



A system dynamics approach to the simulation of urban sustainability

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Abstract

This paper is a continuing effort to develop a framework for an indicator system to measure Taipei's sustainability (Huang et al.[1]). In order to study the interactive behavior of sustainability indicators, an urban systems model is developed which consists of six subsystems: land use, population, transportation, water resources, solid waste, and waste water. In all, fourteen urban sustainability indicators are included in the model developed. Using Taipei as a case study area, STELLA software is used to simulate the changes of indicators overtime. Three scenarios are formulated to study the likely effects of different urban policies on Taipei's sustainability.

1 Introduction

It is expected that one-half of the world's population will live in urban areas by the end of this decade. Whether we achieve a greater degree of sustainability over that time will therefore be determined largely by our cities. Evidence of progress on urban sustainability is important for justifying urban management at a policy level. Agenda 21 drew attention to the importance of indicators as tools of sustainable development (UNCED[2]). Indicators can quantify change, identify processes, and provide a framework for setting targets and monitoring performance. Considerable progress has been made toward developing environmental indicators, but less effort has been given to the development of sustainability indicators.

Indicators are the most effective method of evaluating urban sustainability.



Eighty indicators were selected to measure Taipei's urban sustainability from an ecological economic perspective (Huang et al.[1]). This paper is part of a continuing effort to study the use of indicators in system dynamics modelling. Recognizing the need for improvements in understanding how urban systems interact with environment, and how sustainability indicators interrelated, this research attempts to apply integrated environmental and urban system modeling and analysis in order to: (1) improve our understanding of the interaction between socioeconomic and environmental systems; (2) to measure sustainability indicators of Taipei; and (3) to assess the consequences of the effects of various policy scenarios on urban sustainability. The following sections of this paper begin with a review of the systems approach to urban sustainability indicators. The third section summarizes the framework of a system dynamics model developed for simulating Taipei's urban sustainability. The fourth section discusses the cause-effect relations between sustainability indicators of individual sectors. The policy impacts on Taipei's sustainability of hypothetical scenarios are also evaluated. The paper concludes with a discussion about the usefulness and limitations of applying the system dynamics approach for using indicators in urban management.

2 Systems View of Urban Sustainability Indicators

Indicators often are used independently when the environmental condition is unidimensional or a narrow aspect of problem is of interest. Urban sustainability is a multi-dimensional concept, which should take into account the performance of various sectors. The most common methodologies for measuring whether a city is moving toward or away from sustainability is to use urban sustainability indicators. Sustainability indicators differ from classical environmental indicators in that they do not simply reflect environmental conditions or pressures on the environment, but also indicate interactive characters between socioeconomic and ecological systems (Opschoor and Reijnders[3]). Maclaren[4] distinguished urban sustainability indicators from simple environmental, economic, and social indicators by the fact that they are not only integrating, but forward-looking, distributional, and receive input from multiple stakeholders.

Characterizing sustainability by time trends is appealing because of its simplicity. Sustainability assessments are made in terms of the direction and degree of measurable changes in system properties. Time trends are consistent with interpreting sustainability as an ability to continue. Unsustainability of an urban system may express itself as either a sudden collapse or a gradual change; the reasons for unsustainability trends, such as population pressure, market demands, and consumption activities, in most cases, are external to the system.

Because urban management depends on understanding complex systems, the work of urban planners often involves collection and interpretation of vast amounts of data. Therefore, the development of indicators to guide and measure performance is an important task in urban planning. Maclaren[4] presents a

thorough overview of alternative frameworks for reporting on sustainability, discussing a causal framework that incorporates a condition-stress-response model for development and use of indicators. Using a life-cycle accounting system, Leach et al.[5] developed a modelling framework to assess the effects of technology choice and policy on the sustainability of cities. From an ecological economic viewpoint, Chen and Huang[6] established indices of environmental quality and developed an ecological system model to simulate the symbiotic relationships between Taipei's urban development and environmental quality. System models can be used to study the interactive characteristics of sectors within an urban system and to simulate long term and future impacts of alternative scenarios in a manner that is not possible only with observation or experimentation.

3 System Dynamic of Taipei's Urban Sustainability

Based on the previously developed sustainability indicators for Taipei (Huang et al.[1]), the STELLA software is used to construct a system dynamic model, which consists of six sectors and includes 14 indicators. An overview of the components of the integrated modeling system is depicted in Figure 1. The individual modules are described by variables of stock and flow. It is implicitly assumed in the modelling approach that urban sustainability is influenced by interactive changes in economic activity, land use, transportation, and environmental management. The aim of the system dynamic model can therefore be rationalized into achieving two objectives. Firstly, simulating the interactive relationships between sectors and secondly, predicting the effects that urban policy might have on urban sustainability.

3.1 Population Subsystem

Population density is an important variable as an indicator for urban and infrastructure planning, since increased population density tends to decrease quality of life and therefore decrease a city's sustainability. The population in the city of Taipei reached a maximum of 2.7 million (1000 persons/Km²) in 1990. The statistical data reveals a negative correlation of birth rate with population density. Although higher population density results in higher emigration rates, the immigration into Taipei is driven mainly by the increase of urban productivity. The simulated population is used as input variable for other subsystems.

3.2 Land Use Subsystem

As a result of urban growth, approximately 1300 hectares of agricultural land has been converted to urban land use, which amounts to a 5% increase of total urban area during the past decade. The increased provision of public facility and natural area, as well as the stabilized population have enhanced Taipei's sustainability in

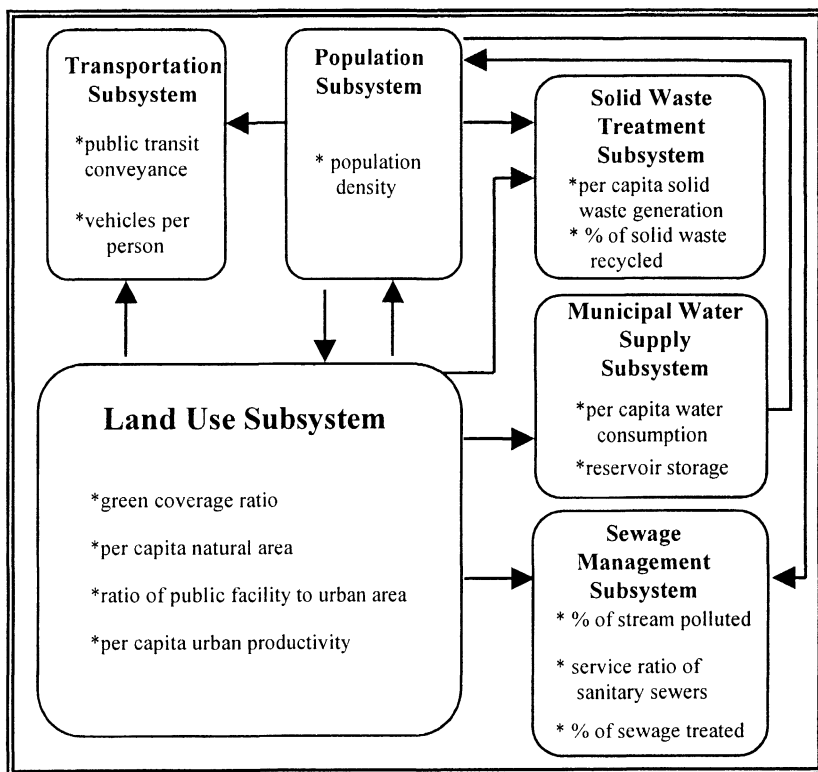


Figure 1: Integrated system model of Taipei's urban sustainability

terms of land use.

The land use subsystem can be considered as the core module of the integrated model developed here; it will affect the other subsystems through cause-effect relations. In addition to the four major stock variables: urban area (URBAN), agricultural area (AGR), public facility (FAC), and urban productivity (UPRO), there are four sustainability indicators included in land use subsystem, namely, green coverage ratio (GCR), per capita urban productivity (PCUPRO), per capita natural area (PCNAT), and ratio of public facility to urban area (RFAC) (See Figure 2).

The land use subsystem model assumes that the stock of urban area will generate the increase of urban floor area, which will then result in the increase of the rate of change of per capita urban productivity. The annual rate of the increase of per capita urban productivity will generate the development of urban area and public facility and the conversion of agricultural land through land development factor (LDF), public facility development factor (FDF) and agricultural conversion factor (AGRF) respectively. The natural area (NATURE) is calculated by subtracting urban area and agricultural area from the total area (TAREA). While simulating the land use subsystem, the four sustainability indicators are

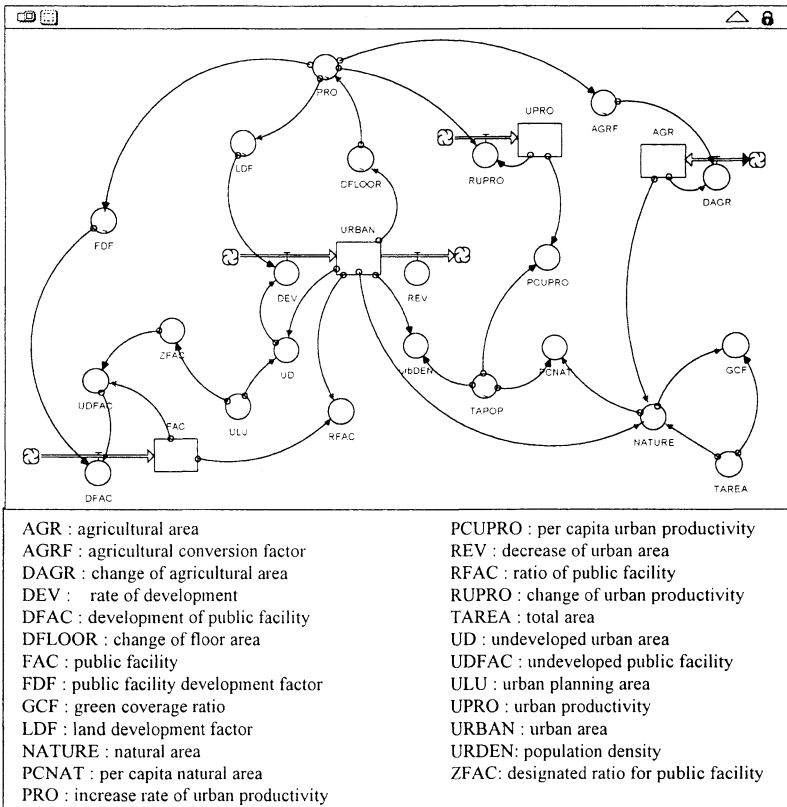


Figure 2: STELLA diagram of land use subsystem

also calculated.

3.3 Transportation Subsystem

Transport is an important issue and plays a key role in efficient urban development. This research incorporates two sustainability indicators for transportation subsystem: number of vehicles per 100 persons and public transit conveyance. The indicator of public transit conveyance is defined as the ratio of passengers to public transit mileage.

In line with the doubling of Taipei residents' per capita income during the past decade, the number of vehicles per person also doubled and exceeds twenty-four vehicles per 100 persons. Based on the correlation analysis of statistical data, the growth of urban productivity enables higher investment in public transit and increases the mileage of public transit. However, the number of vehicles in the city has also increased as a result of the growth of urban productivity and higher



per capita income. Thus the high vehicle ownership resulted in a decrease of passengers and conveyance of public transit passengers (TRANEAS).

3.4 Municipal Water Supply Subsystem

Water resources are one of the most crucial life supporting factors in the daily life of urban residents. Failure to provide sufficient water supply will also threaten to urban productivity. The availability and conservation of water resources are important measures for urban sustainability.

Surface water is the main water source for the Taipei metropolitan region. Although the water infrastructure in Taipei is capable of providing sufficient water supply for 3 million people, but statistical data reveals that the per capita water consumption in Taipei has continuously increased to the current 380 liters of per capita daily water consumption. The storage of water in the reservoir depends on inflow from upstream watershed; the release from reservoir is determined by the amount of water demand and the minimum release required as stream base flow. The total water consumption is strongly correlated with urban productivity. The per capita water consumption (TMPCWC) and the reservoir storage are the two sustainability indicators of the subsystem.

3.5 Environmental Management Subsystems

Rapid urbanization in Taipei has created a variety of environmental problems. The provision of infrastructure for solid and liquid waste treatments and the consequential stream pollution are the main concerns for these modules. The per capita solid waste generation, percentage of solid waste recycled, service ratio of sanitary sewers, percentage of sewage treated, and percentage of stream polluted are the major indicators employed to evaluate Taipei's sustainability.

Because of the insufficiency of municipal sewage treatment facilities, the downstream portion of the rivers in Taipei metropolitan region is polluted beyond the designated quality standard. Although a municipal waste water collection system has been planned and is under construction, progress has been much slower than expected. Currently, less than 40% of the total sewage is collected and treated. In the modules of environmental subsystems, the number of population, simulated from population subsystem, the total water consumption from the water supply subsystem, and the assumed relation between per capita solid waste generation and urban productivity are used to simulate the indicators employed in this section.

4 Simulation Results

An advantage of the systems approach is that the model can be build-up gradually as a series of linked modules. Using statistical data from 1987 to 1995, the performances of each of the six subsystems are validated individually. Further

details concerning the model equation for each of the subsystems can be found in Huang[7].

After testing the validity of each of the subsystems, they are combined into an integrated system model for simulating Taipei's urban sustainability. Figure 3a presents the base simulation results of Taipei's urban system under the existing mechanism. After 1988, the population in Taipei city continued to decrease, however, the urban area surrounding Taipei has continued to expand at the expense of losing agricultural land. Due to the growth of urban productivity, there were increases in the number of vehicles, total water consumption and generation of solid waste. Owing to the decrease of population and development of public facility and infrastructure, the sustainability indicators of per capita natural area, the ratio of public facility to urban area and the service ratio of sanitary sewers indicate improvement of Taipei's sustainability. However, the number of vehicles per person, public transit conveyance, per capita solid waste generation and per capita water consumption are currently threatening Taipei's urban sustainability (see figure 3b). Although the development of Taipei city is

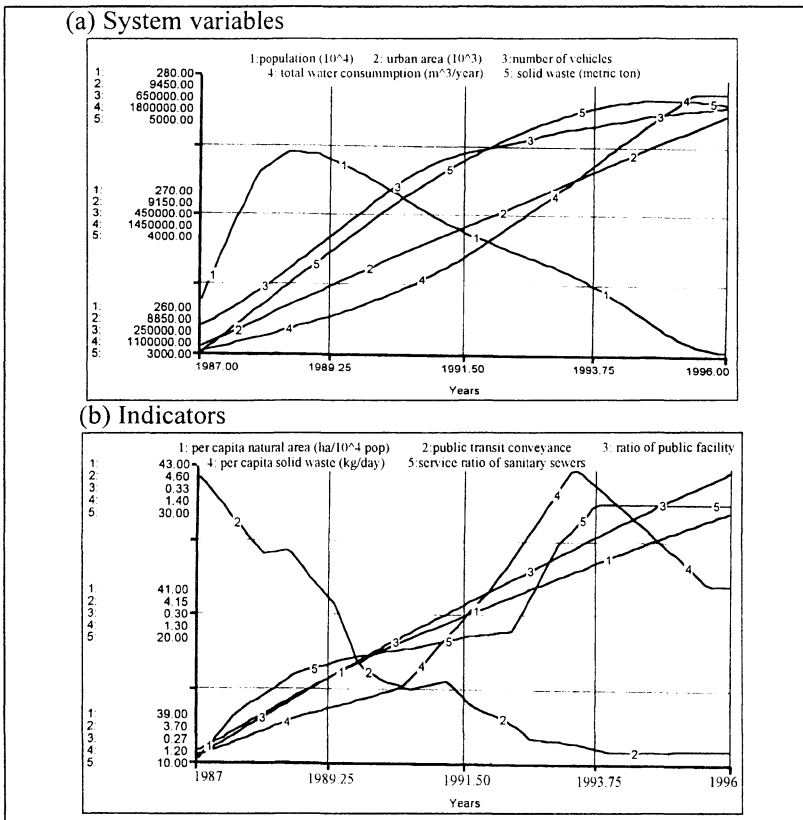


Figure 3: Base simulation of Taipei's urban system

driven by socioeconomic demand, however, policies for self-regulatory growth and minimizing waste generation should be adopted to alleviate the negative effects of urban growth on Taipei's sustainability.

In order to analyze the further development of Taipei, this paper proposes three scenarios for policy simulation of Taipei's urban sustainability:

Scenario 1 - Business as usual. In this alternative, it is assumed that the behavior of each system and the relationships between subsystems and variables remain the same and are extrapolated into the future. This scenario can be used as a base run for comparisons with the other policy scenarios.

Scenario 2 - Hyper expansion. Taipei is not only the national capital but also the key economic center of Taiwan. Its current policy is aiming at becoming the Asia Pacific Regional Operating Center. In this alternative, economic growth is the major goal of urban policy. The improvement of urban environmental quality is also emphasized by the development of infrastructure..

Scenario 3 - Self-regulatory growth. In this alternative, the environmental carrying capacity is emphasized to stabilize urban growth and to enhance the environmental quality for urban residents.

Figure 4 summarizes the results of the comparisons of several sustainability indicators between the three scenarios of Taipei's urban development policies. Under scenario 1, business as usual, the per capita urban productivity continues to grow, which is likely to accelerate the increase of automobiles and decrease the conveyance of public transit. The economic growth provides sufficient financial sources and makes it possible to develop public facility and infrastructure and enhance urban living standards. Although the service ratio of sanitary sewers increases, but due to the increasing per capita water consumption, the problem of stream pollution is not alleviated. The policy of hyper expansion of Taipei (Scenario 2) aims to achieve higher economic growth rate. Although there will be more expenditures on improving living standards, but traffic and environmental problems might not be resolved due to the demand-driven behavior of urban residents. For example, the percentage of polluted stream remained unchanged despite the increase of service ratio of sanitary sewers. The 3rd scenario of self-regulatory growth emphasizes on environmental quality by minimizing water resource consumption and recycling of solid wastes. The conveyance of public transit is improved through the discouragement of automobiles.

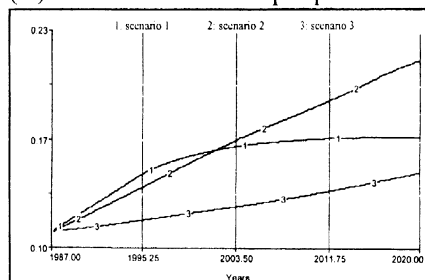
5 Conclusion

The performance of urban sustainability indicators should not be evaluated individually, rather the chain effects between indicators should be assessed through a systems approach. The integrated model allows us to study the causal relationships between subsystems and among indicators. The system approach demonstrated in this paper can be used to analyze the dynamic interaction and the interdependent relationships between sectors of an urban system. Furthermore, the scenario analysis that adjusts the relationships between variables can simulate

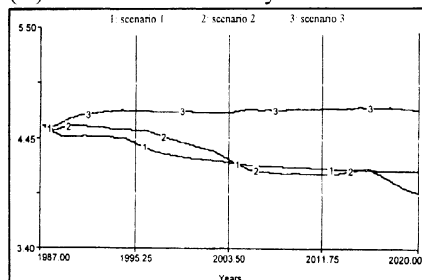
the consequential effects on urban sustainability under different urban policies and, subsequently, can be a basis for policy evaluation.

Due to the limited availability of input data, the usefulness of the simulation model developed in this paper is constrained by its scope. Further improvement can be made by including more indicators and incorporating spatial dimensions into the model. It is hoped that this paper and the concepts in it may further our understanding of the integrated urban systems and stimulate further ideas and research need for urban sustainability.

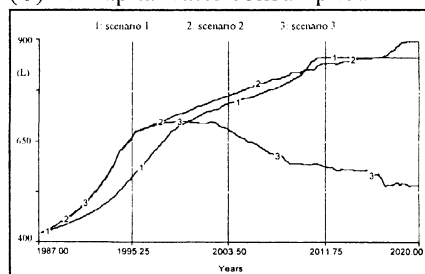
(A) Number of vehicles per person



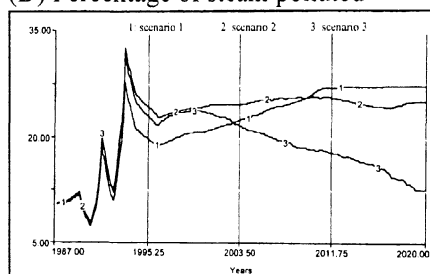
(B) Public transit conveyance



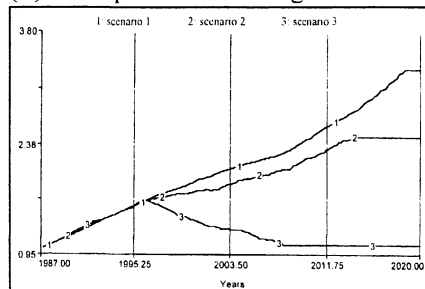
(C) Per capita water consumption



(D) Percentage of steam polluted



(E) Per capita solid waste generation



(F) Green coverage ratio

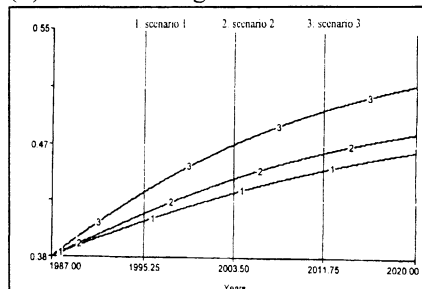


Figure 4: Simulation of the effect of policy scenarios on Taipei's urban sustainability

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