development of a system dynamics model for sustainable land use management. *Journal of the Chinese*

Formatted: Font: Italic

Formatted: Font: Not Italic

Formatted: Font: (Default) Times New Roman, 12 pt

Formatted: Font: Not Italic

Formatted: Font: (Default) MS Mincho

Institute of Engineers, 26(5), 607-618.

Zhang, X. (2015). Sustainable urbanization: a bi-dimensional matrix model. *Journal of Cleaner Production*, 134, 425-433.

Zhang, X., Wu, Y., Shen, L., & Skitmore, M. (2014). A prototype system dynamic model for assessing the sustainability of construction projects. *International Journal of Project Management*, 32(1), 66-76.

Zhao, J., & Chai, L. (2015). A novel approach for urbanization level evaluation based on information entropy principle: A case of Beijing. *Physica A: Statistical Mechanics and its Applications*, 430, 114-125.

Zhou, D., Xu, J., Wang, L., & Lin, Z. (2015). Assessing urbanization quality using structure and function analyses: A case study of the urban agglomeration around Hangzhou Bay (UAHB), China. *Habitat International*, 49, 165-176.

Zhou, J., Shen, L., Song, X., & Zhang, X. (2015b). Selection and modeling sustainable urbanization indicators: A responsibility-based method. *Ecological Indicators*, 56, 87-95.

Zhou, J., Zhang, X., & Shen, L. (2015a). Urbanization bubble: Four quadrants measurement model. *Cities*, 46, 8-15.

Zhou, W., Zhu, B., Chen, D., Griffy-Brown, C., Ma, Y., & Fei, W. (2012). Energy consumption patterns in the process of China's urbanization. *Population and Environment*, 33(2-3), 202-220.

Formatted: Font: Italic