Environmental Carrying Capacity of Seoul Metropolitan Area - Estimation, Implication and Limitations

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Abstract

The purpose of this paper is estimating environmental carrying capacity of Seoul Metropolitan Area for a sustainable city management using system dynamics model. A sustainable development requires a society to define sustainability constraints or environmental limits, environmental carrying capacity. Environmental carrying capacity can be defined as the level of human activity which a region can sustain at an acceptable quality of life level. This concept of environmental carrying capacity has several important applications to sustainable city planning and management. If the limitation of a human activity can be supported by a scientific data on carrying capacity, the resulting decision and actions could more easily win public support for a sustainable development. However, one of the key issues is how to operationalize the carrying capacity. In this paper, the environmental carrying capacity was operationalized as a maximum number of industry structure, population, and housing that can sustain certain level of environmental quality of Seoul Metropolitan Area. The model developed in this paper consisted of 5 sectors; population, housing, industry, land, and environmental sector. The model limits its main focus on the NO_2 *level of ambient air of Seoul. In this paper, Box Model was used to improve the estimation of ambient air quality of Seoul compared with previous one. Box model was translated into system dynamics model and combined to urban dynamics model to estimate the maximum number of population, industry structure, housing at an equilibrium point that sustain a desirable* NO_2 *level. Based on the model estimation, several policy implications for a sustainable city management was discussed.*

1. Introduction

The purpose of this paper is building an environmental carrying capacity model and applying the model to estimate Seoul Metropolitan's environmental carrying capacity.

A sustainable development require a society to define sustainability constraints or environmental limits, environmental carrying capacity. Environmental carrying capacity can be defined as "the level of human activity which a region can sustain at acceptable level of quality of life". This concept of environmental carrying capacity has several important applications to sustainable city planning and management. If the limitation of a human activity can be supported by a scientific data on carrying capacity, the resulting decision and actions could more easily win public support for a sustainable development.

For this purpose, this paper consists of three parts. First, the paper examined the evolving definition of the sustainable development and environmental carrying capacity. Second, having examined the concepts, a model of environmental carrying capacity focusing on a regional NO_2 emission based on both urban dynamics model and box model was built. Third, using the environmental carrying capacity model, this study attempt to estimate Seoul Metropolitan area's environmental carrying capacity. Some discussions on implication of the results were also presented.

2. Concept of Sustainability and Environmental Carrying Capacity

Since the term 'sustainable development' was defined by the Brundland Commission in 1984, the definition has been further developed by UNEP and ICLEI, the International Council for Local Environmental Initiatives (Hams, et.al., 1994:2-3). One way of looking the term is to consider that there are two versions of sustainable development, a weak version and a strong one. The weak version just requires that environmental considerations are given greater weight in public decision making. The strong version, however, require society to define sustainability constraints or environmental limits, environmental carrying capacity.

Carrying capacity is formally defined as the maximum population that can be sustained by an ecosystem over time (Miller, 1979 recited from Baldwin 1985:11). From a regional point of view, carrying capacity can be defined as "the level of human activity which a region can sustain at an acceptable quality of life level" (RSPB, 1993; Miller, 1979; Bishop et.al., 1974).

There has been three uses of the concept of environmental carrying capacity for environmental planning and management. The first use of the concept of carrying capacity is in studies to determine the threshold of human activities that will cause ecological damage to a natural environment. The second is the development of impact thresholds such as air and water quality standards. The last use of the concpet is to calculate the sustained yields of renewal resources that are possible without damaging the resource base for the future (Baldwin, 1985:13).

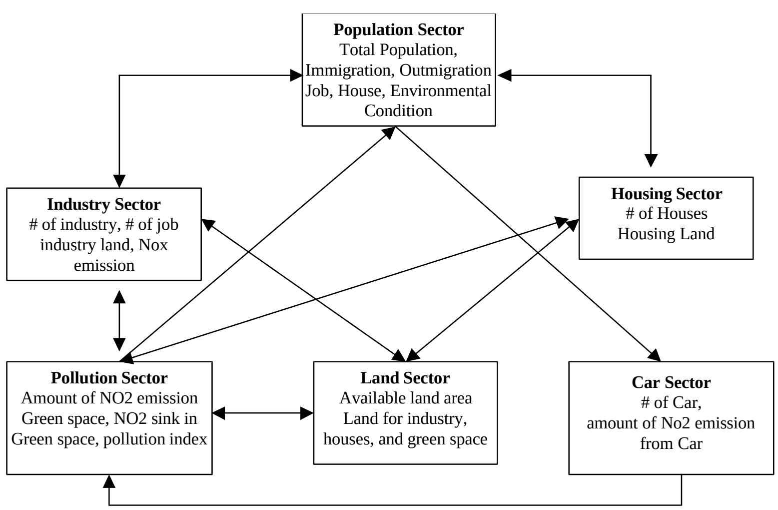
This paper belongs to the first line of research that seeks the use of the concept because the purpose of this paper is to estimate the maximum threshold value of human activities that can sustain a desirable NO2 level. Previous studies on this area includes studies on maximum number of tourists that can sustain wildlife habitat(Shelby & Colvin, 1982; Tarrant & English, 1996), research on finding optimum population density for a successful agriculture(Fearnside, 1985), and on maximum number city population that can sustain certain level of quality of life and environmental quality(Onishi, 1994; Moon, 1999, 1998; Lee, 1999, 2000)

This concept of environmental carrying capacity has several important applications to environmental planning and management. If the limitation of a human activity can be supported by scientific data on carrying capacity, the resulting decisions and actions can be more easily win public support. However, one of the key issues in the approach to defining a strong sustainable development is how to operationalize the carrying capacity and how to model it. System dynamics approach can be a alternative approach for this purpose.

3. Overview of the Model Structure

In this study, an environmental carrying capacity model was developed by adding environmental sector to the simple urban dynamics model (Alfeld et.al., 1976). The model consists of six sectors; population, housing, industry, car, land, and environmental sectors. Each secotors are dynamically related to other sectors as shown in the <Fig1>. The model purpose is to figure out how the size of population, industry, houses, number of cars, and green space is changing dynamically over time to reach equilibrium point to sustain a certain desired level of NO_2 in the ambient air quality of region.

<Fig.1> Environmental Carrying Capacity Conceptual Model

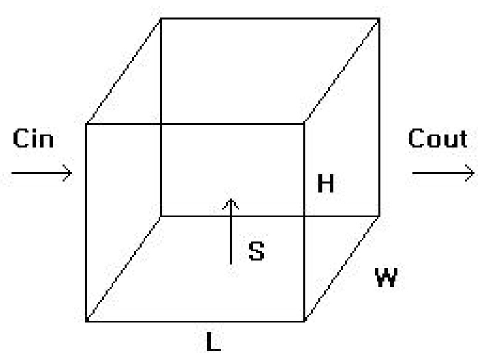


Model starts from the assumption that available land area is limited. Industry activities occurs within this limited land. Industry activities are affected by the availability of labor supplied. Labor availability is in turn, affected by the number of population in the population sector which is affected by the urban attractiveness; job availability, housing availability and environmental quality. When jobs are abundant, housing availability and environmental quality is good, population will be increased by in-migration, supplying enough labor force for active industry activities. However, if job availability, housing availability and environmental quality in the urban area is becoming worse, in-migration will be decrased and out-migration will outnumber in-migration rate, constraining industrial activities which would further limit industrial growth. However, even if inflow of population from other region is high, industry expansion can not be sustained indefinitely because available land for constructing industry structure is limited. When fraction of land occupied by houses and green space is high and available land for new industry construction is scarce, industry growth will be constrained. Model was constructed to see how these five sectors affect each other and how behaviors of interests variables are changing over time.

4. Prediction of nitrogen dioxide concentrations in Seoul using a box model

In the model, environmental sector is the most important part since this model is for estimating environmental carrying capacity. Box model approach is related to CSTR (Continuous Stirred Tank Reactor) concept that assumes air pollutants are uniformly dispersed in the atmosphere by active advection. In this study, the amounts of annual influent and effluent nitrogen dioxide(NO2) including dry deposition and chemical conversion amounts over Seoul were estimated using a simplified box model.

<Fig2> Box Model



$$V\frac{dc}{dt} = qC_{in} - qC_{out} + S - K_{dd}CLW - K_{cr}CV$$

where, q = volumetric flow rate(/sec)

C_{in} = influent concentration of a pollutant

C_{out} = effluent concentration of a pollutant

K_{dd} = dry deposition velocity(/sec)

K_{cr} = First order chemical reaction constant(1/sec)

qC_{in} = influent mass flow rate of pollutants(g/sec)

qC_{out} = effluent mass flow rate of pollutants(g/sec)

S = source emission rate(g/sec)

$K_{dd}CLW$ = the amount of pollutants removed by dry deposition(g/sec)

$K_{cr}CV$ = the amount of pollutants converted by chemical reaction(g/sec)

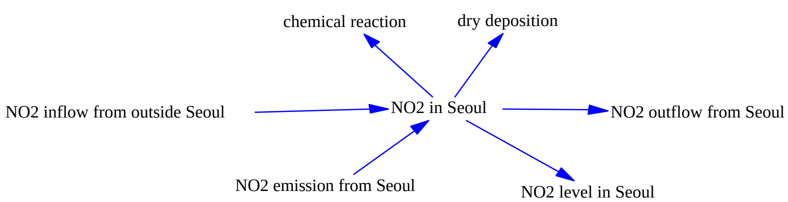
Wi = wind speed(m/sec)

In equation, V(=L×W×H) and q represent volume of Seoul( ) and volumetric mass of influent and effluent air, respectively. Since air is incompressible, it was assumed that inflow air mass is equal to outflow air mass. Seoul covers an area of 605 square kilometers approximately, so that length(L) and width(W) of the box were assumed as 25 , respectively. H(m) presents mixing height by which air pollutants can be mixed homogeneously. The first and second terms on the right hand side represent total amount of influent and effluent NO2 for one year, respectively. Assuming steady state($V\frac{dc}{dt} = 0$), volumetric flow rate can be calculated as follows; q=H×W×Wi×Time(1yr). The third term shows the amount of NO2 emission(kg/yr), which was recalculated using NO2/NOx ratio(=0.456) measured in Seoul('98) to take account of NO2 conversion into NO. The fourth term represents dry deposition removal, and dry deposition velocity(K_{dd}) was assumed as 0.5 /sec in the simulation. The fifth term shows the amount of NO2 participating in chemical reaction.

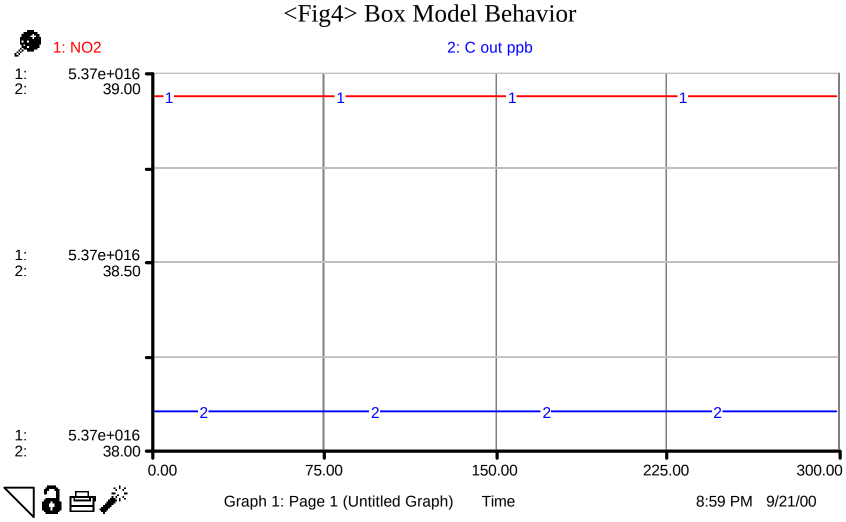
Box model was then translated into system dynamics language and its conceptual causal loop diagram is shown in the <Fig3>. Level of NO_2 concentration in Seoul Metropolitan Area can be affected by several factors such as height of the box, inflowing NO_2 concentration, wind speed, and changes in dry deposition rates. But for the simplicity of the model simulation, it was assumed 1 Km of box height, 30 ppb of inflowing NO_2 concentration, 1.5 m/sec of wind speed, 0.033 cm/sec and 0.098 cm/sec of dry deposition rate in CBD and green space, respectively. Behavior of the box model is shown in the <Fig4> and it indicates the NO_2 concentration in Seoul is stabilized around at 38 ppb when NO_2 emission from

Seoul is held constant.

<Fig3> Box Model and Causal Loop



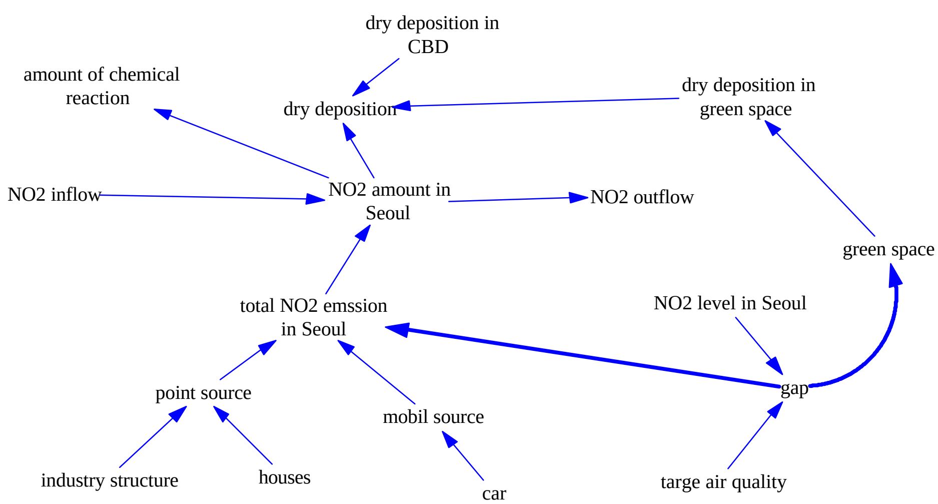
<Fig4> Box Model Behavior



<Fig 5> shows causal loop diagram of environmental sector with above explained box model part. The figure shows that the NO_2 concentration in Seoul Metropolitan Area is determined by the amount of NO_2 inflow from the outside of the Seoul, NO_2 emission from point and mobile sources of Seoul, and the amount of NO_2 converted into other chemical due to chemical reaction and dry deposition. Bold lines in the causal model do not represent causal relationship between variables. It was simply inserted as an policy leverage which exerts an influence to move the system toward an equilibrium point that can sustain desired level of air quality in Seoul.

When the gap between desired and actual NO_2 concentration become larger, two types of response is possible. First, total amount of NO_2 emission from Seoul Metropolitan can be reduced either by developing clean technology or by reducing total amount of NO_2 emission from industry and transportation sector. Second, NO_2 concentration in Seoul can be improved by increasing sink source of NO_2 which is the green space of Seoul Metropolitan Area. Green space in a city can act as both a source of supplying fresh oxygen and sink source of NO_2 from point and mobil sources. However, green space in Seoul cannot be increased without constraints because available land is limited. Increasing green space in Seoul can constrain new development of industry structure and new housing construction. Competition of land use among green space, industry land and housing land becomes evident. Environmental quality in the diagram was calculated as a ratio of actual NO_2 concentration in Seoul to target NO_2 concentration in the model ($\frac{actual \quad NO_2 \quad concentration}{desired \quad NO_2 \quad concentration}$).

<Fig5> Causal Loop Diagram of Environmental Sector

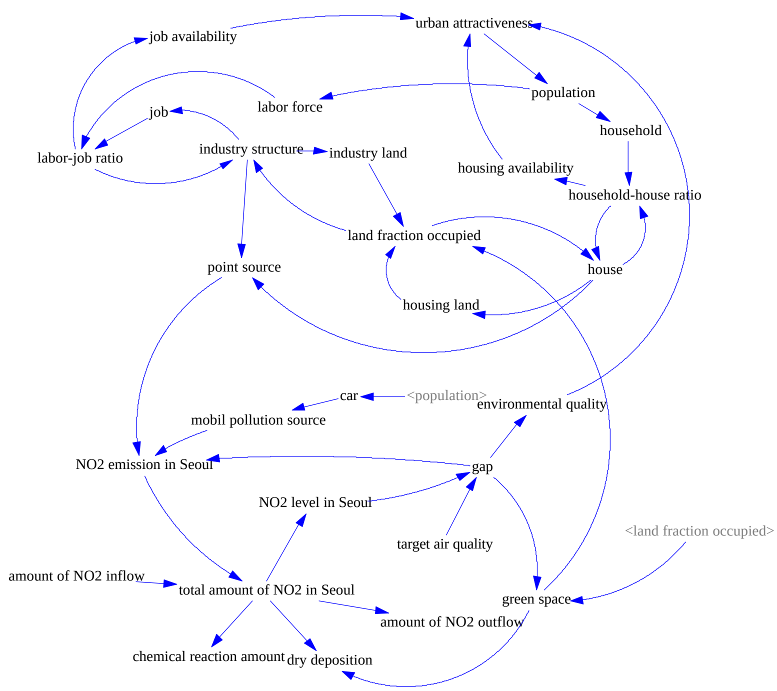


5. Combining Box Model and Urban Model

Environmental sector based on box model was then combined with urban dynamics model. <Fig6> shows causal loop diagram of environmental carrying capacity model of Seoul Metropolitan Area. A brief explanation of the diagram is in order.

The upper part of the diagram shows the urban dynamics model and the lower part shows the environmental sector. Growth and decline of city in terms of its population size is affected by urban attractiveness. This urban attractiveness is determined by the job availability, housing availability, and environmental quality. City attracts population from surrounding regions when job availability, housing availability, environmental quality is good. However, increasing number of city population decrease urban attractiveness because jobs and houses become scarce and expensive while environmental quality continues to be degraded. Since the model was constructed to move toward achieving a desired air quality of Seoul, city population, industry structure, houses, green space in each sector is adjusted against each other to reach at an equilibrium point where desired NO_2 conncetration is achieved. Then, the size of city population, the number of industry structure, houses and the total area of green space at an equilibrium point that sustain the desired NO_2 concentration can be regarded as the environmental carrying capacity of Seoul Metropolitan Area.

<Fig6> Causal Loop Diagram of Environmental Carrying Capacity of Seoul



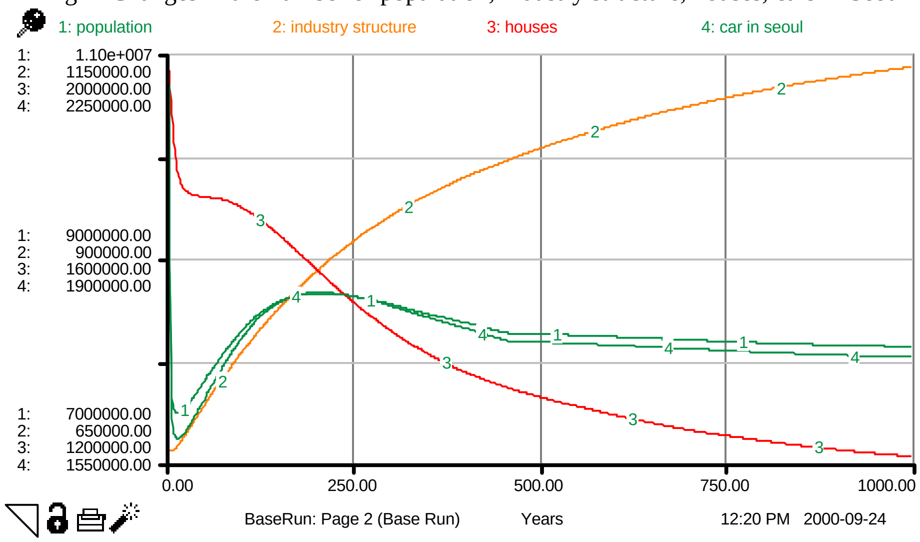
6. Model Behavior and Environmental Carrying Capacity

Causal loop diagram of environmental carrying capacity model was converted into system dynamics model and simulations were conducted. Followings are the results of the simulations.

1) Base Run

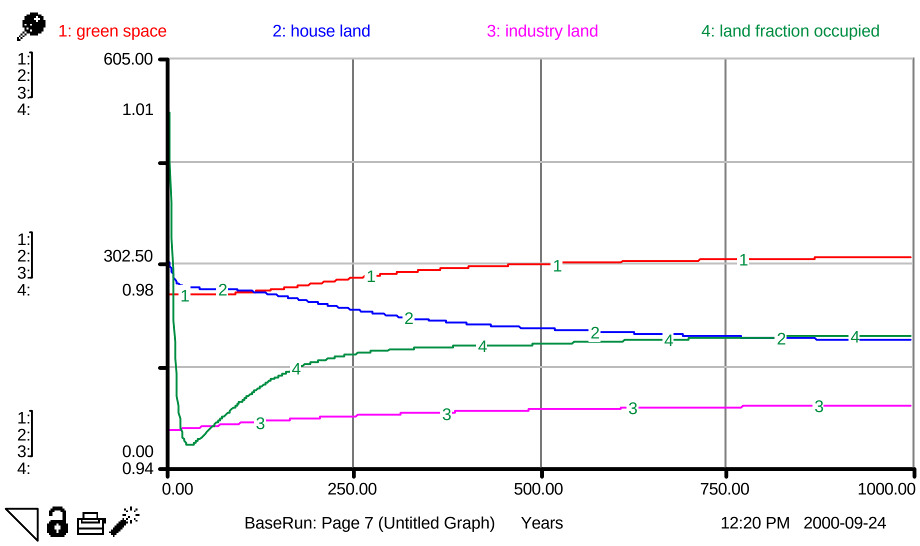
Base run simulation start from the assumption that desired level of NO_2 concentration in Seoul Metropolitan is 50 ppb which is equilivant to the national standard. It was also assumed that there are no technology change. Only green space was allowed to be changed so that the system can achieve an desired NO_2 concentration. Simulation results are shown in the <Fig7>, <Fig8>, <Fig9> and <Table1>. Figures show behaviors of interest variables over time. Approximate values at the equilibrium point represent maximum number of houses, industry structures, population and green space area that sustains a desired level of NO_2 concentration in Seoul Metropolitan. Thus, the number of houses, population, industry structures at this equilibrium point can be regarded as an environmental carrying capacity that can sustain a target level of NO_2 concentration.

<Fig7> Changes in the number of population, industry structure, houses, cars in Seoul

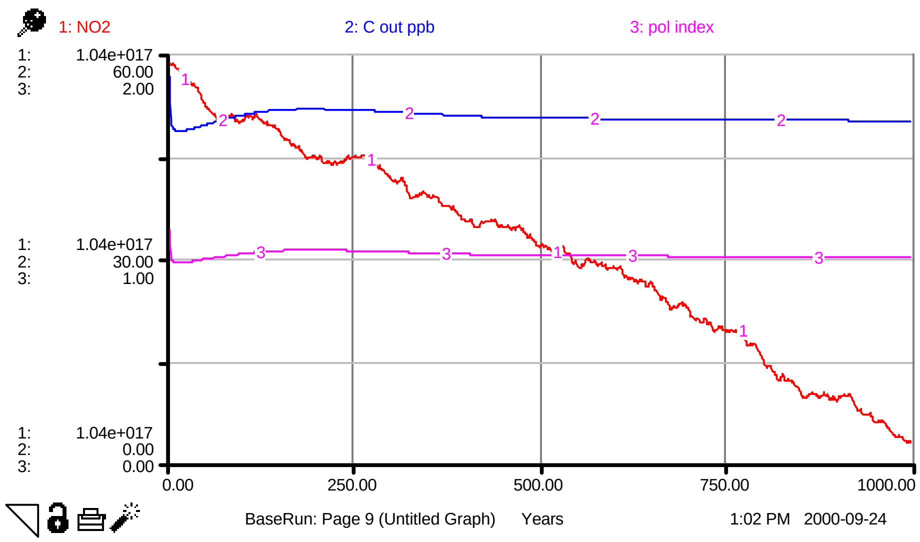


<Fig8> Changes in Green Space, Housing Land, Industrial Land,

Land Fraction Occupied



<fig9> Changes in NO_2 concentration and Environmental Indicator



<Table 1> Population, Industry Structure, Houses, Car and Land Use at an Equilibrium Point

	Initial Value (current Seoul)	Base Run Equilibrium Value*	Unit
Population	10,321,496	8,060,481	Person
Industry Structure	663,293	1,203,878	Unit
House	1,968,054	1,155,908	Unit
Car	2,196,062	1,714,996	
Industry land	52.24	94.82	km2
Housing land	300.43	176.45	km2
Green Space	253.28	311.79	km2
NO_2	56.79	50	ppb
Environmen-tal Index	1.14	1.00	$\frac{NO_2\ concentration\ in\ Seoul}{Taeget\ NO_2\ level}$
Households to House Ratio	1.27	1.82	$\frac{Household}{\#\ of\ Houses}$

Labor to Job Ratio	1.07	0.64	$\frac{\#\ of\ labor}{\#\ of\ job}$

Base Run : when green space changes according to air quality while there are no changes in technology (Green Space test=1, Technology factor=1)

<Table1> shows initial values used in the model and several equilibrium values resulted from the base run. Initial values used in the model are current statistics of Seoul Metropolitan. Equilibrium values in ‘base’ run column shows maximum number of houses, industries, population and cars the Seoul City can sustain in order to achieve NO_2 concentration of 50 ppb.

2) Simulations with different assumptions

Simulations with different assumptions were conducted with different level of target NO_2 concentration; 50 ppb, 40 ppb, and 30 ppb. Also some combination of different type of policy response were assumed in each simulation. The results are shown in the <Table 2>. At each level of NO_2 concentration, three types of policy response were simulated and simulation results that achieve target NO_2 concentration were listed in the <Table 2>.

<Table 2> Changing Environmental Carrying Capacity of Seoul Metropolitan with different NO2 concentration level

Taeget NO_2 level	Policy response	Pop (mil)	Industry (mil)	Hous (mil)	Industry land (km^2)	Housing land (km^2)	Green space (km^2)
50 ppb	Increasing green space	8	1.20	1.15	94	176	311
	Reducing NO_2 emission	9.8	1.45	1.40	114	215	253
	Increasing green space & emission reduction	9.8	1.45	1.40	114	215	253
40 ppb	Increasing green space	5.15	0.77	0.73	61	112	409

	Increasing green space & emission reduction	6.4	0.96	0.92	76	141	367
30 ppb	Increasing green space	2.04	0.34	0.28	27	43	514
	Increasing green space & emission reduction	2.80	0.44	0.39	35	60	489

Simulation results shown in the above table can be summarized as follows.

First, when desired NO2 concentration level is 50 ppb and there is no technology change that can reduce NO2 emission amount, maximum carrying capacity of Seoul is estimated as 8 million of population, 1.2 million of industry structure, and 1.15 million unit of houses. Population size of Seoul need to be reduced from current 10.3 million to 8 million because increased green space constrains additional land use for industry and housing. However, if NO2 emission reduction through technology development is possible up to 20%, environmental carrying capacity of Seoul increases substantially. Seoul can accommodate as much as 9.8 million people without increasing green space. This population size is close to the current population of Seoul, 10.3 million.

Second, if desired NO2 level is strengthed to 40 ppb, environmental carrying capacity of Seoul is reduced equivalently. If Seoul achieve this target by relying only on increasing green space, population size need to be reduced to 5.15 million. When Seoul responds by both increasing green space and developing technology that can reduce emission amount together, environmental carrying capacity of Seoul is increased to 6.4 million of population size with commensurate increases in other sectors.

Third, when target NO2 level is further strenghened to 30 ppb, Seoul Metropolitan's carrying capacity decreases substantially. Maximum population size ranges from 2.04 to 2.8 million with green space change and technology development.

7. Conclusion - Implications of the Simulation results

Simulation results explained so far indicate that Seoul metropolitan has exceeded environmental carrying capacity at all level of desired NO2 level. The results also suggest that in order to achieve NO2 level higher than 50 ppb, 20% of emission reduction through technology development alone is not enough. Either higher percentage of emission reduction or combining green space increase and emission reduction together is necessary to achieve higer than 50 ppb of NO2 concentration level. Because of inherent limitation of box model and limited analysis on the types of pollutants which was limited to the NO2 concentration, numbers from the simulation results cannot be readily applied to guideline of environmental management.

However, the simulation results suggest severl policy implications as follows.

First of all, Seoul needs to put more effort on increasing green space and on decreasing the amount of pollutant emission. Curbing pollutant emission is not only necessary for improving air quality in Seoul, but it is also necessary to increase environmetal carrying capacity of Seoul. Three types of alternatives are available to keep air quality at a desirable level. It can be achieved by decreasing the level of human activities, increasing green space, and by improving inflowing air quality from outside of Seoul.

Reducing the amount of pollutant emission is a key factor to increase environmental carrying capacity because it does not needs additional green space which can be used for additional industrial and housing purpose. But as explained earlier, without increasing green space and without constraining human activities within Seoul Metropolitan, pollutant emission reduction alone is not enough to achieve higher level of air quality. Increasing green space has also limitation. Even if Seoul can achieve desired air quality by expanding green space, this can cost job and housing shortage because available land for industry and housing use become scarce. This result is contradictory to the aim of sustainable development which pursue economic, social, and environmental development at the same time. One viable solution in this case may be developing green space with higher forest stock per unit area.

Second, government need to put more efforts to decentralize population of Seoul Metropolitan. In fact, government has been implementing population decentralization policies since 1970s but in vain. It was because the decentralization policies relied heavily on regulating and controlling population concentration rather than increasing urban attractiveness of other areas. It is hard to find capital city in the world that has 23 percentage of total population in a area less than 0.6% of total national land. Recently, population concentration control policy in Seoul city has weakened 'to improve' Metropolitan region's competitiveness. Population decentralization polices need to be more closely related to policies for improving urban attractiveness of small and medium cities instead of relying heavily on regulatory control system.

Thirdly, land use pattern or zoning policy of Seoul Metropolitan need to be changed dramatically to improve environmental carrying capacity of Seoul. Following table compares current land use pattern in Seoul to the land use pattern resulted from the simulation test. Proportion of residential area need to be reduced and that of green space needs to be increased dramatically.

<Table 3> Changes in Land Use Pattern

		Industry land (%)	Housing land (%)	Green space (%)
Current land use pattern		8.4	49.9	41.7
50 ppb	Increasing green space	15.5	29.1	51.4
	Increasing green space and emission reduction	18.8	35.5	41.8
40 ppb	Increasing green space	10.1	18.5	67.6
	Increasing green space and emission reduction	12.6	23.3	60.7
30 ppb	Increasing green space	4.5	7.1	84.9
	Increasing green space and emission reduction	5.8	9.9	80.8

Fourth, green belt area surrounding Seoul Metropolitan need to be preserved. The government is now planning to deregulate greenbelt area which has been preserved since 1971 to keep pledge made during the presidential election campaign. However, it is contradictory to deregulate greenbelt area and reducing green space when the importance of green space is gaining its weight more than ever not only for quality of life but also for a city's sustainability.

Finally, as noted earlier, since the model used in this paper has some limitations, results from the simulation may not readily applied to detailed policy guideline. This may be the limiation of this study and remaining task for further study. However, limitations of this study may be easily overcomed by incorporating more pollutants and by conducting wide range of sensitivity analysis which was not done in this study.

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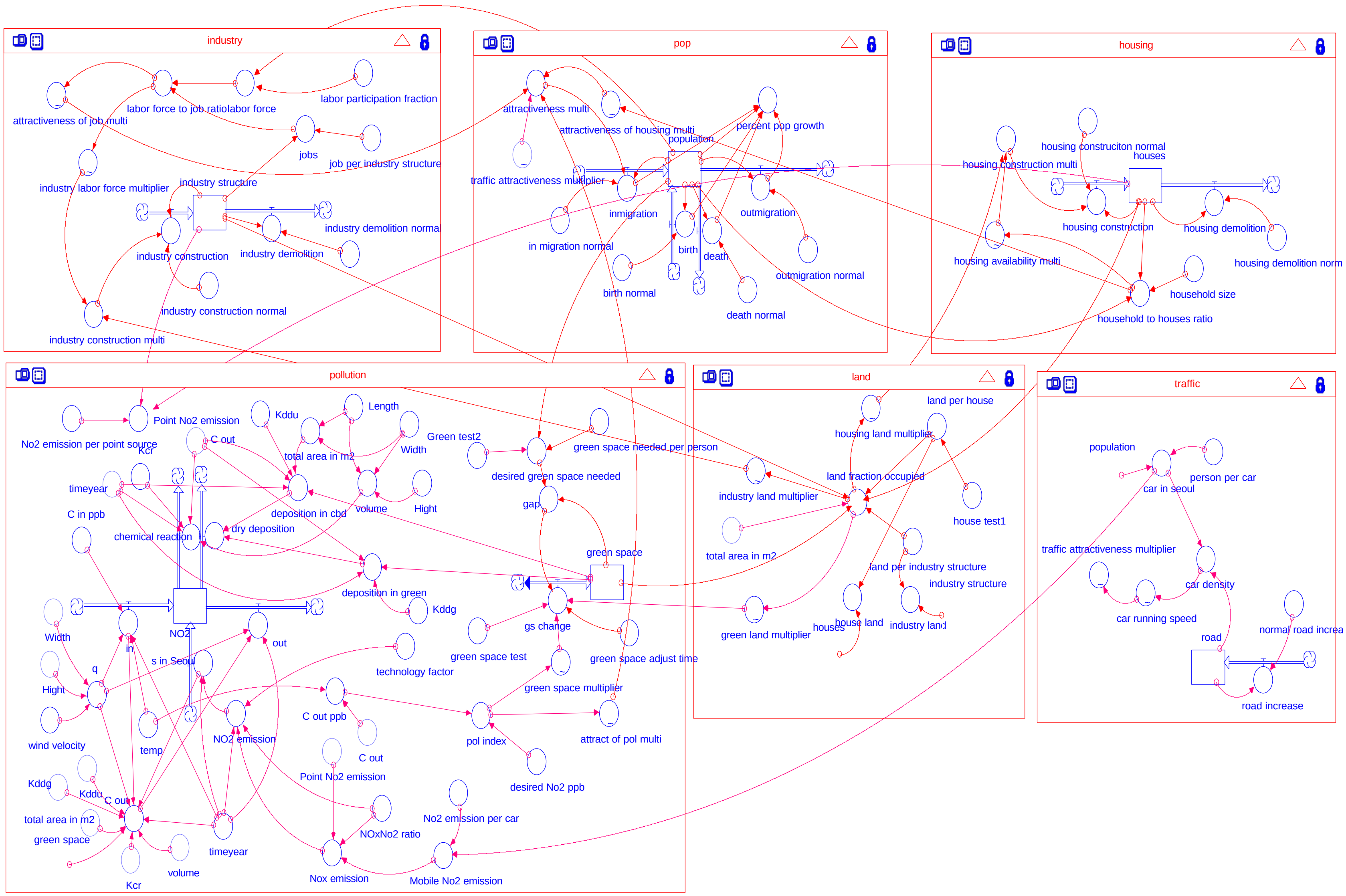
Seoul's Environmental Carrying Capacity Model ECC4-211 with box mode



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