DEVELOPMENT OF A SIMULATOR FOR THE URBAN ENVIRONMENTAL LOAD PREDICTION USING SYSTEM DYNAMICS

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ABSTRACT

In this study we are investigating the urban environment, including complicated social dynamics, as the "urban system". We have developed a simulator which can predict the environmental load for a city, comprised mainly of buildings, over the medium and long term. In this paper we describe the development of this simulator and verify its accuracy by comparing the calculated values with real data, investigating the population, housing, non-residential building, traffic and environment sectors, all elements of the simulator

OBJECTIVES FOR DEVELOPMENT OF THE SIMULATOR

In a city and buildings which support a basis for human life, resources and energy are consumed and waste products are inevitably discharged. At the July 2008 Toyako summit a shared goal of cutting at least 50% of global greenhouse gas emissions was agreed. As a result the amount of resources devoted to "Post-Kyoto Protocol" activities in city planning and architecture has increased greatly. In Japan various technologies for carbon reduction have been developed in the past, but total energy expenditure from year to year keeps increasing. Almost 40% of the energy consumption of a typical city occurs due to the construction and daily operation of buildings.

Existing top-down goal setting and current technologies have limitations for the development of sustainable cities and buildings in the future. So bottom-up methodologies which urge changes to behavior on an individual level in order to effect larger changes to the civic environment, and investigation into which energy technologies can be disseminated, how they can be spread and what social systems and the economic backing is necessary for spreading them, are becoming more important. In order to facilitate such methodologies, prediction of the environmental load, energy consumption and CO_2 emissions, and the effect of environmental load reduction measures, various energy technologies, and economic backing targeted to the urban system is important. It is also necessary to support the planning and execution of effective measures for developing sustainable cities and buildings. Although various control and social measures for developing sustainable cities have been taken up until now, there are no tools or methodologies for determining long-term predictions of environmental load in the whole of a city and its buildings and thus direction of government policy in various areas has perhaps not had a sound enough scientific basis.

We have applied various energy technologies to buildings and have evaluated statistically the effects of their introduction with time and lifecycle. But now it is necessary to dynamically evaluate environmental load reduction measures whilst considering the complex dynamics of the target city including buildings and infrastructures.

Based on this background, this study aims to develop a simulator for urban environmental load prediction which can predict the medium and long term effect on environmental load targeted to a highly-nonlinear urban system. In this paper we show the development of a new approach to modeling urban systems that improves upon methodologies used in the past, and we verify the accuracy of some models by comparing the simulation result to actual obtained data.

PREVIOUS MODELING METHODS

Some prior investigations into modeling cities and societies as one system have been carried out not only in the field of economics and sociology but also architectural fields. Such cases, that predict and deal with both the urban and societal aspect of a city, are labeled as complex systems, and previous approaches towards them are outlined below.

Long-term prediction using a statistical approach

Statistical approaches are the most common prediction methods across various fields, such as economics, sociology and natural science. In some statistical approaches, prediction formulae are made by regression analysis based on observational data. This approach assumes that the relationships between variables and results are linear and the resulting prediction accuracy is high when there is no fluctuation in system variables. However feedback between individual variables is neglected as they are assumed to be discrete and non-dependent on each other, and so problems arise when system variables are interdependent, as in complex systems.

Long-term prediction by system dynamics

System Dynamics (SD) was developed by J. Forrester in the 1950s as a way of modeling dynamic characteristics of a system using differentials.

(1) World Dynamics (WD)

Pioneered by the Club of Rome, WD[1] is one of the most popular simulation methods and takes account of population, capital, resource, agricultural and pollution factors around the globe. WD models the dynamic behavior of non-linear systems by setting threshold amounts of resource reserves and environmental acceptability and by modeling the delay of responses to quantities above the threshold amounts. However WD attaches importance to analyzing the dynamic behavior of parameters rather than duplicating realistic data closely.

(2) Urban Dynamics (UD)

Forrester's UD[2] focuses on the mechanism of growth, maturity and decline of the targeted virtual city. However, similarly to WD, UD attaches more importance to qualitative trends than actual figures from the simulation.

In Japan many UD models, for example the Hyogo, Saitama and Kanagawa models, were created in the 1970s and 1980s. UD models in Japan are used mainly as supporting tool for the formulation of comprehensive plans in local administrations, and so a certain level of quantitative accuracy is required. In UD "an attraction multiplier" is used to model the relationship between the outside and the centre of the city because it treats open urban systems as closed urban systems.

Modeling complex systems

Recently the multi agent system (MAS) has attracted attention as an alternative approach for dealing with complex systems. MAS investigates complex systems such as artificial societies by using many agents which make individual decisions and act autonomously. Tanimoto et al.[3] have applied evolutionary game theory to the artificial society model developed by MAS and have studied the emergent possibility of a sustainable society. In SD the system makeup is determined by the user-defined components. However in MAS the system behavior is more user-independent and is determined by the interaction between agents and the response of agents to feedback from the system.

DEVELOPING THE MODEL USING SYSTEM DYNAMICS

Modeling Method

When thinking about an element of the population in a city, the population in the year the calculation is initiated is taken as the first year value. This population is changed by number of live births, number of people dying and the amount of migration, and the amount of migration in the future depends on sequential changes in the rate of migration. The rate of migration is affected by "migrant attraction". If there is a plentiful supply of roomy housing, i.e. a large amount of living space per person, a growth in immigration bringing a growth of the population occurs. But this growth in population brings a reduction in floor space and thus a population decrease due to decreasing immigration. The rate of immigration also relates to the presence or absence of employment and gap in income levels. The living space per person is also influenced by household structure and number of housing stocks, which is in turn influenced by the rate of houses constructed, the rate of houses demolished and the land use structure. Taking into account all of these factors, it is possible to simulate complicated social dynamics of a city by modeling a city as system composed of various elements (Fig.1).

We have modeled sectors using SD[4] which can easily describe dynamic behavior and the causal relationship between the system and its variables. SD also calculates

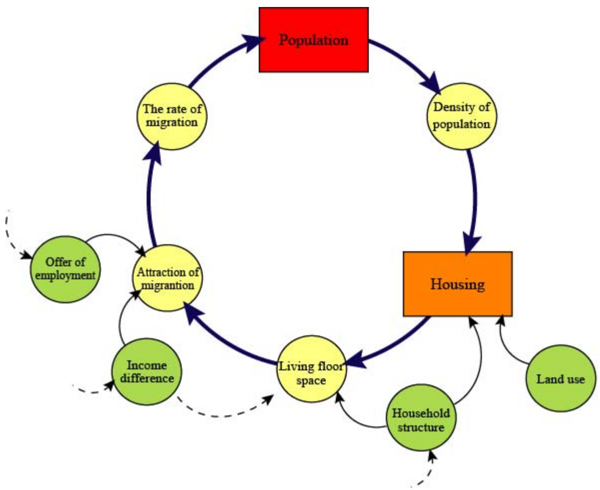


Fig.1 The feedback structure between population and housing

dynamic characteristics of the system using simultaneous ordinary differential equations.

Procedure for developing the urban environmental load prediction simulator

The procedure for modeling and simulating is shown in Fig.2. First we studied the dependence and causal relationship between the elements of an urban system comprised mainly of buildings. We collated and organized past statistical data on several system variables, and we made each model after calculating values for the first year of the models and the structural equations for the parameters. After that we confirmed the accuracy of each model by comparing calculated values with real data and we integrated each model into the simulator for the urban environmental load prediction. Finally we evaluated the sustainability of the urban system by predicting the amount of environmental load reduction for each scenario until 2050. When evaluating, we measured the efficacy of environmental load reduction measures by studying not the absolute environmental load reduction but the percentage change in environmental load.

Components of the simulation

The elements and sectors of our simulator are shown in Fig. 3. The system is comprised of a huge quantity of elements, but it is not necessary to take account of all the elements in the system, if it is possible to determine the elements which are the main causes of changes to the environmental load. Thus we have the population, the housing, the non-residential building, the traffic and the environment sector.

In the case of modeling the urban system using SD, the causal relationship between elements is defined by the structural equations. The structural equations are estimated using multiple linear regression analysis when the relationships between elements are assumed to be linear. However if this is not the case, the structural equations are estimated using attraction multipliers. They are defined by the degree of influence of the element by applying functions, such as convergence and logistic functions, to conform to the actual values and the dynamic behavior in the past (Fig.4). Also attraction multipliers are index quantified using various factors like quality of the living environment and the numbers of jobs available to attract migration.

However, due to the method of collecting input data, a certain amount of arbitrariness may be introduced into the system, reducing reliability of the results. On the other hand, if multiple regression equations are used with too much emphasis on the reliability of prediction, the dynamic behavior of model can be lost. So it is necessary to balance use of the attraction multiplier approach and the approach by multiple regression equations to gain the best understanding of the system.

MODELING EACH SECTOR

Calculation flow of the population sector is shown in Fig.5. Population is changed by natural increase and decrease (live births and people dying) and social increase and decrease (immigration and emigration) in the population model. Growth of a service industry makes the urban area more attractive, so an attraction multiplier for the rate of

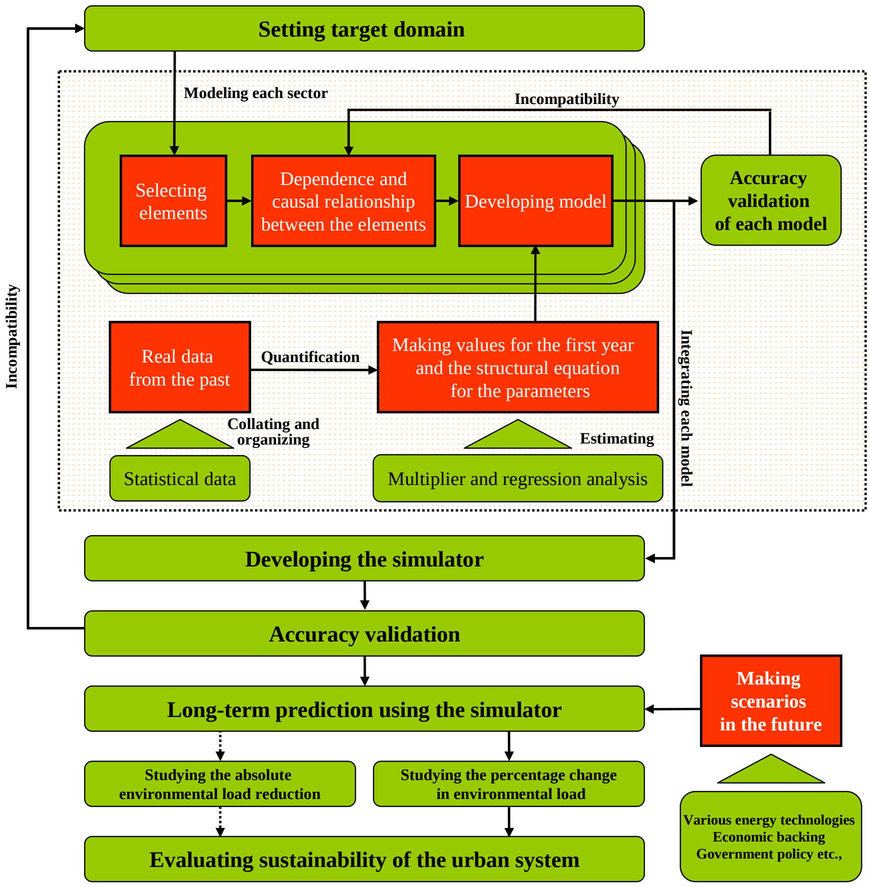


Fig.2 The procedure for modeling and simulating

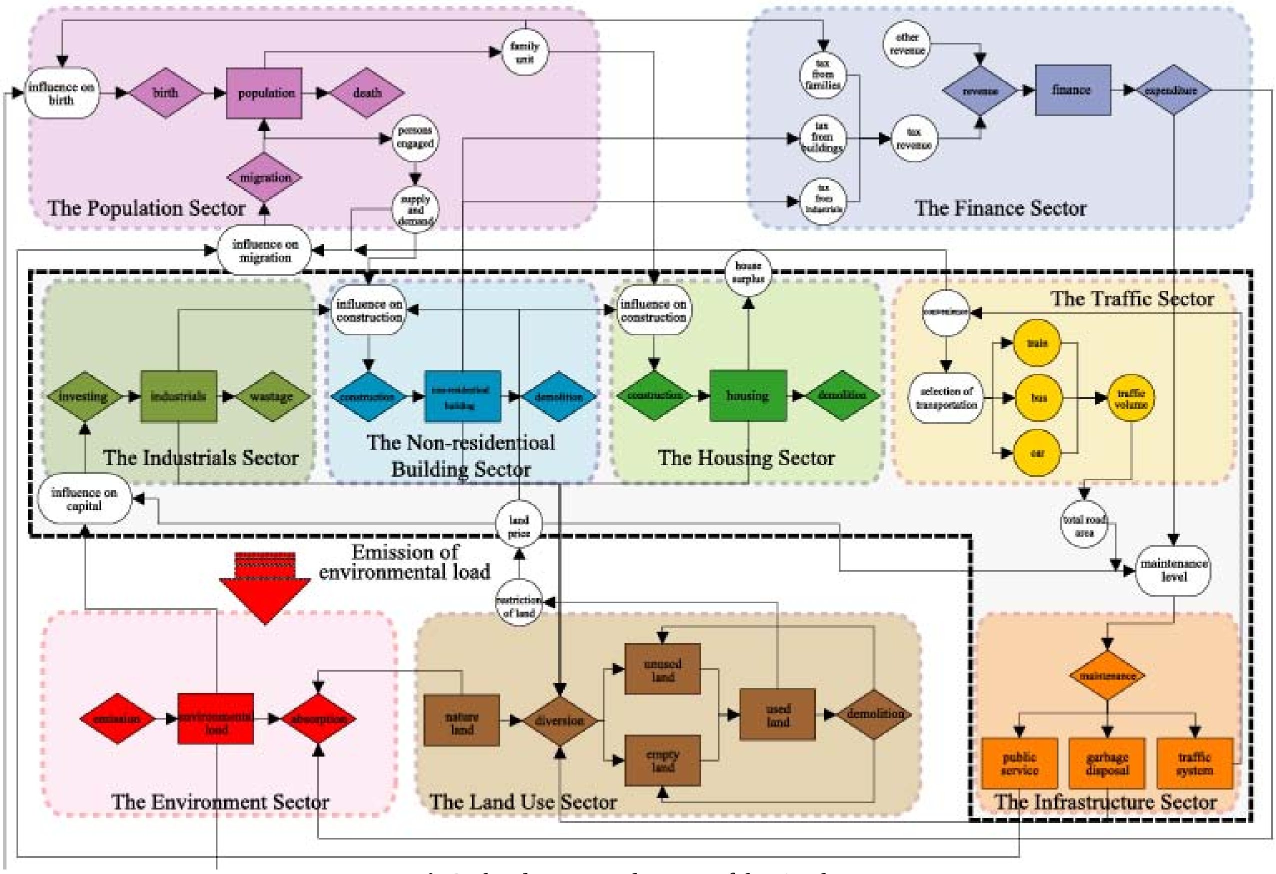


Fig.3 The elements and sectors of the simulator

service employment was built into the calculation flow for the amount of migration. Growth in the service industry can cause a decline in the birthrate due to the tendency to marry later, so an attraction multiplier dependent on the proportion of service employment was also built into the calculation flow for the birthrate.

Calculation flow for the housing sector is shown in Fig.6. The change of housing stocks was modeled using housing construction and demolition flow. In addition we divided housing into detached and apartment housing types. Housing construction is controlled by attraction multipliers depended on the residential density and the housing occupancy rate. In the attraction multiplier controlled by the residential density, housing construction is limited when the amount of housing increases too much. In the attraction multiplier affected by the housing occupancy rate, housing construction is limited when the number of housing units is more than number of households, resulting in empty housing stocks.

Calculation flow for the office building sector as an example of the non-residential building sector is shown in Fig.7. In the non-residential building sector, the change of the total floor area stocks was modeled using the floor area construction and demolition flow. The non-residential

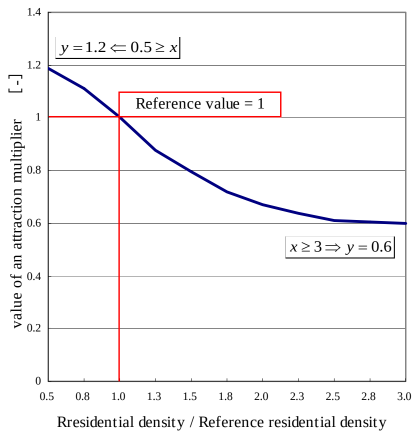


Fig.4 An attraction multiplier for the residential density and the construction rate of housing

building sector was divided into 7 sectors according to usage: the office building, wholesale and retailing industry, catering trade, lodging industry, medical practice, educational facilities and other service industries sector. In the office building sector an attraction multiplier affected by the growth rate of population and commercial accumulation was built into the calculation flow for the office building construction, because we believed that the population concentration and commercial accumulation would promote office building construction. Also in the

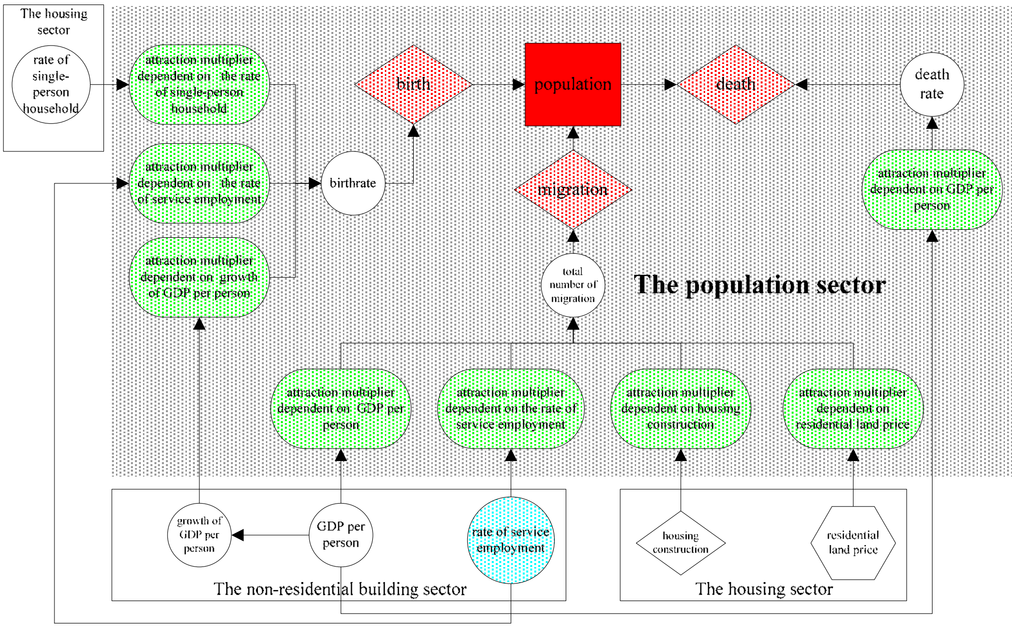


Fig.5 Calculation flow for the population sector

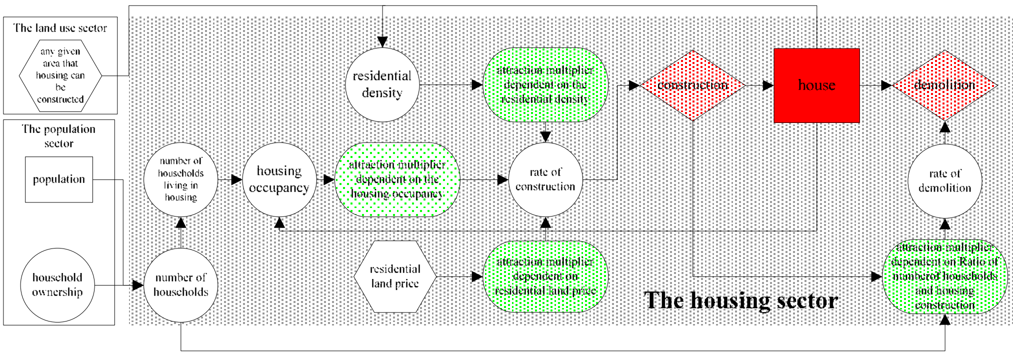


Fig.6 Calculation flow for the housing sector

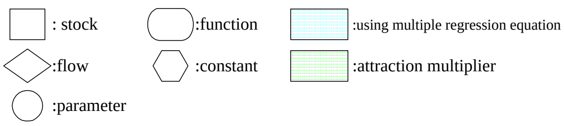
wholesale and retailing industry, catering trade, lodging industry, medical practice and educational facilities, attraction multipliers related to supply and demand, sales total, number of patients and number of students, were built into these models as an influence on the rate of construction.

Calculation flow for the traffic sector is shown in Fig.8. In the traffic sector, the traffic volume according to the traffic purpose and transportation means is calculated. Due to the increase in commuter traffic volume that accompanies an increase in the amount of employment, attraction multipliers depending on the population concentration and the car ownership ratio were incorporated into the model.

In the environmental sector, to calculate amount of CO_2 emissions, CO_2 emission basic units are multiplied by the amount of each sector's activities – number of housing and total floor area etc.

STUDY OF SIMULATION RESULT

After we integrated each sector, we studied the efficacy of



the simulator by comparing the calculated results from 1975 to 2050 to the actual values from 1975 to 2005 for Fukuoka City, a medium-sized city in Japan. However the residential and commercial land prices from 1975 to 2005 were given their actual values and those values from 2005 to 2050 were given the 2005 value, because it was difficult to model future prices using only current model.

A comparison of the predicted and actual population data is shown in Fig.9. Comparison of the number of living births, deaths and amount of migration is shown in Fig.10. The population was calculated to keep increasing until about 2035, due to the over-estimation of the amount of migration. The amount of migration was predicted to increase, influenced by the quantity of service employment, because the influence of the service employment is much larger than other factors. The number of living births was

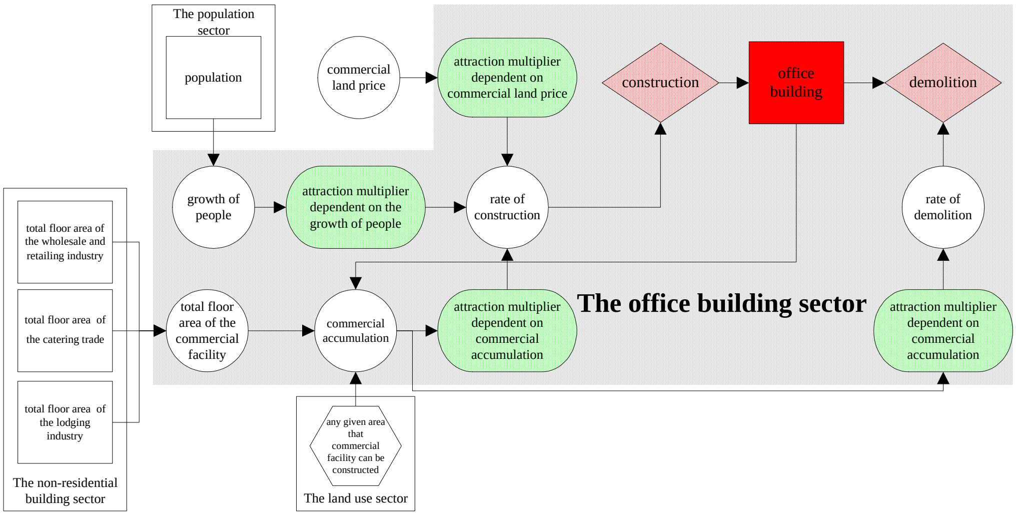


Fig.7 Calculation flow of the office building sector

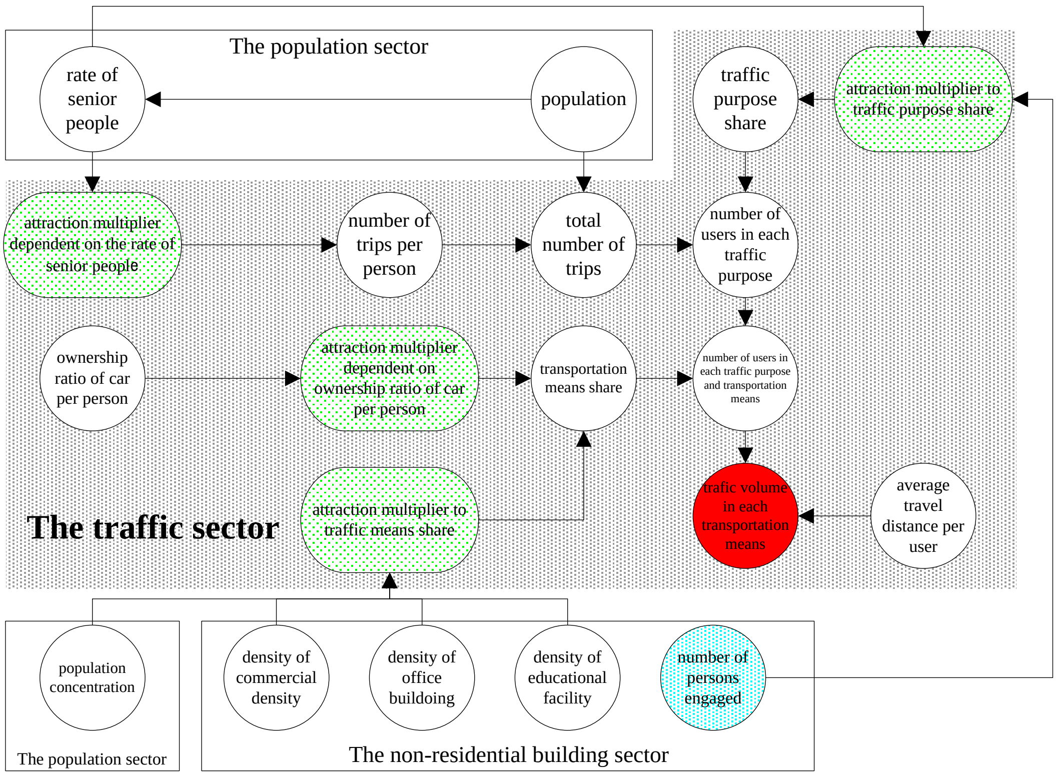


Fig.8 Calculation flow of the traffic sector

also predicted to increase around 2035 due to the rate of service employment decreasing. In this way, if there are biases in the degree of influence of an attraction multiplier, the system behavior is determined mainly by strong influencing factors, and the influence of other factors becomes difficult to determine.

A comparison of the traffic volume according to means of transport is shown in Fig.11. It was difficult to model the traffic volume according to transportation means using only the elements of our model, especially considering the decreasing trends in the volume of car traffic from around 2000. Owing to this we thought it best to model policy and public transportation services within the administrative and financial sector, and use the population distribution in the land use sector to best model traffic selection behavior.

Comparison of the number of each kind of housing stocks is shown in Fig.12. If the number of apartment housing stocks increases more than number of households, the housing occupancy rate decreases and therefore the construction rate of apartment housing also decreases. However if the value of the residential density becomes three times more than the value in 1975, the attraction

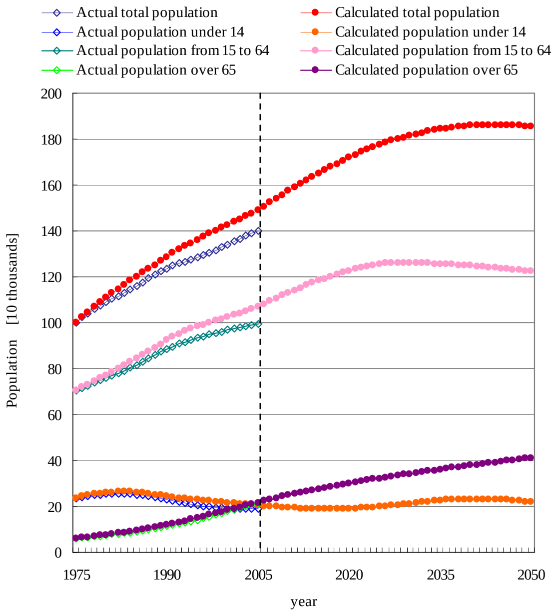


Fig.9 Population

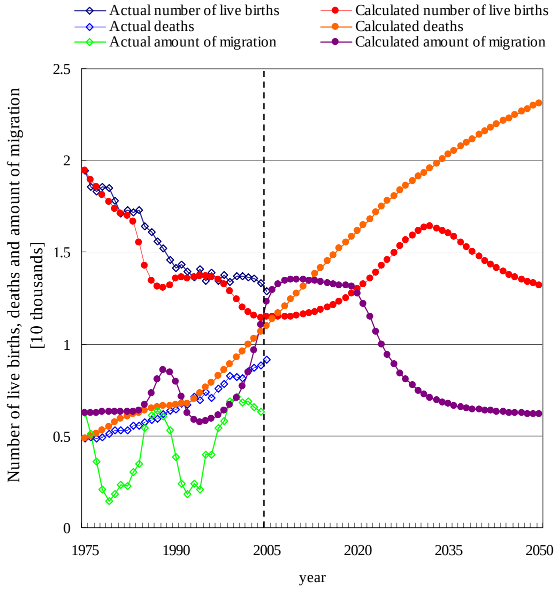


Fig.10 Number of living births, deaths and amount of migration

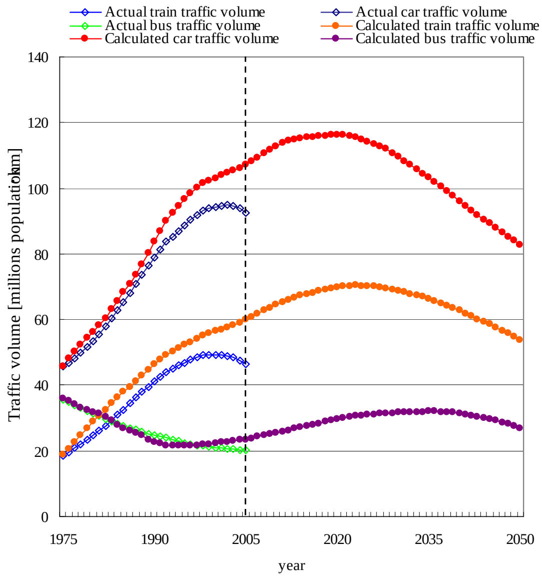


Fig.11 Traffic volume according to means

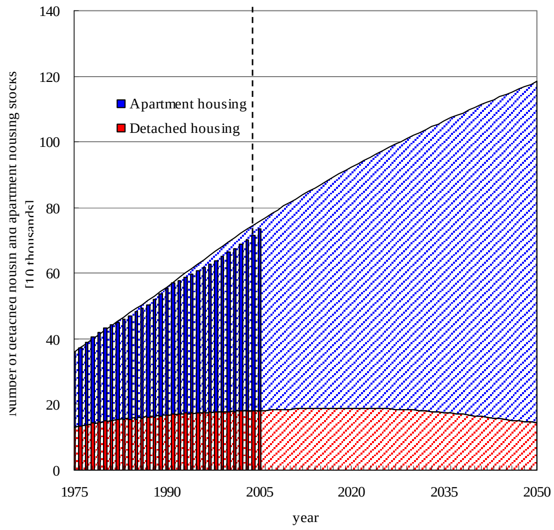


Fig.12 Number of each kind of housing stocks

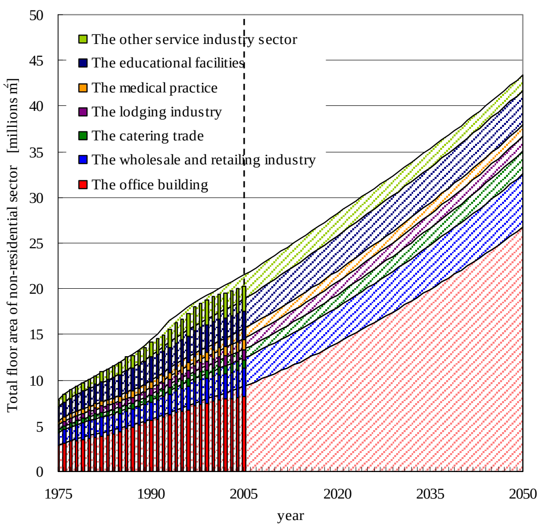


Fig.13 Total floor area for the non-residential building sector by the according to usage

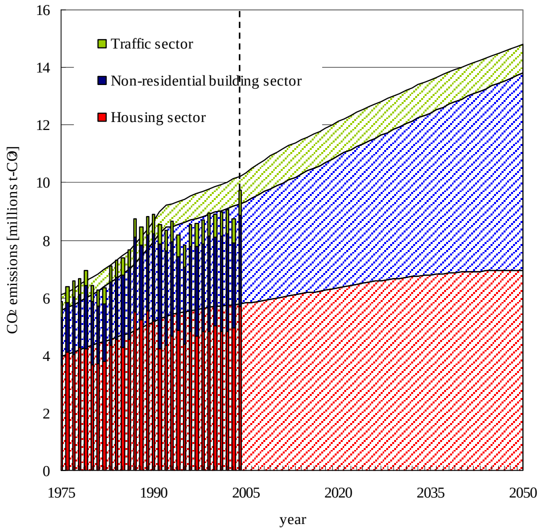


Fig.14 CO_2 emissions of each industrial sector

multiplier affected by the residential density takes a constant value of 0.6 (Fig.4). So it appears that this attraction multiplier will not decrease further after 2010. Thus the decreasing trend in the construction rate of the apartment housing will slow down and number of the apartment housing stocks will continue to increasing.

A comparison of the total floor area of non-residential building sector according to usage is shown in Fig.13. It appears that the construction rate will not decrease for the office building, wholesale and retailing industry and the catering trades, so their total floor area will keep increasing until 2050. The growth rate of the population and commercial accumulation will also decrease, so the construction rate of office buildings will continue on a downward trend. However the construction floor area will not decrease due to a corresponding increase in the total floor area, according to past actual values. However the trends and the degree of influence in the future, which can not be adequately defined using only the past values, affect the dynamic behavior of the construction rate, and so making a forecast in which the construction rate decreases cannot be carried out. There is also a possibility that other influencing factors which decrease the construction rate exist, and as yet unknown factors which exert a big influence in the future may also exist.

Comparison of the CO_2 emissions of each industrial sector is shown in Fig.14. The amount of housing stocks and the total floor area of the non-residential sectors are predicted to increase, and thus the CO_2 emissions also increase. There is possibility that the environmental load increase will result in a concomitant decline in birthrate, and a high resource price in the future. However it is difficult to predict these influences with any degree of accuracy, so our simulator does not incorporate feedback from the environmental sector to other sectors.

CONCLUSIONS

In this report we have explained the reasons behind developing a simulator for urban environmental load prediction for a complex urban environment, and development of such a system. The methods of modeling using system dynamics method were also shown. The effectiveness of the simulator was also shown by comparing calculated values to actual values and the results discussed above are summarized below.

1) The urban dynamic behavior can be simulated by modeling the urban system using a system dynamics method.
2) The size of attraction multipliers should be defined with due consideration for the balance of more than one parameter.
3) It is necessary for us to organize collating questionnaire results and specialist knowledge to investigate the trends in, and the degree of influence of attraction multipliers in the future.

REFERENCES

[1]Donella H. Meadows, Dennis L. Medows, Jorgen Randers, and William W. Behrens III , 1972, The Limits to Growth, New York : A Potomac Associates Book.

[2] Forrester, Jay W, 1969, Urban Dynamics, MIT Press.

[3]Jun Tanimoto, 2005, Environmental dilemma game to establish a sustainable society dealing with an emergent value system, Physica D Vol.200, 1-24.

[4] Isee Systems, Inc. , 1985-2004, STELLA Software.