Applying Fuzzy Delphi Method to Select the Variables of a Sustainable Urban System Dynamics Model

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Abstract

A system dynamics model is composed of many variables. These variables simplify complex phenomena and provide a description of a system's current state or problems. Basic variables that describe the real-world urban development can be established from the elements that make up a city's different dimensions such as industry product, population growth and vacancy rate. The urban development framework takes a system-based approach by systemizing the city's internal elements. The systemic variables then provide not only a clear reflection of the interactions between all of the sub-systems but also how they relate to the overall system. It is therefore very important to select the appropriate variables. Most variables of system dynamics models are, however, set up by the designer, served as a subjective and unscientific approach. This study therefore applies the Fuzzy Delphi Method to the selection process of system variables to increase the confidence of the model. This was accomplished by first examining the system relationships as well as the intent and meaning of the sub-system variables to be created. After establishing the criteria for variable selection, an empirical case study was used to devise the evaluation variables for each sub-system.

1. Introduction

Over the past 20 years, an acute demand or national environmental information has emerged due to the increase in international awareness of environmental issues. Many environmental variable programs have therefore been set up in developed countries to provide better channels for communication. In 1989, the G7 summit of industrialized nations asked the OECD (Organization for Economic Co-operation and Development) to propose a suitable solution. This eventually led to the creation of sustainability variables that take both environmental and socio-economic development into account. The call for sustainability variables reached its peak at the 1992 Earth Summit and laid the foundations for the sustainable development variables promoted by the UN (United Nations) CSD (Commission on Sustainable Development). In 1991, the IUCN (World Conservation Union), UNEP (United Nations Environment Programme) and WWF(World Wildlife Fund) joined together to draft the “Caring for the Earth” guidelines. This specified two areas of coverage for any sustainable development variables: quality of life and ecological sustainability. Here quality of life included longevity, knowledge and income; ecological sustainability was measured by:

1. Conserving life-support systems and biodiversity;
2. Ensuring the use of renewable resources are sustainable and minimizing the depletion of non-renewable resources;
3. Keeping within the carrying capacity of supporting eco systems.

In 1992 the city of Seattle in Washington State, USA passed a growth management plan. Four principles for selecting “good variable” were developed by the working group: “vision”, “ease of understanding and acceptance”, “benefits and attractiveness” and “measurability”. These were used to choose 40 variables out of 100 to establish a system to guide Seattle’s transformation into a sustainable city. The system was then used as the basis for an empirical study titled “Sustainable Seattle 1993”. The collection and analysis of data has now begun on 20 of those 40 variables. Seattle also launched a 20-year Comprehensive Plan 91994~2014) in 1994 with the goal of developing Seattle into a sustainable city. The UNCHS (United Nations Center for Human Settlements) and the World Bank partnered to propose the Variables Programme (1997) for comparing the level of sustainable development between the cities of the world (Table 1).

Table 1 The UNCHS (Habitat) Variables Programme (1997)

Background Data	Land Use	Environmental Management	Percentage of Wastewater Treated
	City Population		Solid Waste Generated
	Population Growth		Disposal methods for Solid Waste
	Woman Headed Households		Regular Collection and Transportation of Solid Waste
	Average Household Size		Housing Destroyed
	Household Formation Rate	Local Government	Major Sources of Income
	Income Distribution		Per-Capita Capital Expenditure
	City Product per Person		Debt Services Charge
	Tenure Type		Local Government Employees
Socio-Economic Development	Households Below Poverty Line		Wages in the Budget
	Informal or Unreported Employment		Contracted Recurrent Expenditure Ratio
	Hospital Beds		Government Level Providing Services
	Child Mortality		Control by Higher Levels of Government
	School Classrooms	Housing Affordability	Ratio of House Price to Income
	Crime Rates		Ratio of Renting Cost to Income
Infrastructure	Household Connection Levels		Average Floor Area per Person
	Access to Potable Water		Durable Assets
	Consumption of Water		Housing Commitment
	Median Prices of Water, Scarce Season	Housing Supply	Planning Permission Multiplier (Increase in Value)
Transportation	Modal Split		Public Infrastructure Expenses
	Travel Time		Total Bond Value
	Expenditure on Road Infrastructure		Housing Supply
	Automobile Ownership Ratio		Housing Investment

Source: UNCHS (Habitat), 1997

Sustainable development is a system-integration concept that encompasses the environmental, economic and social dimensions. Sustainability variables must therefore possess the following characteristics:

1. Support clear policies, targets and action plans for sustainable development;
2. Expresses the balance between environment, economy, technology, industry and society;
3. Has a PRS (Pressure-State-Response) structure to allow the evaluation of interactions between human activities and the environment;
4. Variables' values must be measurable or at least observable. The data must exist or be available;
5. The methodology for establishing the variables must be clear and cost-effective;
6. The variables framework must be politically acceptable and has the ability to promote or influence decision-making;
7. The variables must achieve widespread acceptance in society in order to serve as an effective tool for exchange and communication between sustainable development and society.

Sustainable development basically starts from ecological conservation and the sustainable use of natural resources. Its essence is to balance environmental protection with economic development. Sustainability variables based on these concepts can not only serve as a tool in decision-making but can also be used to evaluate overall progress in sustainable development. For the general public, sustainability variables offer the dual advantages of being "qualitative variables" and "quantitative variables" as well. The use of sustainability variables facilitates the building of understanding and consensus. The devising of sustainability variables therefore makes a worthwhile contribution to sustainable development.

To create a comprehensive and practical sustainability variables system, involves more than just clearly defining the variables and implementation framework. The system must also respond appropriately to policy needs as well. A sound variables system therefore not only reflects the current state of development but must also taken into account the time factor and be integrated with policy tools for it to be truly effective. Sustainability variables therefore serve a range of purposes: a decision-making tool for sustainable development; evaluate progress and trends in efforts at promoting sustainable development; study the relationship between goal and target as well as implementation performance; compare the effects of changes in time and space; and provide warning information on environmental change. In this study, a set of sustainable variables for urban development are proposed based on the principles of sustainable development and the Taiwanese experience in urban development. These are listed in Table 2.

Table 2 Sustainable urban development variables

Subsystem	variable	Subsystem	variable
Industry subsystem	Number of companies	Housing/ Land use subsystem	Rate of unoccupied houses
	Productivity of IA staff		Average housing price
	Industry value		Rate of land development in IA
	Net revenue of capital		Land area per IA staff
	Amount of imports		House rental rate in IA
	Amount of exports	Environmental pollution subsystem	Amount of dust fallen
	R & D expenditure		Total amount of suspended particulates
Population subsystem	Total population		Daily sew age disposal per capita
	Population growth rate		Daily refuse production per capita
	Natural increase rate		Amount of refuse collected per day
	Social increase rate		No. of motorcycles per 1000 persons
	Average size of household		No. of vehicles per 1000 persons
	Urban-to-total population ratio		Number of factories registered
	Population density		Number of environmental pollution law suits
	Age structure	Economy subsystem	Amount of saving per household
	Education level		Total regular income per family
	Water consumption per capita		Housing-to-total family expenditure ratio
	Power consumption per capita		Rate of self-owned houses
	Population of IA staff		No. of automobiles per 1000 persons
	Age structure of IA staff		Rate of unemployment
	Education level of IA staff		Low income-to-total population ratio
Housing/Land use subsystem	Area of agricultural land		No. of industrial units
	Urban-to-total area ratio		Indus trial population
	Urban area per capita		Indus trial-to-total population ratio
	Population served by piped water		Indus try value
	Residential floor area per capita		Area of Indus trial land

2. The Fuzzy Delphi Method

The definition of detailed variables provides the basic elements and references for understanding sustainable urban development. The relevant literature was studied to compile a list of detailed variables in accordance with the guidelines for variable selection. Urban characteristics unique to cities were also taken into account in the interactions between the sub-systems within the sustainable development system to arrive at a suite of variables for urban dynamics model.

Large numbers of variables however make building the model more complex and difficult. There are also some semantic uncertainties in how some sustainability variables should be evaluated, making a clear answer difficult to give. This study looked at the multitude of fuzzy theory derived analytical methods before finally settling on the Fuzzy Delphi Method. This will be used to establish a basis and method for evaluating an urban sustainability variables system. A general outline of the Fuzzy Delphi Method's characteristics is followed below.

The Fuzzy Delphi Method is an analytical method based on the Delphi Method that draws on the ideas of the Fuzzy Theory. The Delphi Method is a type of collective decision-making method (Linstone & Turoff, 2002), with several rounds of anonymous written questionnaire surveys conducted to ask for experts' opinion. As a direct prediction method based on the expert judgment and expert meeting investigation method, it possesses the following properties:

1. Anonymity: The experts involved with the prediction process do not see each other, remain anonymous and don't know how many experts are involved. This helps to prevent them from influencing and encourages objectivity.

2. Feedback: The survey feedback gives the participants an idea about the main ideas in the group. They can then draw from it information relevant to them, make a new judgment, and then submit it to the group again.

3. Statistical: The expert opinions are processed statistically and a splines

graph produced with the expert opinion frequencies arrayed chronologically. The top is the majority consensus (50% experts) representing the prediction team's opinion. The top and bottom quarter percentile (each representing 25% of the experts) represent the prediction deviation.

4. Convergence: Through multiple reverse feedback make the final prediction results converge.

The purpose of the Delphi Method is to achieve a consensus among the experts on the subject being evaluated. When used with one-to-many objectives, multi-principle, multi-proposal and multi-participant decision-making problems, the method not only serves to draw on a large body of opinion but also meets the requirement for independence in the experts' judgment.

The Delphi Method requires multiple repetitions when asking experts for their opinion. This must continue until the experts arrive at a consensus. As a result, it generally has the following weaknesses: (Ho and Chen, 2007)

(1) Repeatedly surveying experts and collecting their opinions is very time consuming.

(2) Experts must be surveyed and the collated results analyzed multiple times, increasing costs.

(3) Expert cooperation is required before a consensus is reached, needlessly increasing the difficulty of coordination and communication.

(4) Consensus of expert opinion occurs during a certain part of the analytical process. The fuzziness of this part is however not taken into consideration. This makes it easy to misinterpret the expert's opinion.

(5) The analytical process has problems with some opinions being systematically weakened or suppressed.

To solve the problem of fuzziness in expert consensus in group decision making, researchers from around the world came up with new methods: Murray, Pipino & Gigch (1985) proposed the application of Fuzzy Theory to the

Delphi Method, with semantic variables used to solve the problem with fuzziness in the Delphi Method. Kir and Folger (1988) proposed a mean normalization mode. Ishikawa *et al*. (1993) used the Maximum-Minimum Method together with cumulative frequency distribution and fuzzy scoring to compile the expert opinions into fuzzy numbers. The expert prediction interval value was then used to derive the fuzzy numbers, resulting in the Fuzzy Delphi Method. Hsu and Chen (1996) proposed the fuzzy similarity aggregation method. Using the similarity function, similarities between experts were collated and fuzzy numbers assigned directly to each expert to determine the agreement degree between them. The consensus coefficient was then used to aggragate all experts' fuzzy evaluation values. If the agreement degree between experts is too low however the survey must be conducted again.

A comparison of the strengths and weaknesses between the Fuzzy Delphi Method and the traditional Delphi Method is provided below in Table 3.

Table 3 Comparison of the strengths and weaknesses between the Fuzzy Delphi Method and the Delphi Method

Method Description		Strengths and Weaknesses
Traditional Delphi Method	Goal is to achieve consensus in expert opinion. Draws on a wide range of opinions while providing quality of independent expert opinion. The expert survey is repeated and experts asked to revise their own opinions based on the results from the previous survey until the opinions converge.	Takes more time to collate expert opinions.
		Higher cost.
		Survey must be repeated multiple times. The survey recovery rate is low.
		In pushing for a consensus it' easy to misinterpret expert opinion.
		Consensus of expert opinions only applies to a certain rage. The fuzziness of that range is not taken into account.
Fuzzy Delphi Method	As Delphi Method surveys have some semantic fuzziness in both the questions and the answers, cumulative frequency distribution and fuzzy scoring were therefore used to collate the expert opinions into fuzzy numbers. Here similarity function is used to evaluate the agreement degree between two experts. The consensus coefficient for each expert was then used to derive the fuzzy evaluation value from all experts.	Saves survey time.
		Lower cost.
		Reduces number of surveys, increases questionnaire recovery rate.
		Experts can fully express their opinions, ensuring the completeness and consistency of the group opinion.
		Takes into account the fuzziness that can't be avoided during the survey process. Does not misinterpret experts' original opinions and provides a true reflection of their response.

3. Questionnaires and Analysis Method

To establish a set of general variables for urban sustainable system dynamics model, a general perspective of the urban development system must be gained first. This study therefore carried out a questionnaire survey of experts and academics in different fields. After collating the evaluating a wide range of data, a total of 20 experts in the industry, academic, profession and government organizations were selected for the survey. The goal of the expert questionnaire survey was to gain an understanding of the variables that must be taken into account within a sustainable urban system dynamics model. After reviewing the relevant literature and developing a theoretical urban system, this study began screening the variables. These could be sorted into three parts according to content:

(1) Basic Information

Gender, age, specialization and level of professional experience.

(2) Questionnaire instructions

Provides instructions on how to answer the survey with samples provided. This gave the respondents a better idea of the survey format, reducing the time they need to spend and speeding up the survey.

(3) Variable definitions & answers

The survey focused on asking the respondents to rate the importance and range of variables. A precise definition of each variable was also given for the respondents to refer to when answering. The explanations were provided as follows:

A. “Optimal” level of importance: Please evaluate the importance of this and write down what you personally think is the optimal value.

B. Importance scope: Please evaluate the acceptable range for the importance of this variable, and also write down what you think is the maximum and minimum acceptable value for this variable.

Weighting:

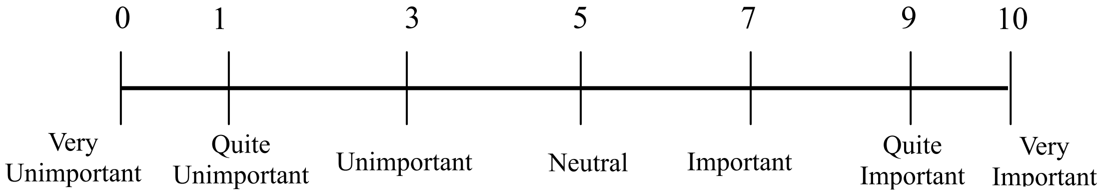

Table 4 Importance of environmental variable to the influence of price of land development

Variable	Importance (0-10)							Export evaluation
	Very Unimportant	Quite Unimportant	Unimportant	Neutral	Important	Quite Important	Very Important	
Accessibility of school								
Accessibility of cultural facilities								
Accessibility of park								

The statistics from the survey showed that the experts' average age was 44. Experts surveyed included those involved in the technology industry, economics, environmental engineering, land administration, urban planning, architecture and landscape. The most numerous were urban planning followed by environmental engineering. The results of this expert survey were representative of the perspectives from a range of different disciplines and satisfied the requirement for a general perspective in this study.

Based on the collated information, this study conducted an expert questionnaire survey on the 52 variables proposed in Table 2. The evaluation method adopted was the evaluation fuzzy number defuzzification analysis used by Tzeng (1993). In accordance with the Delphi Method, the 25% percentile above and the 25% percentile below the median was used to calculate the expert value. The magnitude of the expert value was then used for screening the variables. In evaluation fuzzy number defuzzification analysis, the fuzzy semantic level is converted into the variables and a more colloquial format used to help experts perform their evaluation more precisely. The function relationships were then subjected to defuzzification analysis to derive the value for that evaluation factor. This method avoids the problem of experts being constrained by their own maximum and minimum values. It also converts the expert's own fuzziness into an overall fuzzy evaluation of the variables. This produces an evaluation result more in keeping with the overall expert opinion. The calculation principles are described below:

Tzeng used a semantic approach to collect information on the respondents' preferences. That is, the "importance" semantic variable was used as the interface to evenly divide the semantic scale into triangular fuzzy numbers. This quantification was then used to calculate the membership as shown in Fig. 1. For the fuzzy semantic scale, Tzeng proposed the concept and method used by Chen and Hwang (1992) to convert the terms of semantic expression into fuzzy numbers. The fuzzy set was then converted into crisp score.

The solution for this analytical process is as follows:

1. Mean of the sustainable variables

First, use function (1) to calculate the mean of the triangular fuzzy numbers for each variable. This gives a value for each variable that can be used for defuzzification analysis.

$$Vm=(1/N)[n_{m1}(0,0,1/(L-1))+n_{m2}(0,1/(L-1),2/(L-1))+\dots$$
$$+n_{m2}((k-2)/(L-1),(k-1)/(L-1),k/(L-1))+\dots+n_{mL}((k-2)/(L-1),1,1)] \quad \dots\dots (1)$$

In function (1), Vm is the mean of the m-th variable; n_{mk} is the number of times that the k-th semantic scale was selected for the m-th variable. N is the sum of n_{mk}; L is the number of partitions along the semantic scale; K is k-th semantic scale.

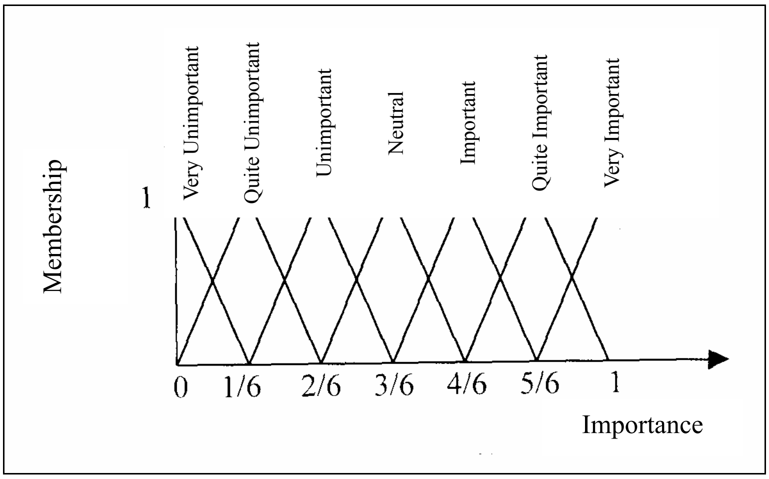

Figure 1. Importance semantic variables

(2) Fuzzy Number Defuzzification Analysis

The goal of defuzzification analysis is to convert the triangular fuzzy numbers into an exact value so the factors can be analyzed and ranked. The steps are as follows: (1) Define the "maximum set" and "minimum set" of the semantic scale set, where

$$\mu_{max}(x) = \begin{cases} x, 0 \leqq x \leqq 1 \\ 0, \text{otherwise} \end{cases} \quad \ldots\ldots (2)$$

$$\mu_{min}(x) = \begin{cases} 1-x, 0 \leqq x \leqq 1 \\ 0, \text{otherwise} \end{cases} \quad \ldots\ldots (3)$$

u_{max} and u_{min} each intersects with the right and left boundary of Vs as shown in Fig. 2. Vs=(a, b, c) is known and represents the three coordinates (a,0), (b,1) and (c,0). Its triangular fuzzy numbers then form a fuzzy linear equation:

$$y = (x-a) / (b-a) \text{ and } (x-c) / (b-c)$$

The relationship between the maximum membership equation of u_{max} (x) and the Vs fuzzy equation is as shown in function (4):

$$\mu_R(m) = \sup \min_x[\mu_{max}(x), \mu Vs(x)] \quad \ldots\ldots (4)$$

In function (4), the two focal coordinates on the right boundary are:

(a/(1+a-b),a/(1+a-b)) and (c/(1+c-b),c/(1+c-b))

Take the y value of the larger y coordinate (membership) to represent u_r (x).

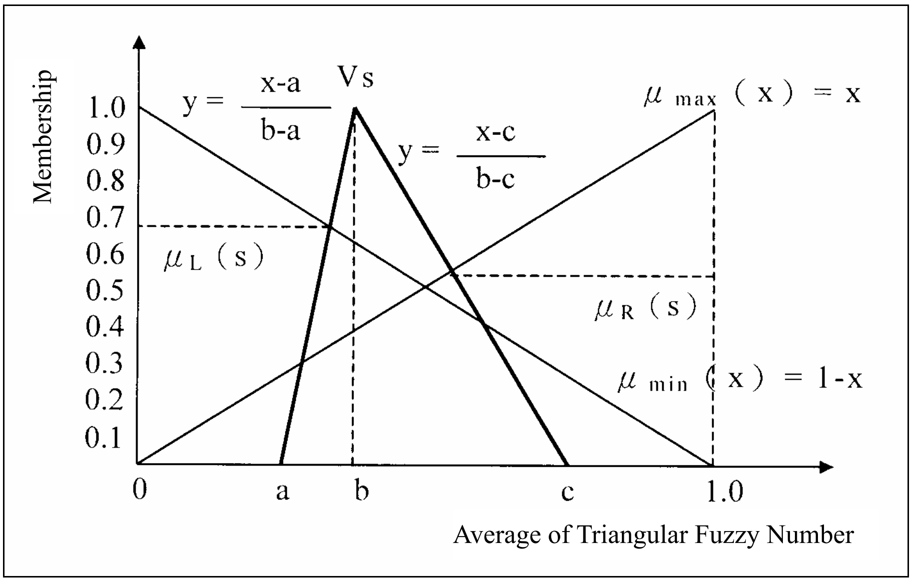

Figure 2. Defuzzification Chart

The same also applies to the relationship between the minimum membership equation of u_{min} (x) and the Vs fuzzy equation is as shown in function (5):

$\mu_L(m) = \sup \min_x[\mu_{min}(x), \mu Vs(x)]$ …… (5)

In function (5), the two focal coordinates on the left boundary are:

(b/(1+b-a),(1-a)/(1+b-a)) and (b/(1+b-c),(1-c)/(1+b-c))

Take the y value of the larger y coordinate (membership) to represent u_L (x).

Finally, use defuzzification to calculate the fuzzy set and derive the defuzzified point:

$\mu_T(m) = 0.5[\mu_R(m) + 1 - \mu_L(m)]$

From this, it is possible to see that as the triangular fuzzy numbers tended towards the right (importance is hence higher), its defuzzification value u_t (m) becomes greater. By using this method to establish the fuzzy semantic scale allows the traditional method to be bypassed for fuzzy evaluation. Respondents can then express their preferences in a colloquial everyday manner.

4. Results

To ensure the objectivity of the screening process while screening the variables according to the magnitude of their scores, this study chose to use the method of Ho, Wang, & Lu (2002) and set separate thresholds for each sub-system as it best matched the principles of this study. First, the arithmetic mean of the internal variables in each sub-system was used as the baseline. The standard deviation was then set as the cut-off point and variables identified in expert feedback as being of relatively low importance were removed. The arithmetic mean for the retained variables was then calculated for use as the threshold value for that sub-system. This process avoided any subjectivity in the setting of the threshold value while preserving the experts' feedback on the importance of each sub-system. The relatively important variables in each sub-system were thus retained.

Basically, after the evaluation fuzzy number defuzzification analysis the variables with an expert score higher than the threshold value were retained and the rest discarded. Table 5 lists the urban sustainability variables retained by the screening process.

The screening results showed that 22 variables were chosen based on their importance to the variable system. Of the 3 variables from the industry sub-system, the industry output was the highest at 0.77. Of the 6 variables for the population sub-system, population density was the highest at 0.76. Of the 6 variables in the residential land sub-system, the average amount of urban land per capita was the highest at 0.72. For the 3 variables in the environmental pollution sub-system, the wastewater generated per capita was the highest at 0.83. For the economy sub-system, industry output was the highest at 0.82.

Table 5 Sustainable variables and their evaluation value

Subsystem	variable	Value	Subsystem	variable	Value
Industry subsystem	Number of companies	0.66	Housing/ Land use subsystem	Rate of unoccupied houses	0.70*
	Productivity of IA staff	0.72*		Average housing price	0.70*
	Industry value	0.77*		Rate of land development in IA	0.69*
	Net revenue of capital	0.69		Land area per IA staff	0.70*
	Amount of imports	0.64		House rental rate in IA	0.58*
	Amount of exports	0.65	Environmental pollution subsystem	Amount of dust fallen	0.69
	R & D expenditure	0.70*		Total amount of suspended particulates	0.72
Population subsystem	Total population	0.63		Daily sew age disposal per capita	0.83*
	Population growth rate	0.74*		Daily refuse production per capita	0.81*
	Natural increase rate	0.56		Amount of refuse collected per day	0.75
	Social increase rate	0.70*		No. of motorcycles per 1000 persons	0.64
	Average size of household	0.63		No. of vehicles per 1000 persons	0.70
	Urban-to-total population ratio	0.65		Number of factories registered	0.58
	Population density	0.76*		Number of environmental pollution law suits	0.82*
	Age structure	0.71*	Economy subsystem	Amount of saving per household	0.68*
	Education level	0.71*		Total regular income per family	0.71*
	Water consumption per capita	0.56		Housing-to-total family expenditure ratio	0.67
	Power consumption per capita	0.57		Rate of self-owned houses	0.61
	Population of IA staff	0.59		No. of automobiles per 1000 persons	0.55
	Age structure of IA staff	0.60		Rate of unemployment	0.70*
	Education level of IA staff	0.71*		Low income-to-total population ratio	0.57
Housing/Land use subsystem	Area of agricultural land	0.46		No. of industrial units	0.61
	Urban-to-total area ratio	0.58		Indus trial population	0.60
	Urban area per capita	0.72*		Indus trial-to-total population ratio	0.65
	Population served by piped water	0.65		Indus try value	0.82*
	Residential floor area per capita	0.70*		Area of Indus trial land	0.64

Note: * A dopted by higher values than the threshold:0.695 (industry subsystem), 0.675 (Population subsystem), 0.669 (Housing/Landuse subsystem), 0.760 (Environmental pollution subsystem), 0.674 (Urban economy subsystem)

Drawing on the expert survey results and the system interaction relationships, the author provides the following description of the cause-and-effect relationships for the variables within the five sub-systems of sustainable city development:

1. Industry Sub-System

In the industry sub-system, the city's secondary and tertiary industry output is the primary stock while the number of employees is the secondary stock. Here labor demand and labor productivity are the main factors that influence changes in the sub-system. As the number of industry employees increases, total industry output increases as well, creating a positive feedback loop within the system. However, if industry development stagnates as the number of employees increases, there is then a corresponding decrease in unit productivity. This lowers the overall industry output, resulting in a negative feedback loop within the system. Research and development is the basis for industrial progress as the technical innovations it brings stimulate business and industrial growth. The higher the industrial output, the more money is spent on R&D. This generates more R&D results and boosts unit productivity. The result is an increase in overall output and a positive influence on the system as a whole. The industry sub-system therefore has 3 feedback loops, with 2 positive and 1 negative.

2. Population Sub-System

In the city population sub-system the total population is the primary stock in the cause-and-effect loop. The primary factors that influence the total population of the Science City are natural population change and social population change. Analysis of the expert surveys indicates that the social growth rate is far more important than natural growth for population changes in the Science City. Natural change is based on the permanent population while social change is based on the transient population. Of these two key factors, the cause-and-effect loop for natural change is influenced by the positive contribution from the number of births and the negative contribution from the number of deaths. As for social change, the number of immigrants makes a positive contribution to the Science City population while the number of emigrants makes a negative contribution. In terms of impact, as the number of births increase, the total population increases as well. This forms a positive feedback loop. As the total population increases, the number of deaths increases as well. This leads to a decrease in the total population, forming a negative feedback loop. With social change, if a region enjoys higher personal income, better quality of life and has more employment opportunities, the number of people who move to the region will increase. If the situation is reversed, the contribution becomes negative as the number of people moving out of the region increases instead. When the Park's industrial output is high, its manpower demand will be high as well, attracting workers from other regions; conversely, if the Park's high-tech industry output is decreasing, its manpower demand will decrease as well, leading to a loss of population as workers move away. The population sub-system therefore has 3 feedback loops, including 2 positive and 1 negative.

3. Housing Sub-System

The housing sub-systems primary stocks are the number of households and the number of housing units. City population growth generates a demand for housing and stimulates the housing supply. This drives the development of residential land and construction of housing, forming a positive feedback loop. As the city's industrial output grows, this in turn drives the demand for labor in the Park and brings in more workers. This has the indirect effect of increasing builders' willingness to construct housing. The total number of housing therefore increases, forming another positive feedback loop that affects housing stock. Excessive residential development however leads to over-supply and high vacancy rates. This impacts the willingness of consumers and builders to buy or construct housing, resulting in a control loop based on negative feedback. This sub-system therefore has 4 feedback loops in total, with 2 positive and 2 negative.

4. Environmental Pollution Sub-System

The key issue in the environmental pollution sub-system is the level of impact from environmental pollution. The main considerations during analysis are the interactions between the Science City and the different types of pollution sources. This study initially divided environmental pollution into three types: water, air and waste. The analysis of the expert survey results indicated that all of the air pollution related variables scored lower than the threshold value. Air pollution is therefore not a significant issue for the Science City. Waste is a byproduct of the industrial manufacturing processes. At Science

City, the main development focus is the high-technology industry. For the high-technology industry, the source of main pollution is water pollution rather than air pollution. Water and waste pollution is also produced by the population. This study therefore chose to discount air pollution and base the cause-and-effect loop for the Science City's environmental pollution sub-system on water and waste pollution. In terms of impact, water pollution can be reduced through the negative control of sewage treatment; waste pollution can also be reduced through the negative control of waste collection and processing. Pollution treatment therefore forms a negative feedback loop that regulates this sub-system from the inside and prevents it from expanding unchecked. This sub-system therefore has 4 feedback loops in total, with 2 positive and 2 negative.

5. Economy Sub-System

Once the expert survey opinions were collated, they showed that the emphasis for this sub-system is on evaluating the change in total industrial output. The system's cause-and-effect loop can be derived through the number of industry workers, demand for labor and labor productivity. The supply and demand of labor is the main factor that influences the total industrial output. Generally speaking, if labor productivity is a constant, then increasing the industrial output will increase the demand for labor. This results in more industry workers, creating a positive feedback loop. As the number of workers increases however, average productivity decreases for industrial output that are fixed against time. If achieving the same industrial output is used as the evaluation criteria, lower average productivity will consume more resources and increase basic expenditure. This impacts indirectly on willingness to invest in the industry and eventually slows the rate of growth in industrial output. The result is a negative feedback loop and this is the most important control loop within the city economy sub-system. As the city output increases, the demand for labor from the service industry increases as well. This forms another positive feedback loop within the system. This sub-system therefore has 5 feedback loops in total, with 3 positive and 2 negative.

Based on the targets, implications and structure of the sub-systems described above, this study looks at the relationships between the variables in the sustainable urban development system and considers the City's development characteristics. By linking the sub-systems together through variables such as industrial output, population and pollution volume, a causal loop for the sustainable urban development system was constructed (Fig 3). In the diagram, there are 22 feedback loops in total, with 14 positive and 8 negative.

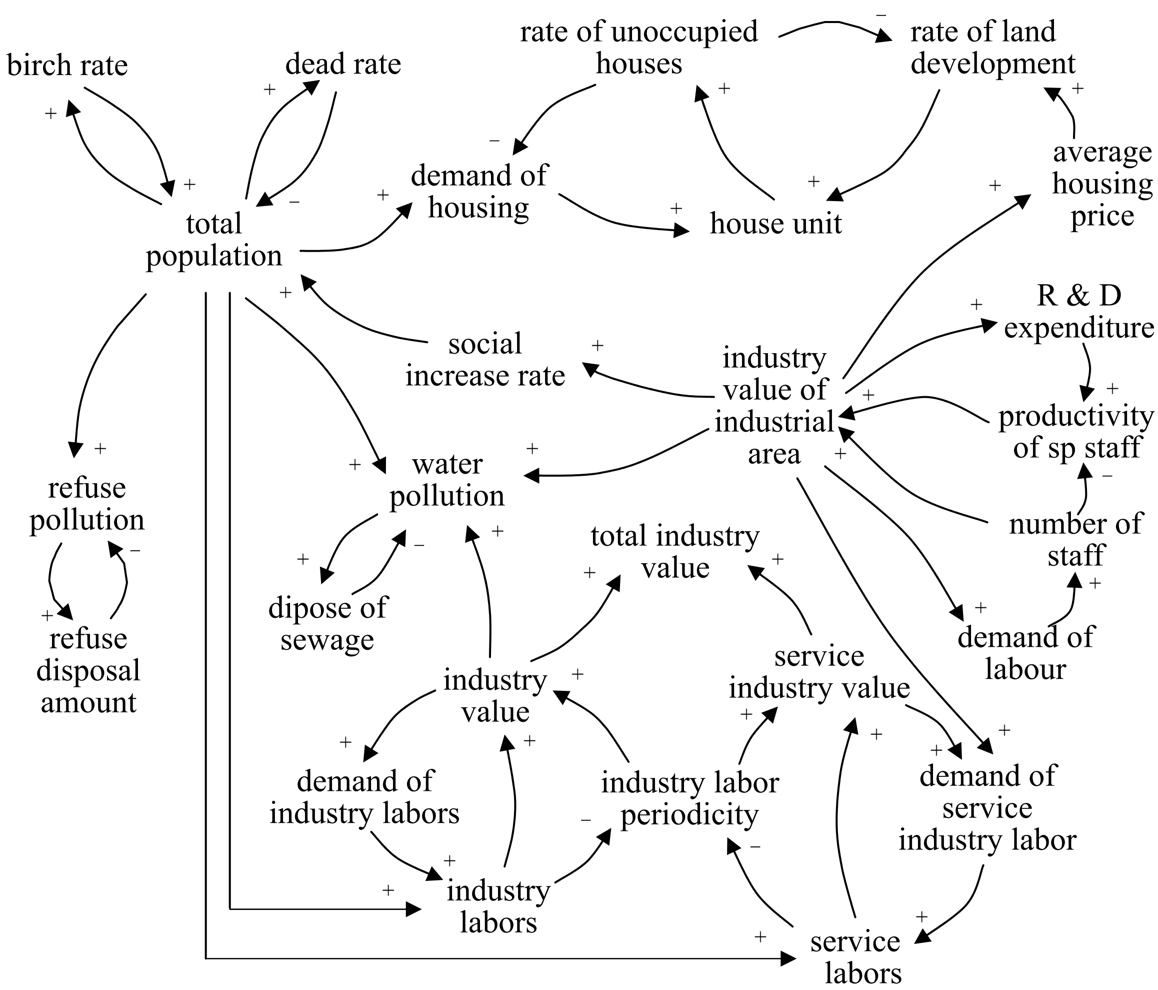

Fig 3 Causal loop diagram for sustainable urban development

5. Conclusion

To construct a sustainable urban development system, this study set the development of the industry as the main axis while balancing the needs of the urban ecological environment and social dimensions. The system's variable sets were made up of 5 sub-systems: industry, population, housing/landuse, environmental pollution and economy, By conducting an expert survey and analyzing the results with the Fuzzy Delphi Method, an urban sustainability variables system was established. This framework will serve as the foundation for the construction of a system model in the future. After using the Fuzzy Delphi Method to analyze the results, the ranking of the sub-systems' screened value from the highest to the lowest were: industry, environmental pollution, population, economy then housing/landuse; the ranking of the threshold values from the highest to the lowest were in order: environmental pollution, industry, population, economy and housing & land. Examination of the variable values showed that the 20 experts generally had assigned higher ratings to the variables related to the industry sub-systems. This showed that the industry was the most important for the city's development. This result agreed with the hypothesis of this study that the industry forms the main axis of development. Apart from the industry, the variables related to the environmental pollution sub-system also received higher ratings as well. This showed that the environmental dimension still plays a very important role in sustainable development.

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