Measures to Reduce SOx Emissions in a Coal-Dependent Area†

—A Case Study of Shenyang, Liaoning Province, China—

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1. Introduction

Developing countries that depend primarily on coal as an energy source are plagued with SOx emissions associated with the sulfur in coal. China has achieved rapid economic growth in recent years, and energy consumption (primarily coal) is increasing as a result. However, in many developing countries, desulfurization technology has not yet been introduced, even though significant SOx emissions are discharged through coal consumption. This not only causes acid rain, which is a border-transgression problem, but has resulted in damage to the health of the communities that consume the coal.

The purpose of this research is to present a road map to show how developing countries that use coal as their main energy source could implement measures to reduce SOx emissions, while still pursuing future economic growth. Moreover, this research has focused particularly on the local environment, and we address the case of Shenyang, Liaoning province, located in the northeast part of China, which consumes a significant amount of coal.

Such environmental problems encompass various fields, including engineering, hydrodynamics, medical science, politics, and economics, and often require an interdisciplinary research approach to reach a solution. Accordingly, in this research we have integrated four models. One is the multisectoral economic model, which can accommodate engineering information. The second is the air diffusion model, which distributes the amount of SOx emissions drawn from the economic model to local grids. The third is the patient-generating model, which calculates the proportion of the population that will show symptoms of respiratory disease from the SOx emissions concentration in each grid.

A number of measures may be used to counter SOx emissions. These include desulfurization technology, fuel conversion, and so on. The Chinese government, for example, currently promotes policies for gasification. However, to use the abundant coal resources in China effectively, we adopt a desulfurization technology, where we assume flue gas desulfurization (FGD) equipment is used for large-scale boilers, and bio-coal briquettes are the alternative to coal for households. Bio-coal briquettes are made from coal powder, lime, and biomass compressed under high pressure, and

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regarded as a fuel that produces a low quantity of SOx emissions in comparison with regular coal.

Our research shows, first, how SOx generated by coal use could spread, and could damage the health of local residents. Next, we assume a scenario in which desulfurization technology is introduced and then determine the amount by which SOx emissions would decrease, how many people would be spared health damage, and how the introduction of desulfurization technology would influence the economy of Liaoning province. Based on the results of the simulation, we propose measures against SOx emissions in coal-dependent areas.

2. The Model

2.1. Economic Model

The basic model framework is the same as that in Nakajima, Asakura, and Nakano (2002) in which a more detailed description is provided. In this paper we briefly outline the model's characteristics. (Please see Figure 1. We have printed the equation system and the economic/environmental variables as Chart 1-3).

The economic model is a short-run Keynesian model in which management policies on the demand side operate effectively. In other words, this model differs from the neoclassical model in that it focuses on allocation of production mediated by reserved factors. However, we assume that supply does not always increase ad infinitum with an increase of demand, and that the supply function equals the short-run marginal cost. For raw materials, the price of goods rises to equilibrium if demand increases. Because there is still an unlimited labor supply in China, we treat labor as different from raw materials. Initially, agricultural sector labor is defined as the remainder when the labor is absorbed by nonagricultural sectors from the labor force population. The agricultural sector wages are determined by dividing the distribution to labor of the income of the agricultural sector by the number of laborers. Furthermore, we assume that the nonagricultural sector wage is equal to the wage of the agricultural sector multiplied by a high fixed rate. It is assumed that if the demand for labor increases in the nonagricultural sector, the sector can always absorb more labor from the agricultural sector. These assumptions are considered most proper if the labor market has unlimited supply and the potential labor supplier works for the minimum wage in nonagricultural sectors. This particular labor market is the first characteristic of the model.

The second characteristic of the model is that we calculate the CO_2 and SOx emissions by sector in Liaoning province, China. The "1997 Liaoning Input-Output Table" is the primary source. The input-output table shows the industrial structure and the technological structure of each industry. The theoretical values of the CO_2 and SOx emissions by sector can be calculated by utilizing the input-output table, the energy statistics, and the Chinese environmental input-output table.

The third characteristic is that the economic model makes environmental simulation possible. For example, installation of new technology for environmental protection requires new investment and it increases the investment item of final demand. On the other hand, the input coefficients of energy fall, and the short-run marginal cost decreases, and it may decrease the product price. Furthermore, if all of the new investment is provided by a domestic fund, interest rates rise and it suppresses crowding out. Because all influences are processed in the model, a cost-benefit analysis for installation of new technology is possible. The basic form of the model is shown in Figure 1. We can use this technical information to draw focused conclusions by varying the inputs.

2.2. Soil Reclamation Model

The soil reclamation model calculated the quantity of the desulfurization gypsum and ashes from bio-coal briquette consumption and the increase of food production from the reclamation of soil utilizing the desulfurization gypsum and the ashes of bio-coal briquettes.[4] Yang et al. (2001) report the results of a soil reclamation experiment in Shenyang, Liaoning, and show the change in corn production varying according to the quantity of the desulfurization gypsum or the ashes of bio-coal briquettes applied. We use their conclusion that 11.6 ton/ha of the desulfurization gypsum and the bio-coal briquette ashes produced 3.123 ton/ha and 2.696 ton/ha of corn, respectively, in Yang et al. (2001) and calculate the corn production from the area of alkali soil reclaimed by the gypsum and the ashes.[5] We multiply the increase in corn production by the unit price of corn in 1997 and add it the production of the agricultural sector in the economic model.[6]

2.3. Air Diffusion Model

2.3.1. The Outline of Stationary Smoke Source Data and the Linkage with the Economic Model

When we analyze the effect of SOx on the local area, we need to set grids for several hundred square meters (or several square kilometers) and simulate air diffusion. This is because the distance from the smoke sources determines the differences in SOx concentration. The total field analyzed is 20 km from east to west and 14 km from north to south with a central focus on the City Hall of Shenyang, Liaoning. Using Editorial Board of China City Map (1994) and Editorial Board of China National Map (1995) as a map of Shenyang City, we set grids and specify districts and the location of factories. Figure 2 shows the grids set in our model and the location of the factories.

As a part of the “Research for the Future Program” under the Japan Society for the Promotion of Science, we interviewed approximately 50 factories that had large-scale boilers in Shenyang and obtained information about the industrial sector, coal consumption, sulfur content of fuel, the height of the smoke stack, SOx emissions per hour, location, and so on in 1994. However, several factories

4 We assume that the ashes are equal to 15% of the bio-coal briquette by weight.

5 The data on bio-coal briquettes in this research are based on Chengdu Research Group for Bio-Coal Briquettes (2000). Therefore the properties of soil in Chengdu Research Group for Bio-Coal Briquettes (2000) are different from those in Yang et al. (2001). We also do not consider any regional differences in pH and the alkalinity of the soil.

6 According to 'China Price over 50 Years (1949–1998)' (Cheng, 1998), the price of middle-class corn was 2.24 yuan/kg in 1997.

have missing data and we cannot then derive full information on SOx emissions from these factories. We use the mean in Liaoning to replace this missing data. We also can specify the districts where each factory is located, but not accurately specify the location of one-third of the factories. Additionally, we distribute average smoke sources over the grid where more than one factory in the district is located. We also establish SOx emissions and coal consumption of factories that have smaller boilers by district, and allocate household coal consumption to each district according to population and assume that the SOx is discharged from low-rise outlets. Based on this smoke data, we fix the coal consumption share of each factory in 1994 and link the economic model and the air diffusion model.

2.3.2. Air Diffusion Model

The air diffusion model estimates SOx concentration on the ground (average annual atmospheric SOx concentration) by each grid of 1 square km, using SOx emissions from the smoke sources. Figure 2 shows the distribution of smoke sources in the central part of Shenyang. We divide this area into grids of 1 square km and allocate SOx emissions to each grid. For each calculation, we assume that the smoke sources in the grids lie centrally, and the emissions from the smoke sources are generated steadily (there is no fluctuation over time). To calculate the annual average SOx concentration, we carry out a diffusion computation by climate condition and weight it by the frequency of each climate district annually. The climate districts are as follows:

- Wind direction: Eight directions
- Equation term: One day (we do not divide terms for less than one day)
- Atmospheric stability: C (weak instability)
- Wind velocity: Annual average of daily average velocity (m/s) in each direction

We aggregate daily average velocity by wind direction using the report of the World Meteorological Organization and calculate the annual average. The plume model, which is one of the most widely used models for air diffusion in the presence of wind, estimates the diffusion concentration from the smoke sources. In this case, the average concentration of the smoke source grid is represented by the concentration at the point where half of the grid width (500 m) lies downwind. Finally, we carry out the diffusion computation by smoke source and wind direction, and aggregate the concentration by grid.

The SOx concentration on the ground C (g/m^3) at the point (X, Y) is expressed in the next equation. (X, Y) indicates a point that lies X (m) downwind of the smoke source and is Y (m) from the central axis of the smoke plume.

$$C = \frac{Q}{\pi \sigma_y \sigma_{zu}} \exp\left(-\frac{Y^2}{2\sigma_y^2}\right) \exp\left(-\frac{He^2}{2\sigma_z^2}\right)$$

where Q is SOx emission (g/s) from the smoke source, σ_y is the wind-spreading width (m) of the vertical direction downwind, σ_z is the spreading width (m) of the vertical direction, He is the effective height (m) of the smoke stack, and σ_y is:

$$\sigma_y = \sigma_{yp} + X \tan(\omega)$$

where σ_{yp} is Pasquill's spreading width, which differs according to atmospheric stability and downwind distance. Given atmospheric stability C, we can approximate the spreading width by:

$\sigma_{yp} = 0.1772 X^{0.924}$ (Smoke source grid (X < 1 km))

$\sigma_{yp} = 0.232 X^{0.885}$ (Receptor grid (X > 1 km))

We assume that wind direction and velocity maintain the same condition during the equation term, but wind direction is actually changing and the actual spreading width is wider than σ_{yp}. Thus, we correct σ_{yp} by adding the spreading width to the standard deviation ω of the fluctuation in wind direction. The fluctuation during one day, which is calculated as the fluctuation of wind direction over four hours in Shenyang, is approximately 30° in any one season. Therefore, we use ω = 30°.

σ_z is the spreading width (m) of height direction (Z direction) and we can use Pasquill's spreading width (m).

$$\sigma_z = 0.1068 X^{0.918}$$

The next equation converts from mass concentration (g/m^3) to volume concentration (ppb):

$$C(\text{ppb}) = C(\text{g/m}^3) \times (22.4 / \text{molecular weight}) \times (273 + T) / 273 \times 106$$

where the molecular weight of SO_2 is 64 and the annual average air temperature in Shenyang (T) is 10 °C. In the air diffusion model, we calculate each smoke source and each wind direction above and estimate the annual average concentration (A) of each grid weighted by the frequency of each wind direction. We obtain the annual average concentration of each grid adding (A) to the smoke source.

2.4. Patient Generating Model

We calculate the generating number of patients by using SOx concentration and estimate the number of patients by grade at the end of each term. The number of patients by grade of environmental pollution damage under compensation law[7] generates demand for medical services. Additionally, patients exit the labor market and the total labor supply decreases. The increase in demand for medical service and the decrease in total labor supply feedback into the economic model.

2.4.1. The Estimation of Generating the Number of Patients by Grade

We use parameters, which indicate the relationship between SOx concentration and generation of patients by grade in order to estimate the generating number of patients by grade. Kito et al. (1998) estimated these parameters using two databases. One of these databases organizes the movement of officially certified patients in Yokkaichi city, Japan, by linking the patient recognition system by the Yokkaichi city government, the patient recognition system under the "Special Measures Law for Pollution-Related Health Damage Compensation", and the patient recognition system under the "Japanese Pollution-Related Health Damage Compensation Law". The second is the distribution of SOx concentration in Yokkaichi estimated by the simulation of SOx diffusion using data on smoke sources in 1975 (fiscal year) and data for the wind direction and velocity in 1971 (fiscal year). We use these databases and calculate parameters (a_i, b_i), which indicate the relationship between SOx concentration in each grid and the generation of patients by grade, consistent with the movement of officially certified patients in Yokkaichi.

The number of generating patients by grade (i) in each grid in term (t) is calculated as follows:

$$N_i^t = \max\{[a_i \times SO^t - b_i] \times P_m^t, 0\} \quad (*)$$

where

SO: SOx concentration (ppb)

P_m: Population of grid except patients.

2.4.2. The Estimation of the Cumulative Number of Patients by Grade at Term End

To calculate the number of patients at the term end, we need the number of revocation, the death toll, and the number changing grade by grade. However, there is no data by grade. Thus, Kito (1998) estimates the data by grade given some assumptions and our research is based on Kito (1998).

Firstly, our assumption about the numbers of death and revocation, which is the number of

7 We use the information in "Japanese Pollution-Related Health Damage Compensation Law" and so on.

withdrawals from the system, is as follows. Because of limited data availability of the death toll by grade, we apply the same rate of death for all grades and estimate the death toll in term (t), by multiplying the number of patients at the term end (t-1) by the death rate. We gather from circumstantial evidence on revocation by recovery that a portion of patients recovers a couple of years after certification and the remainder develops chronic disease. Thus, we assume that patients that are certified as the third grade, i.e. those with the mildest symptoms of all grades, are revoked at the same annual rate of revocation for four years and the rest become chronic and remain as certified patients until they die.

Next, our assumption about the change of patients' symptoms, namely the movement between grades, is as follows. The movements of the number of generating patients and the cumulative number of patients by grade at the term end after 1974 shows the existence of grade movement toward recovery. By contrast, there also exist patients whose symptoms deteriorate and whose grade increases. We assume that the grades change to contiguous grades and calculate the number of the movement by multiplying the number of patients by grade at the previous term end by the movement rate between grades. We estimate these parameters by making the theoretical value of the movement ratio consistent with the observed value, using the condition that the shares by grade of generating patients change with a rapid decrease in SOx concentration.

These procedures are summarized as follows:

$$
\begin{aligned}
S_0^t &= S_0^{t-1} + N_0^t - DS_0^{t-1} - R_{01}S_0^{t-1} + W_{10}S_0^{t-1} \\
S_1^t &= S_1^{t-1} + N_1^t - DS_1^{t-1} - R_{12}S_1^{t-1} + W_{21}S_2^{t-1} - W_{10}S_1^{t-1} + R_{01}S_0^{t-1} \\
S_2^t &= S_2^{t-1} + N_2^t - DS_2^{t-1} - R_{23}S_2^{t-1} + W_{32}S_3^{t-1} - W_{21}S_2^{t-1} + R_{12}S_1^{t-1} \\
S_3^t &= S_3^{t-1} + N_3^t - DS_3^{t-1} - W_{32}S_3^{t-1} + R_{23}S_2^{t-1} - \sum_{i=1}^{4}(1 - R_{out})^{i-1} R_{out} N_3^{t-i}
\end{aligned}
$$

Figure 3 explains these equations and variables. We add the cumulative number of patients by grade at the previous term end (t-1) and the numbers of patients by grade in term (t), subtract the death toll, and add or subtract the movement between grades by the deterioration and recovery of symptoms. Consequently, we can estimate the number of patients by grade at the term end (t). However, we assume the revocation by recovery is limited to recovery from the third grade.

Additionally, the population of the grid except patients in Equation (*) is expressed as:

$$P_m^t = P^t - S_0^t - S_1^t - S_2^t - S_3^t$$

where

P: Population of the grid

S_0: Number of Patients (Special grade)
S_1: Number of Patients (First grade)
S_2: Number of Patients (Second grade)
S_3: Number of Patients (Third grade).

3. The Economic and Environmental Statistics and the Reservation of the Model

We use Chinese statistics, such as the “1997 Liaoning Input-Output Table”, to construct the database for inputs in the economic model. Various parameters of the consumption and investment functions are estimated, but the parameter of the consumption demand function utilizes the value in Kuroda (1989); other parameters are decided by calibration to the input-output table and the statistical yearbook. Because this model is static and not a completely closed model, we assume that money supply, the nominal interest rate, the price of agricultural goods, the import price of goods, the exchange rate, the capital stock, government expenditure, and exports are all exogenous.

4. The Environmental Simulation

4.1. The Introduction of Bio-coal Briquettes

As a part of the “Research for the Future Program” under the Japan Society for the Promotion of Science, we have installed experimental bio-coal briquette production machines, which are simple desulfurization technologies, into Chengdu, Sichuan province, and Shenyang, Liaoning province, in China. Bio-coal briquettes are oval briquettes that can be substituted for coal. The Chengdu Research Group for Bio-coal Briquettes (2000) demonstrated that the bio-coal briquette is produced by mixing coal, biomass, and desulfurizer (powdered limestone) under high pressure of 3-5t /cm^2 and measured raw material composition provided by the experiment. Accordingly, in this simulation, we utilize this technical information and calculate the CO_2 and SOx reduction effect for bio-coal briquettes substituted for coal.

We reduce the input coefficient of coal to correspond to the material composition of the most popular type of bio-coal briquettes as shown in Figure 4. We then increase the input coefficients of agriculture, coal, electric power, and the cement product industry. The method is as follows.

According to Chengdu Research Group for Bio-coal Briquettes (2000), the raw material composition of the most popular type of bio-coal briquettes in Chengdu is shown in Table 1. If we ignore calorific value and combustion efficiency and suppose that 1 ton of coal is replaced by 1 ton of bio-coal briquette, then, as 1 ton of bio-coal briquette contains 664 kg of coal, we can consider the coal input factor to be 0.664.

$$a_{bcoal,j} = 0.664 a_{coal,j}$$

where

$a_{bcoal,j}$: Coal input coefficient for bio-coal briquettes production by the j-th sector

$a_{coal,j}$: Original coal input coefficient of the j-th sector.

For other raw materials, we factor in the material cost necessary for 1 ton of bio-coal briquette, multiply $a_{bcoal,j}$ by the ratio of other raw materials cost to coal cost, and add the result to the original input coefficient of each raw material. In other words, we calculate the additional input value of these raw materials by using the ratio multiplied by the value of coal input. In the case of powdered limestone, for example, UC^{other} equals 25.50 and we change the cement product input coefficients of the sectors consuming bio-coal briquettes. Also, we classify sawdust and straw as agricultural sector materials.

$$a_{i,j}^{bother} = a_{i,j}^{other} + \frac{UC_i^{other}}{UC^{coal}} a_{bcoal,j}$$

where

$a_{i,j}^{bother}$: The i-th raw material input coefficient, which is spent for bio-coal briquettes production by the j-th sector (except coal)

$a_{i,j}^{other}$: The i-th raw material original input coefficient of the j-th sector (except coal)

UC^{coal} : The cost of coal necessary for 1 ton of bio-coal briquettes (= 63.08)

UC_i^{other} : The i-th raw material cost necessary for 1 ton of bio-coal briquettes (except coal).

We also consider the difference in calorific value and combustion efficiency between bio-coal briquettes and coal, and multiply $a_{bcoal,j}$ and $a_{i,j}^{bother}$ by the ratio of the calorific values and combustion efficiency between the bio-coal briquette and coal.

$$a_{nbcoal,j} = \frac{Heat_{coal}}{Heat_{bio}} \frac{Ef_{coal}}{Ef_{bio}} a_{bcoal,j}$$

$$a_{i,j}^{nbother} = \frac{Heat_{coal}}{Heat_{bio}} \frac{Ef_{coal}}{Ef_{bio}} a_{i,j}^{bother}$$

where

$a_{nbcoal,j}$: The j-th sector's coal input coefficient for bio-coal briquettes production, which accounts for calorific value and combustion efficiency

$a_{i,j}^{nbother}$: The j-th sector's i-th raw material input coefficient for bio-coal briquettes production including calorific value and combustion efficiency (except coal)

$Heat_{coal}$: Calorific value of coal (= 20,188 kJ/kg)

$Heat_{bio}$: Calorific value of bio-coal briquettes (= 16,207 kJ/kg)

$\frac{Ef_{coal}}{Ef_{bio}}$: Ratio of combustion efficiency of coal to bio-coal briquettes (= 1.0/1.29).

There is, however, a technical constraint in that the calorific value of bio-coal briquettes cannot be applied in industries with large-sized boilers (e.g. the iron/steel and electric power sectors). We then additionally assume that the coal-mining sector and the coal product sector that produce bio-coal briquettes do not consume them, but that all other industries and households do. We decrease CO_2 emission coefficients to correspond to the decrease in coal input, and the desulfurization rate is 67% following the Chengdu Research Group (2000).

In this simulation, we include the capital cost of the bio-coal briquette machine. In other words, we assume that the environmental protection technology is produced in China as opposed to foreign production and installation.

We determine the optimum size and number of machines for bio-coal briquette demand by using the cost function of the economic model (Equation (**)).

Nakano, Nakajima, and Yoshioka (2005) estimated the cost function of this bio-coal briquette machine using Japanese data. We calculate the total cost of machines according to the size and number, and add this to the final demand investment of the machinery-manufacturing sector. In addition, the cost of bio-coal briquette machines increases the price of goods in the installed sector, and we add the cost of machines over durable years and domestic production to the price equation.[8]

$$C(q,n) = aq^b + n^\alpha \exp(c + d\ln q + \frac{e}{2}\ln q^2) \quad (**)$$

a=0.26, b=0.71, c=−1.62, d=0.34, e=0.25, α =0.6

where

C (q,n): Production cost of bio-coal briquette machines

q: Production capacity of bio-coal briquette machine (t/hour)

n: Number of bio-coal briquette machines.

4.2. The Introduction of the Flue Gas Desulfurization (FGD) Equipment

The desulfurization process of the wet lime-gypsum method is as follows. Waste gas containing SOx enters the reactor through the GGH (Gas-Gas-Heater). The gas reacts with water and alkali materials (limestone), which are absorbers, and is absorbed, oxidized, and neutralized. Accordingly, the gas is

8 We assume that the durable life of these machines is 10 years.

divided into desulfurized gas and gypsum containing water. The desulfurized gas next passes through a dust remover in the mist eliminator, is cooled in the GGH, and discharged from the smoke stack, while the gypsum with water is divided and discharged as wastewater. However, the wet lime-gypsum method is the desulfurization technology for a large-scale boiler.[9]

We assume that the wet lime-gypsum method treats one million Nm^3/h of waste gas with a desulfurization rate of 95% and where inlet SOx concentration of flue gas is 1000 ppm. Additionally, we interviewed Japanese makers of desulfurization plants and collected the technical information containing costs of the FGD equipment. The desulfurization cost consists of the gas system (GGH, fan, reactor, mist eliminator, duct, damper, and the piping system), the liquid system (the material system, the gypsum system, wastewater treatment, and the piping system) and the control system.

We adopt the water film process developed by Professor Xu Xuchang (Tsinghua University, China) as the technology for a small- or medium-scale boiler. This technology is the simplified wet method and treats 23.4 thousand Nm^3/h of waste gas with a desulfurization rate of 70 % and where inlet SOx concentration of flue gas is 1120 ppm. Accordingly, in this simulation, we utilize this technical information and calculate the SOx reduction effect of FGD equipment.

To determine the installed number of FGD equipment, we assume the scale distribution of coal-fired power plants in Liaoning is the same as that in China as a whole. Table 2 shows the scale distribution of coal-fired power plants in China. We assume that the plant operating rates are 70%.

$$n^d = \frac{T_p r_l}{(365 \times 24) r_o}$$

where

n^d : Number of pieces of FGD equipment by scale

T_p : Total power generation in Liaoning (MWh)

r_l : Share of coal-fired power plants by scale

r_o : Operating rate.

We increase the input coefficients of electric power, water supply, and the cement product industry to correspond to the running cost of the FGD equipment as shown in Figure 5.

$$a_{i,npower} = a_{i,power} + \frac{n^d rc_i}{x_{power}}$$

where

$a_{i,npower}$: The i-th material input coefficient, which is spent for desulfurization by the electric power

9 We define a large-scale boiler as exceeding 25 MW capacity.

sector

$a_{i,power}$: The i-th material original input coefficient of the electric power sector

rc_i : Running cost of the i-th material

x_{power} : Total domestic production of electric power.

In this simulation, we include the capital cost of the FGD equipment. In other words, we assume that the environmental protection technology is produced in China, as opposed to foreign production and installation. The production cost of the FGD is determined by the number installed, gas capacity, and inlet concentration and desulfurization rates. The parameter α_k^d depends on the gas capacity; the inlet concentration and the desulfurization rates are obtained from interviews conducted with the plant makers.

$$C^d = \sum \alpha_k^d (q_g, c_e, r^d) C_k^p n^d$$

where

C^d : Production cost of FGD equipment

α_k^d : Parameter

q_g : Gas capacity

c_e : Inlet concentration

r^d : Desulfurization rate

C_k^p : The cost of the k-th part for FGD equipment production.

We calculate the total cost of FGD equipment according to size and number, and add this to the final demand investment of the j-th sector. We can classify the k-th parts into the j-th sector. In addition, the cost of FGD equipment increases the price of service in the electric power sector, and we add the cost of equipment over the number of durable years and domestic production to the price equation.[10]

$$C^d = \sum C_j^d$$
$$IN_j = I_j + C_j^d$$

where

I_j : Original fixed capital formation in the j-th sector

C_j^d : The cost of the j-th material for FGD equipment production

IN_j : Fixed capital formation including FGD equipment cost in the j-th sector.

10 We assume that the durable years of the equipment are 20 years.

$$p_{power} = \sum_i p_{oi} a_{i,power} + \frac{\partial L_{power}}{\partial x_{power}} w_{power} + \frac{C_d}{x_{power} dur_d}$$

where

p_{power} : Domestic price of service in the electric power sector

dur_d : Durable years.

4.3. The Scenario for the Introduction of the Desulfurization Technology

・Simulation [1]: Economic and environmental effect by introduction of the desulfurization technology

We prepare one scenario for the introduction of the desulfurization technology as follows.

1) Introducing the FGD equipment for all boilers of the electric power sector and the bio-coal briquettes for household

・Simulation [2]: Time series simulation of changing SOx concentration and symptoms of patients by introduction of the desulfurization technology

We prepare five scenarios for the introduction of the desulfurization technology as follows.

1) Base case (without introducing the desulfurization technology)

2) Introducing bio-coal briquettes for households after 10 years

3) Introducing FGD equipment for large-scale boilers after 10 years

4) Introducing FGD equipment for all boilers and bio-coal briquettes for household after 10 years

5) Introducing FGD equipment for all boilers and the bio-coal briquettes for household after 13 years

5. Results

5.1. Simulation [1]

When we examine the SOx emissions structure by sector (Figure 6), the highest emitting sector is the electricity production and supply sector with 412 thousand tons (SO_2 conversion), second is the iron and steel industry with 254 thousand tons, third is the cement and cement product industry with 71 thousand tons, and the fourth is the real estate industry with 70 thousand tons. In particular we note SOx emissions from the electricity production and supply sector are approximately 30% of the total. In addition, SOx emissions from all industries are 1.47 million tons (Table 3), and these exceed the China Environment Yearbook value (1998).[11] The SOx from coal is over 80% of the total and greatly exceeds SOx emissions from all other fuel sources.

Let us now look at CO_2. Figure 7 shows CO_2 emissions by sector. The electricity production and

11 According to the China Environment Yearbook (1998), SOx emissions from Liaoning in 1997 were 0.84 million tons and the removed SOx was 0.61 million tons. Thus, SOx generation is 1.45 million tons: almost the same as our estimates.

supply sector is the highest emitting sector (72.9 million tons (CO_2 conversion)) for both SOx and CO_2. The second is the iron and steel industry with 51.4 million tons, third is the cement and cements product industry with 12.5 million tons, and the fourth is the real estate industry with 12.3 million tons. Furthermore, CO_2 emissions from coal are the highest and account for approximately 80% of the total.

The change rate of CO_2 and SOx due to utilizing bio-coal briquettes and FGD equipment is 1.7% and –23.7%, respectively. Table 4 shows that the price of goods rises due to changes in the sectoral input coefficients and the sectoral marginal cost. This has an inflationary effect. Real investment for the bio-coal briquette machines and FGD equipment increases by 11.0%, while real consumption decreases by –0.5% due to inflation. As a result, real GDP rises by 2.8%.

Because SOx directly influences the health of residents, let us now examine the change of SOx concentration (Figures 8 and 9). We can confirm that SOx concentration of each grid decreases due to the introduction of bio-coal briquettes and FGD equipment. If the bio-coal briquettes and FGD equipment are not introduced, the generated number of special, first, second, and third grade patients is 1.45 hundred, 1.47 thousand, 1.62 thousand, and 1.64 thousand, respectively. By way of contrast, if the desulfurization technology is introduced, the number of special, first, second, and third grade patients generated is 1.08 hundred, 1.15 thousand, 1.33 thousand, and 1.37 thousand, respectively. The ashes of bio-coal briquettes and the desulfurization gypsum reclaim 1.3 million ha of alkali soil and 3.1 million tons of corn can be harvested from the area afresh (Table 5). This quantity of corn is approximately 2.9% of total corn production in the whole of China and approximately 45.6% of corn production in Liaoning.[12]

5.2. Simulation [2]

We will see the result of the simulation [2] as reported in Figures 10–15. As shown, the SOx concentration in scenario 2 is slightly lower when compared to scenario 1 (base). The share of SOx emissions from households is relatively low in Liaoning. Therefore, measures against SOx emissions in households hardly contribute to the lowering of SOx concentration. When the FGD equipment for large-scale boilers is introduced (scenario 3), they have a profound effect on lowering the SOx concentration. However, this measure is not enough. Furthermore, if measures for all boilers and households are taken (scenario 4), SOx concentration of each grid becomes approximately 40 ppb (0.04 ppm), which is the environmental standard level in Japan.

Unless the desulfurization technology is introduced, the increase in patients is accelerated due to the rising event probability of patients by rising SOx concentration and the increase of population (Figure 11). Measures against SOx emissions in households have little effect on the decrease of

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12 According to the China Statistical Yearbook (1998), corn production in China and Liaoning in 1997 was 104.3 million tons and 6.7 million tons, respectively.

generated patients (Figure 12). The reasoning is discussed earlier. In the case of introducing the FGD equipment for large-scale boilers, we can observe that the generation of patients is suppressed to some extent, but the number of chronic patients increases cumulatively (Figure 13). When measures for all boilers and households are taken, the generation of patients is substantially suppressed and the total number of patients tends to decrease (Figure 14). If these measures are taken three years later, the generation of patients is sufficiently suppressed, but the total number of patients is similar when compared to scenario 4 (Figure 15).

6. Concluding Remarks

In this paper we outline the basic structure of the economic and environmental models with the soil reclamation, air diffusion, and patient generating models, and show the environmental and economic effects of installing bio-coal briquettes and FGD equipment. We will now summarize the environmental information provided from the model.

We measure the economic and environmental effects as a result of installing the popular-type bio-coal briquette machines and FGD equipment in Liaoning and substituting briquettes for coal in households, and the effect on increased food production by using the briquette ash and the desulfurization gypsum to reclaim saline-alkali soil.

We find that the negative effect on the economy is relatively slight when compared with the large reduction in SOx emissions and respiratory patients. Given the vast Chinese population, the effect of increased food production due to soil improvement is also slight, but as the effect is cumulative it is a promising preventative measure against predicted food shortages.

We next simulate the change in SOx concentration on patient symptoms through introduction of the desulfurization technology. To suppress the generation of patients substantially, and to decrease the total number of patients, it is desirable to introduce the desulfurization technology for all boilers and households. However, if measures against SOx emissions are taken later, the reduction effect of respiratory patients lowers. In the future, we should collect more detailed information on the Chinese economy and environmental conservation technologies, e.g. desulphurization, and elaborate on the economic and environmental models of Liaoning. These may provide our next research project.

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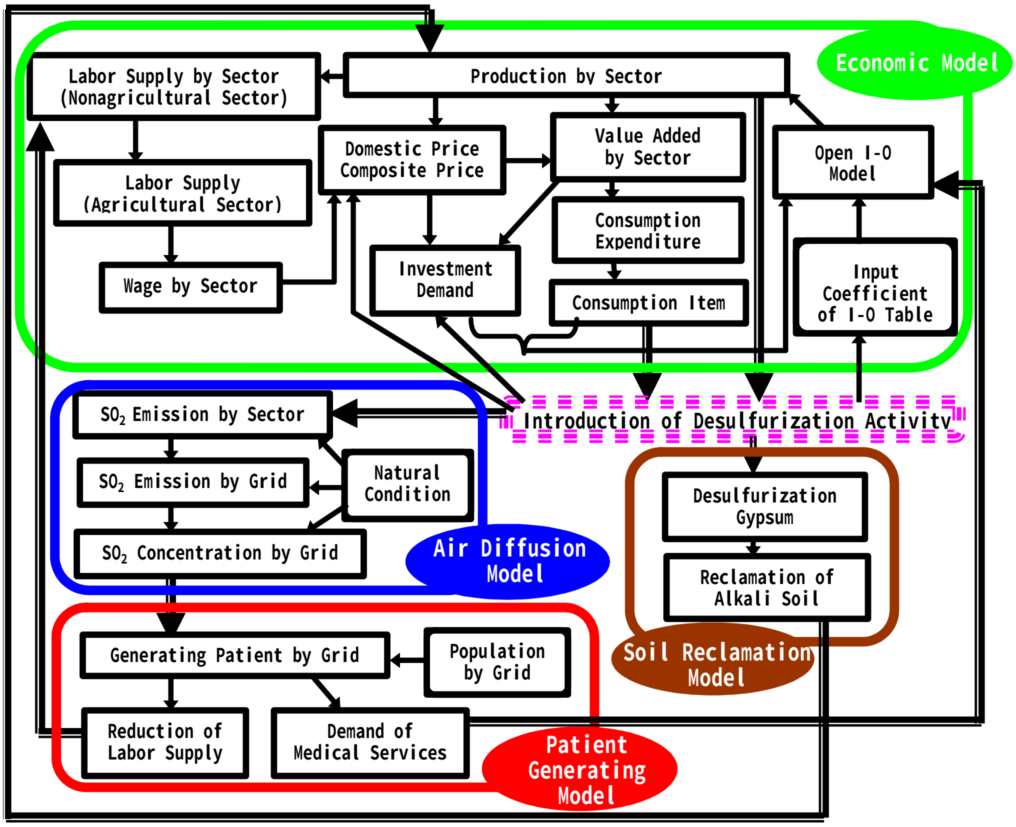


Figure 1: Framework of the Model

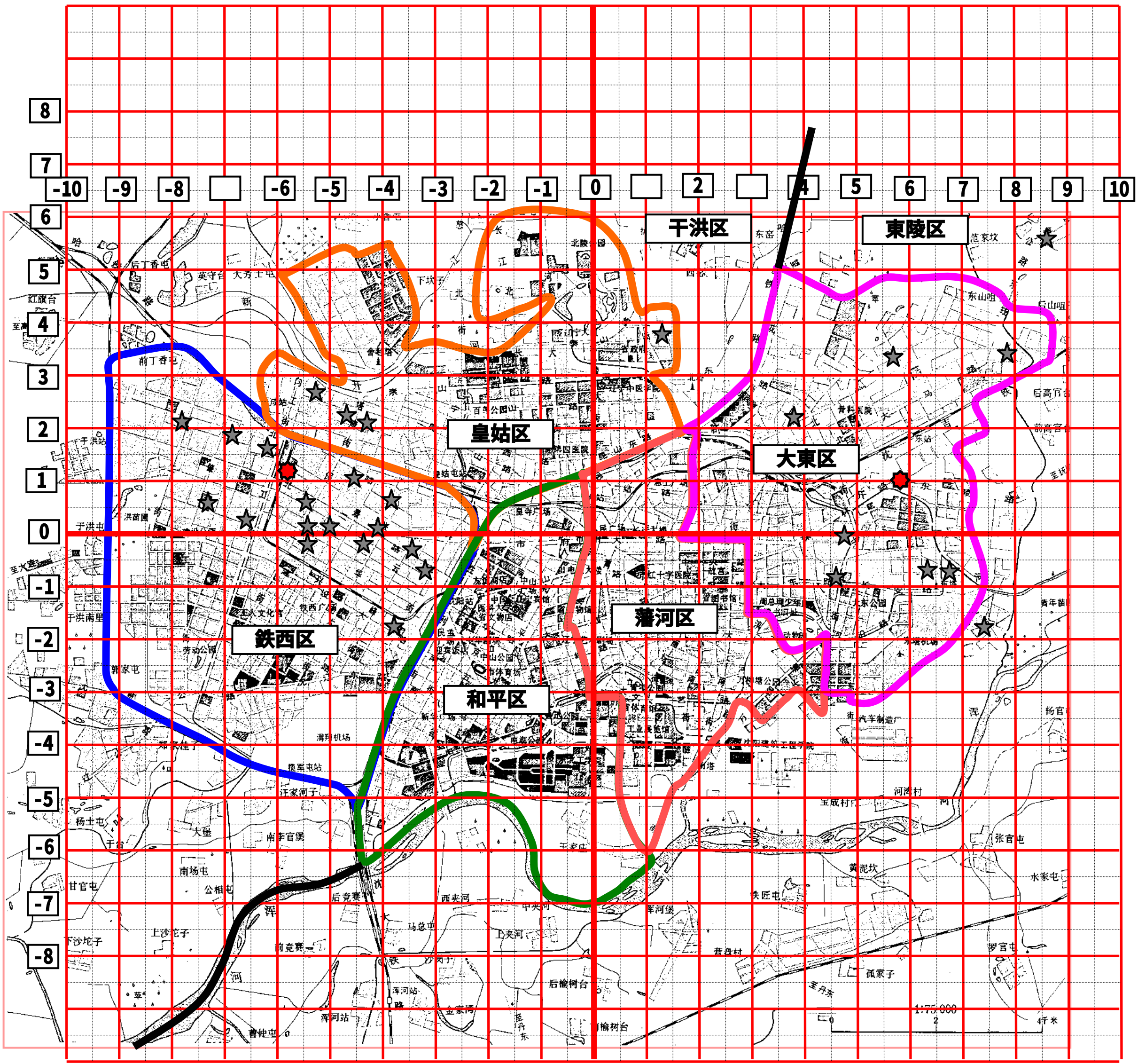


Figure 2: Research Area and Smoke Sources in Shenyang

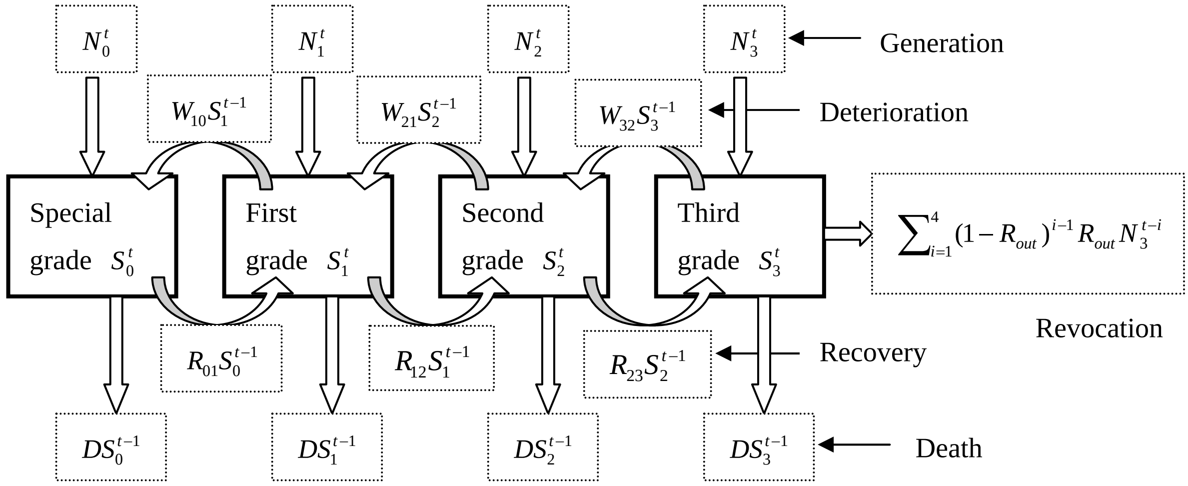


Figure 3: Change of Symptoms

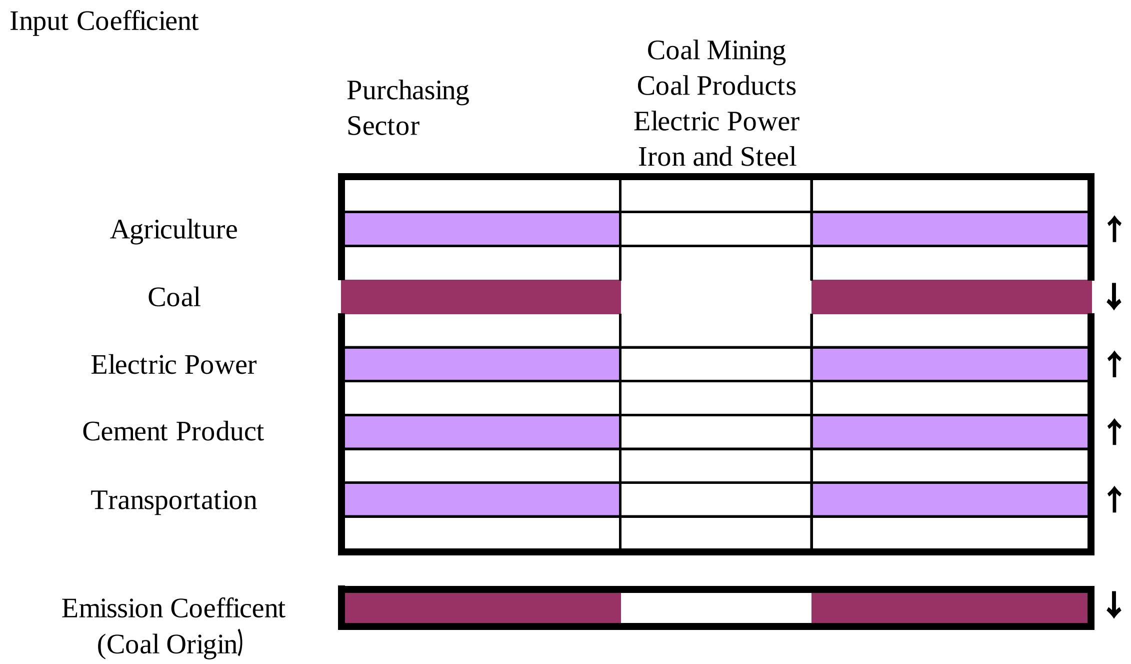


Figure 4: Change of Input Coefficients due to Bio-coal Briquette Installation

Table 1: Raw Material Composition per 1 ton of
Popular Type Bio-coal Briquette in Chengdu*

Raw Material	Unit	Quantity	Unit Price (Yuan/Unit)	Inputs (Yuan)
Coking Coal	kg	664	0.095	63.08
Powdered Limestone	kg	170	0.15	25.50
Sawdust	kg	124.5	0.15	18.68
Straw	kg	41.5	0.05	2.08
Electricity	kWh	30.0	0.57	17.10
Transportation				10.00

*Source: Chengdu Research Group for Bio-coal Briquettes (2000).
Maintenance costs and wages are not included.

Table 2: Share of Power Plants by Scale in China (1996)

Capacity (MW)	Share (%)
Above 300	25.1
200—300	18.5
100—200	16.2
50—100	9.9
25— 50	7.3
12— 25	5.8
6— 12	5.3
Below 6	11.9

Source: “China Electric Power Yearbook”
Allen Blackman and Xun Wu (1997)

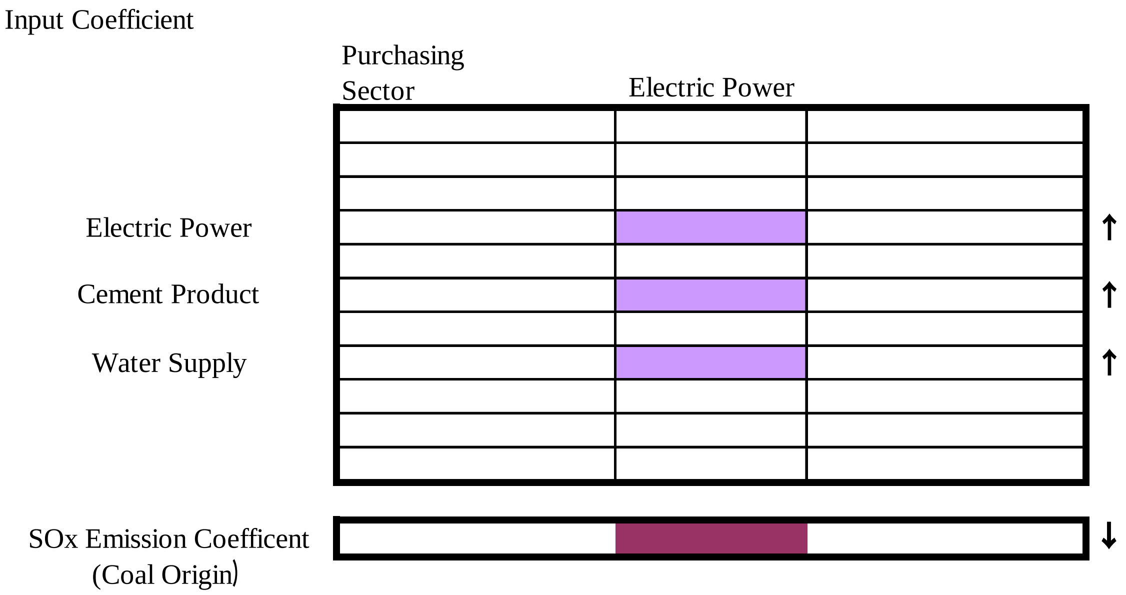


Figure 5: Change of Input Coefficients due to Flue Gas Desulfurization Equipment Installation

Table 3: Main Theoretical Values of the Model

Main Economic Variables		Unit
Wage per capita (Agriculture)	2968	Yuan
Labor Supply (Total)	39.3	million person
Labor Supply (Agriculture)	11.4	million person
Labor Supply (Nonagriculturel)	27.9	million person
Nominal / Real Production	1115.2	billion Yuan
Nominal / Real Import	135.6	billion Yuan
Nominal / Real Consumption	142.0	billion Yuan
Nominal / Real Investment	97.6	billion Yuan
Nominal / Real GDP	349.0	billion Yuan
Interest Rate	8.64	%
GDP Deflator	100	
Domestic Price of Goods	1.00	
Composite Price of Goods	1.00	
Main Environmental Variables		
CO_2 Emission (CO_2 conversion)		
Industry	2708.2	100 thousand ton
Household	5.3	100 thousand ton
Total	2713.6	100 thousand ton
SOX Emission (SO_2 conversion)		
Industry	1474.5	thousand ton
Household	3.8	thousand ton
Total	1478.3	thousand ton

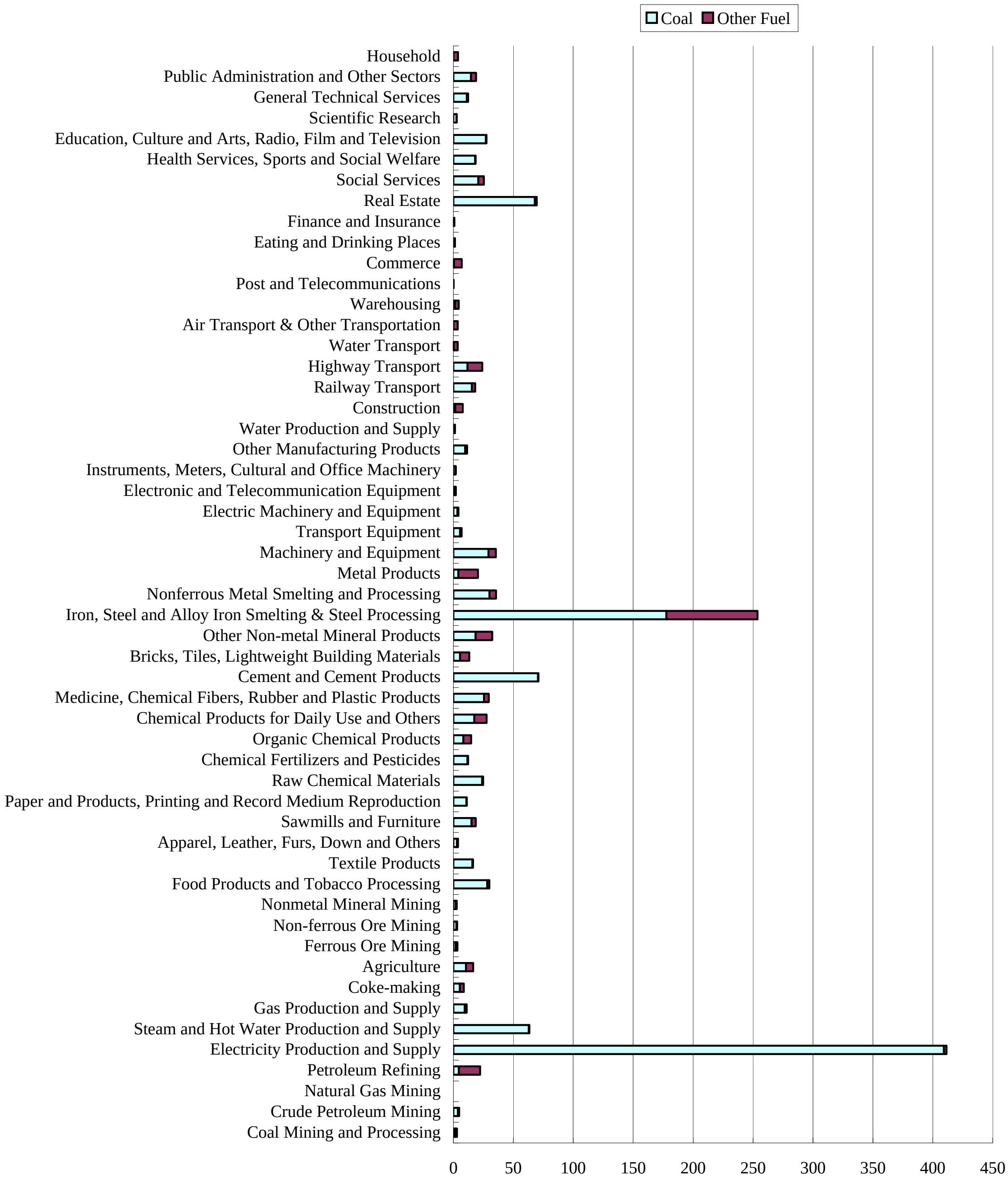


Figure 6: SOx Emissions by Sector in Liaoning (1997, thousand tons-SO_2)

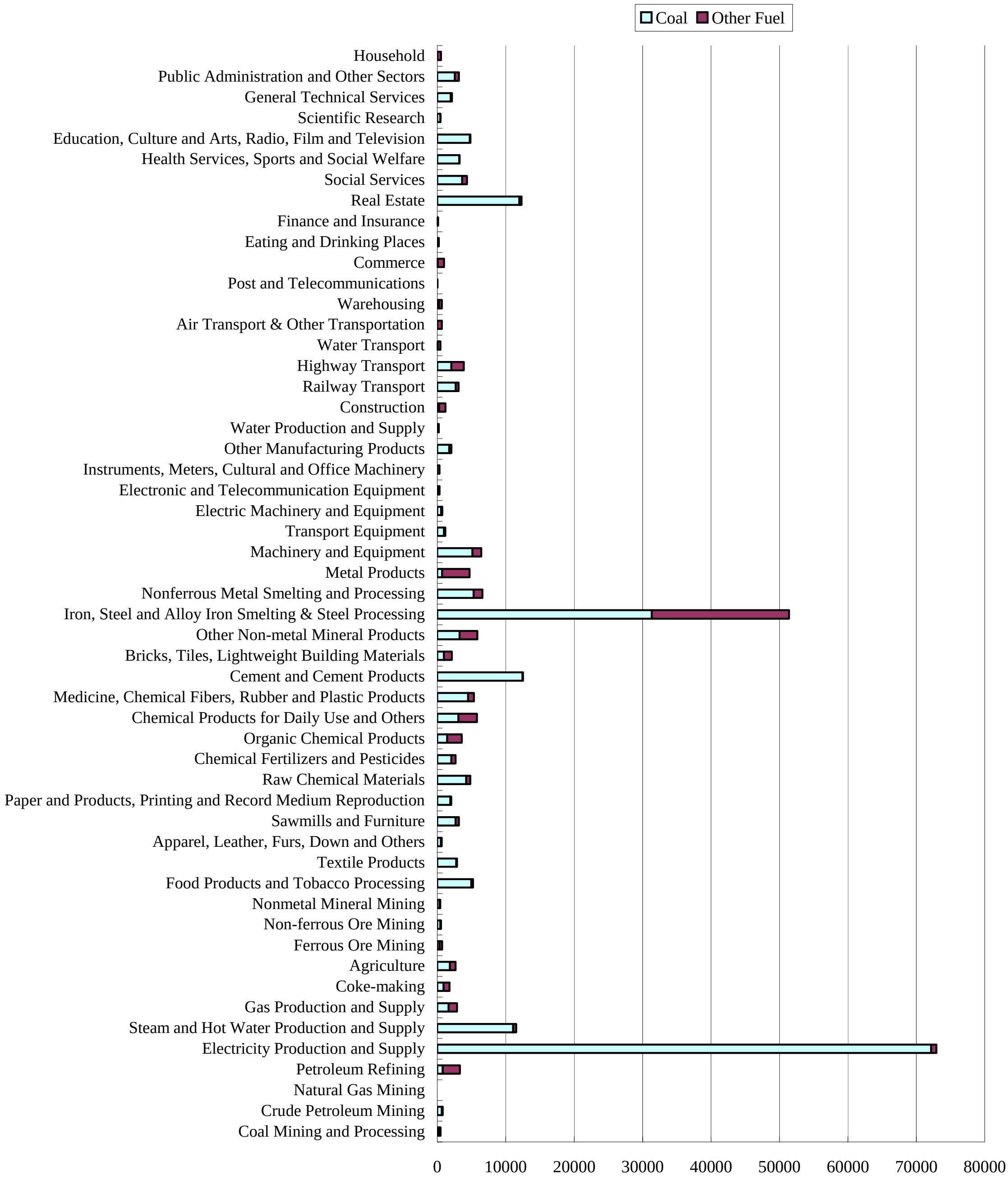


Figure 7: CO_2 Emissions by Sector in Liaoning (1997, thousand tons-CO_2)

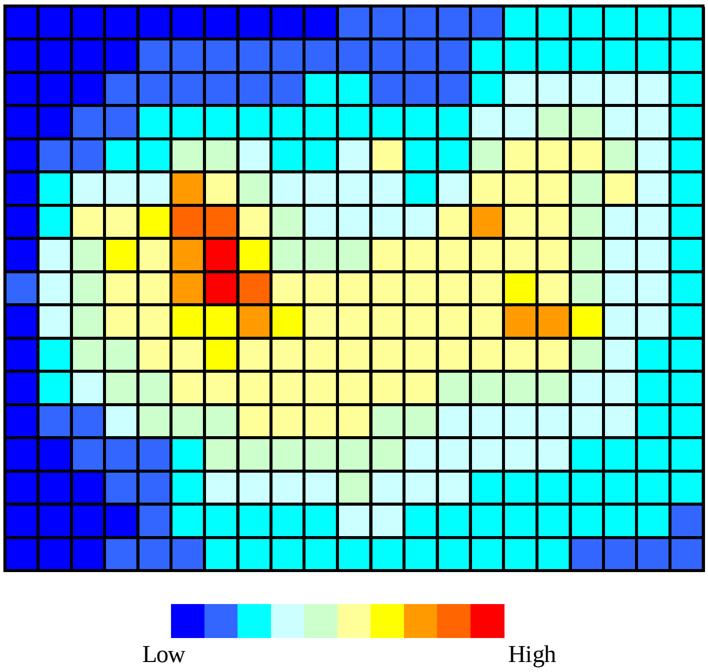


Figure 8: SOx Concentration in Shenyang (1997)

* SOx concentration of red and blue grids is above 200 ppb and below 40 ppb, respectively.

Table 4: Changing Rates of Main Variables (simulation [1])

Main Economic Variables	Unit
Wage per capita (Agriculture)	26.0 %
Labor Supply (Agriculture)	–23.1 %
Labor Supply (Nonagriculturel)	9.4 %
Real Production	1.6 %
Real Import	5.4 %
Nominal Consumption	2.7 %
Real Consumption	–0.5 %
Real Investment	11.0 %
Nominal GDP	14.1 %
Real GDP	2.8 %
GDP Deflator	111.0 base=100
Domestic Price of Goods	14.8 %
Composite Price of Goods	5.1 %
Main Environmental Variables	
CO_2 Emission (CO_2 conversion)	
Industry	1.8 %
Household	–12.8 %
Total	1.7 %
SOx Emission (SO_2 conversion)	
Industry	–23.7 %
Household	–12.7 %
Total	–23.7 %

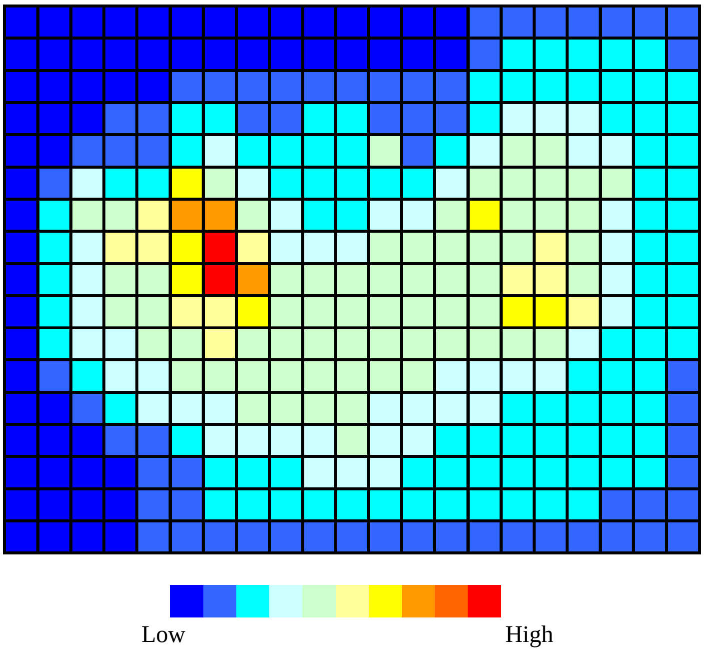


Figure 9: Change of SOx Concentration (simulation [1], 1997)

* SOx concentration of red and blue grids is above 200 ppb and below 40 ppb, respectively.

Table 5: Reclamation of Alkali Soil (simulation [1])

		Unit
Industrial water consumption for FGD equipment	156.6	million ton
Desulfurization gypsum input	14.7	million ton
Ash input of bio-coal briquettes	115.9	ton
Reclamation of alkali soil	1.3	million ha
Increase of corn production by soil reclamation	3.1	million ton

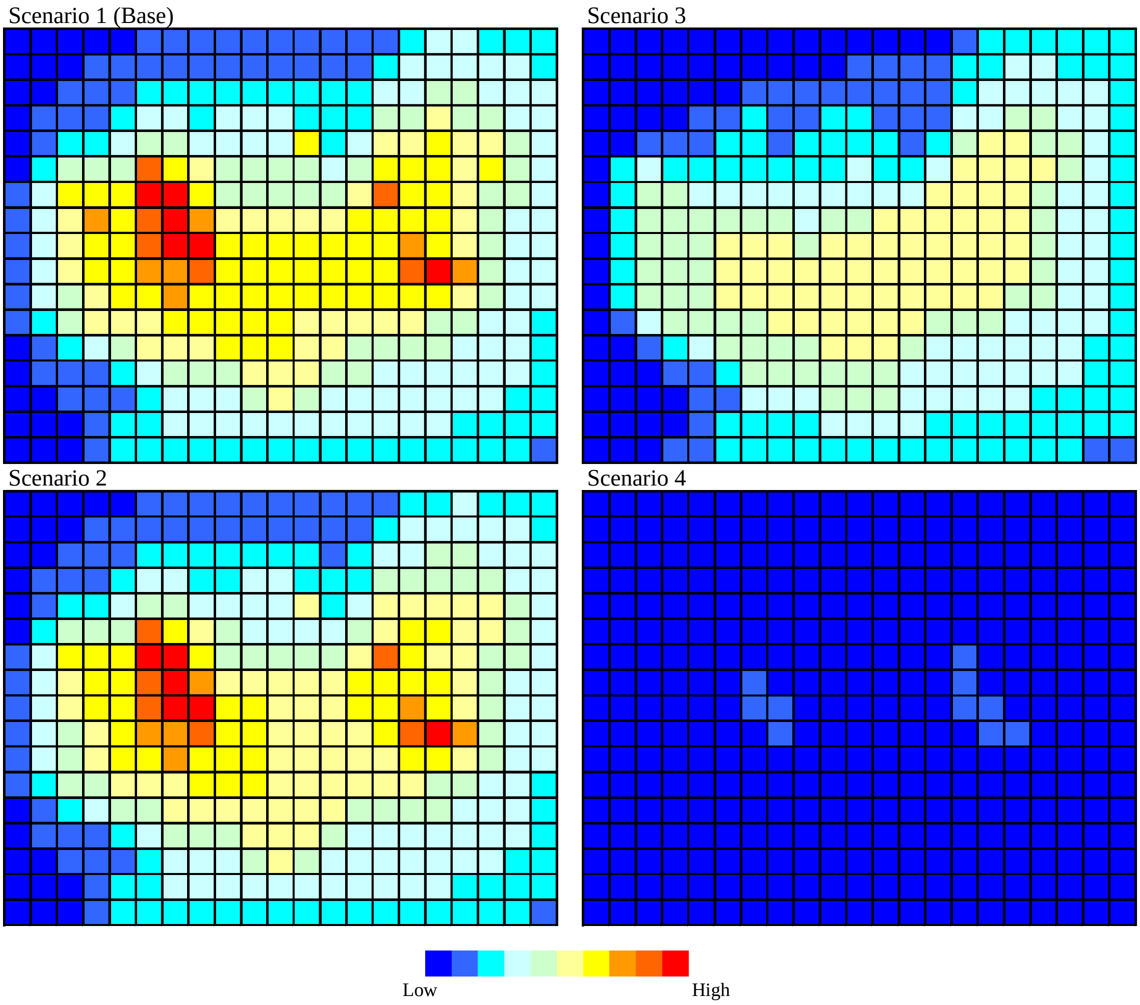
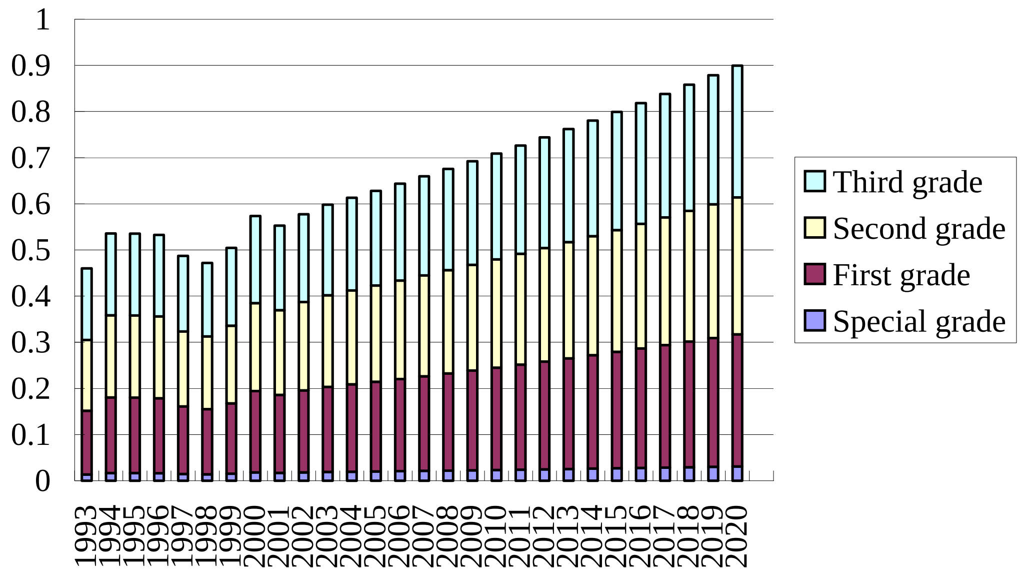


Figure 10: SOx Concentration by Scenario (simulation [2], after 10 years from 1992)

* SOx concentration of red and blue grids is above 200 ppb and below 40 ppb, respectively.

Scenario 1 (base)

Generated patients 10 thousand persons



Patients at the term end 10 thousand persons

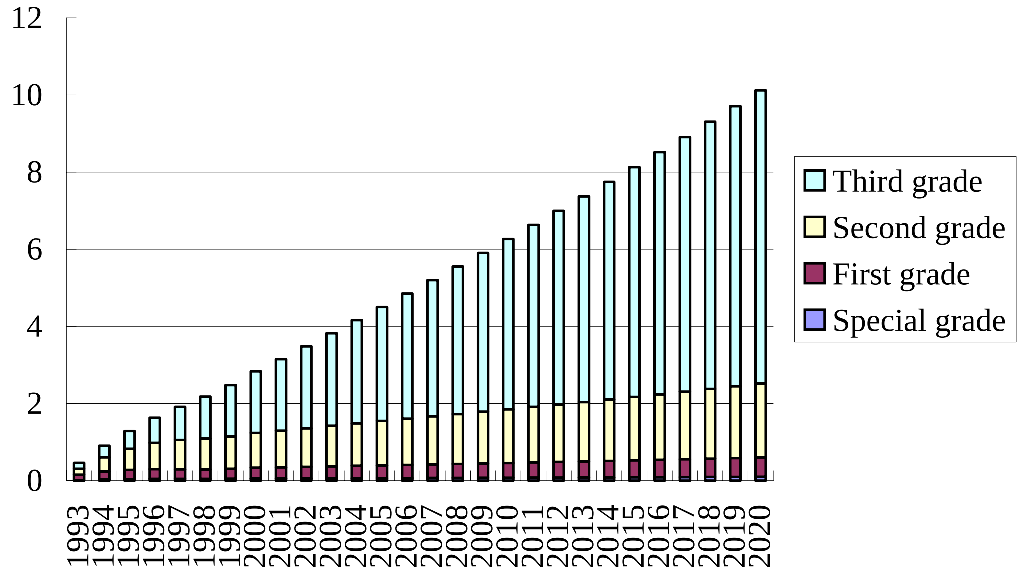
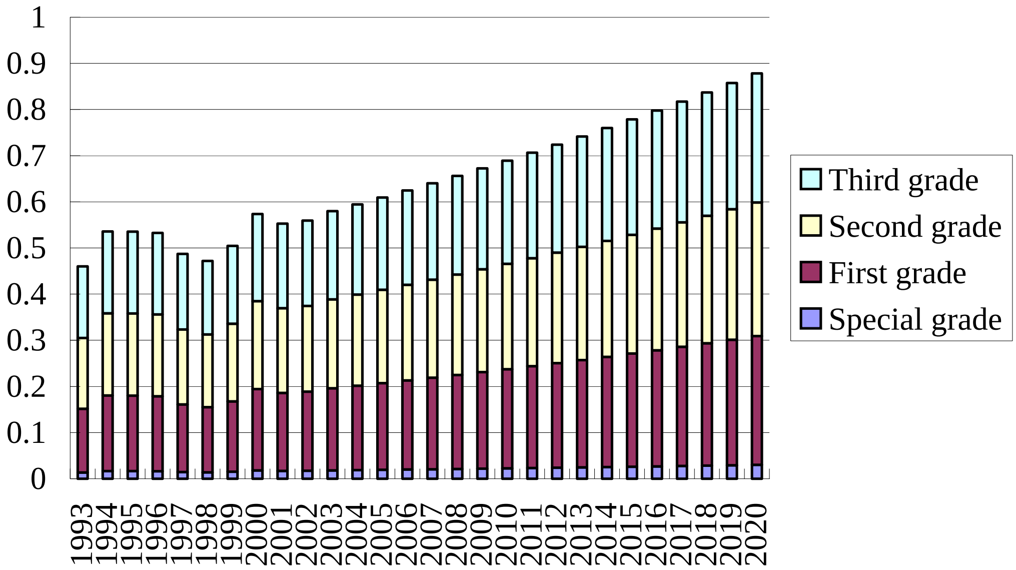


Figure 11: Changing Symptoms of Patients (simulation [2], scenario 1)

Scenario 2

Generated patients 10 thousand persons



Patients at the term end 10 thousand persons

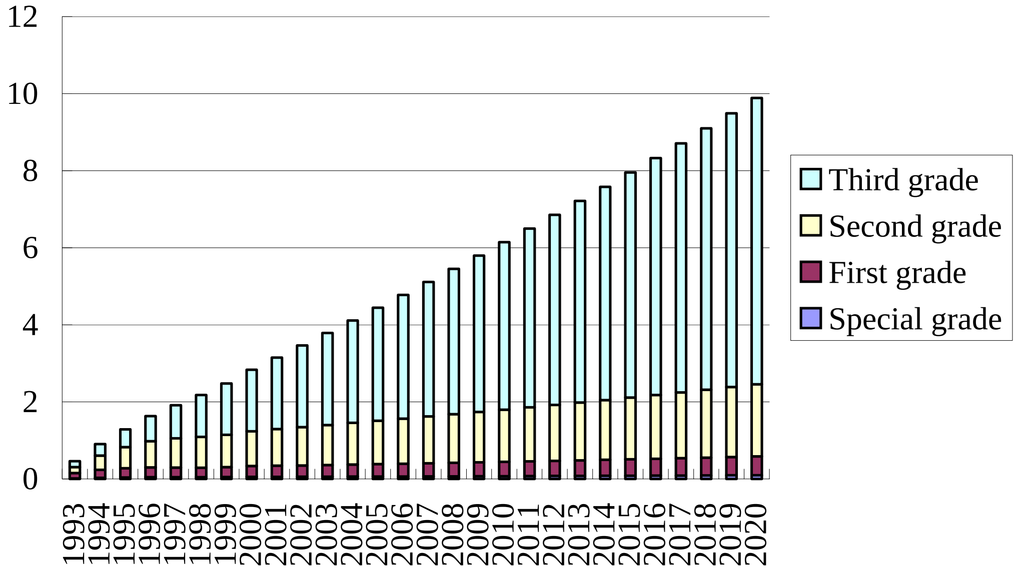
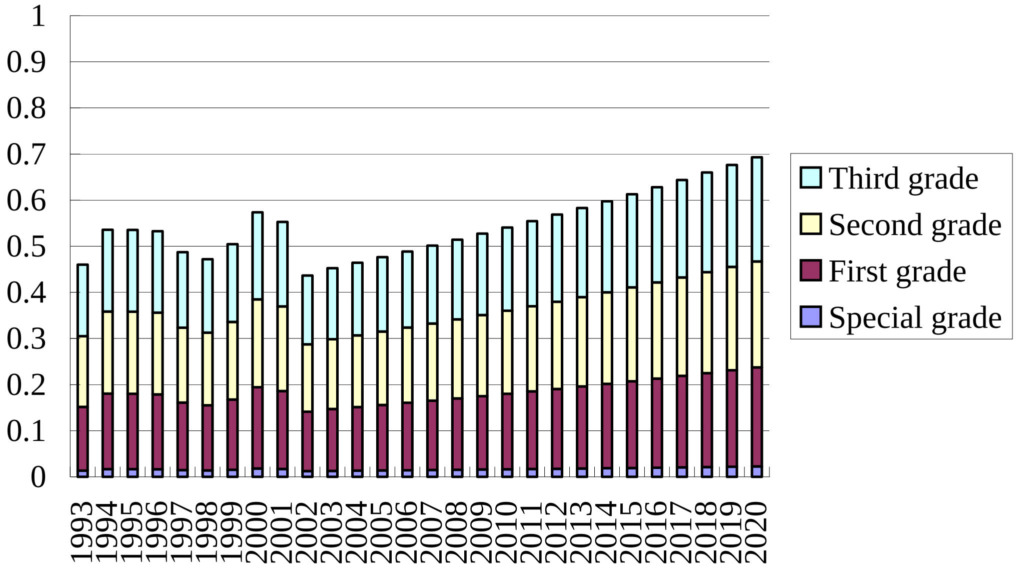


Figure 12: Changing Symptoms of Patients (simulation [2], scenario 2)

Scenario 3

Generated patients 10 thousand persons



Patients at the term end 10 thousand persons

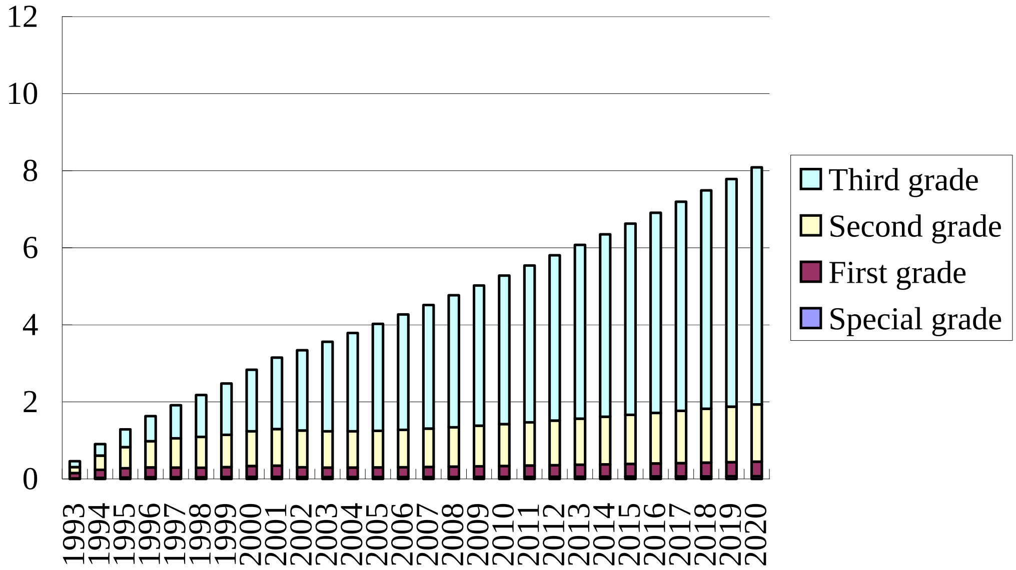
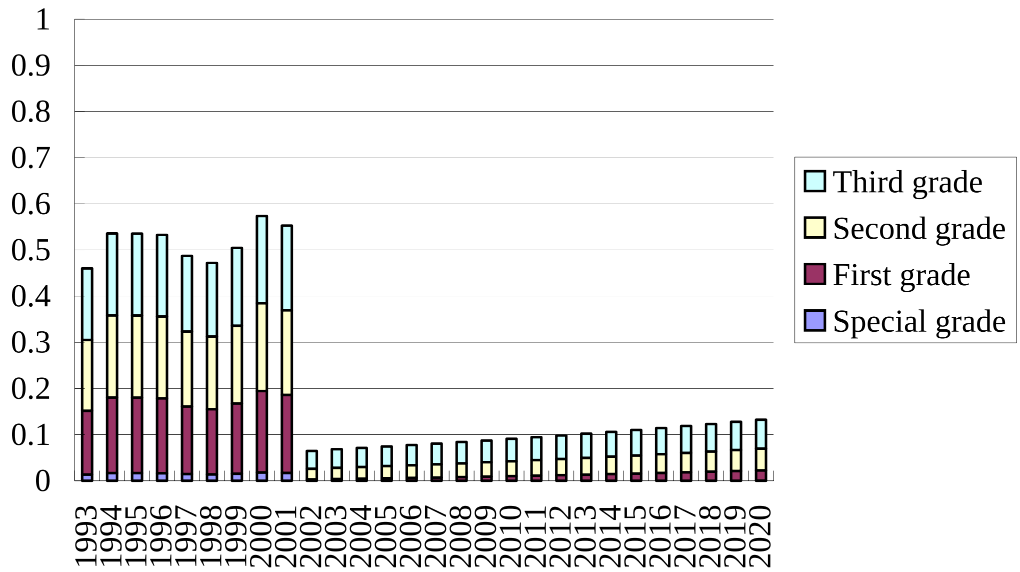


Figure 13: Changing Symptoms of Patients (simulation [2], scenario 3)

Scenario 4
Generated patients 10 thousand persons



Patients at the term end 10 thousand persons

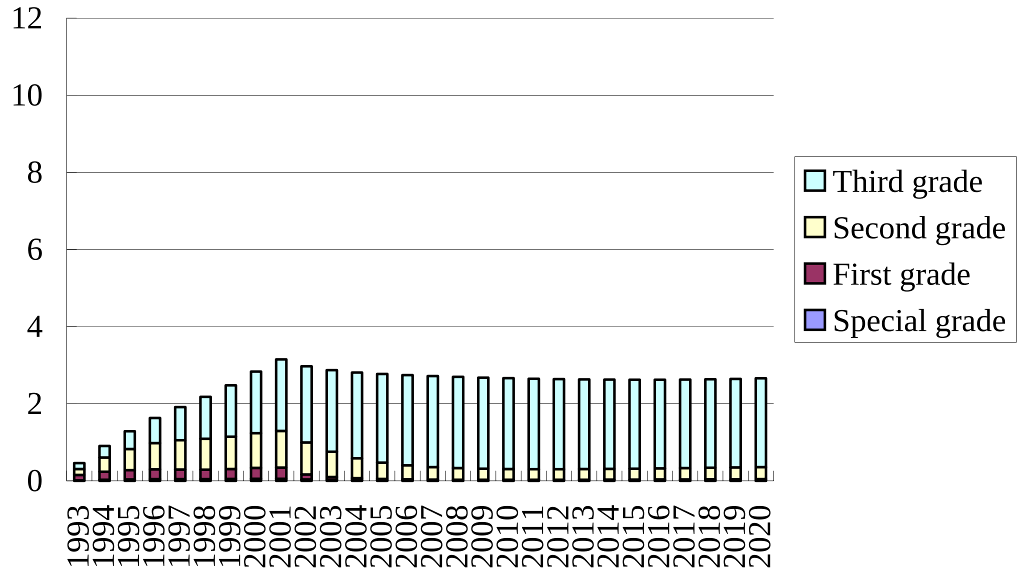
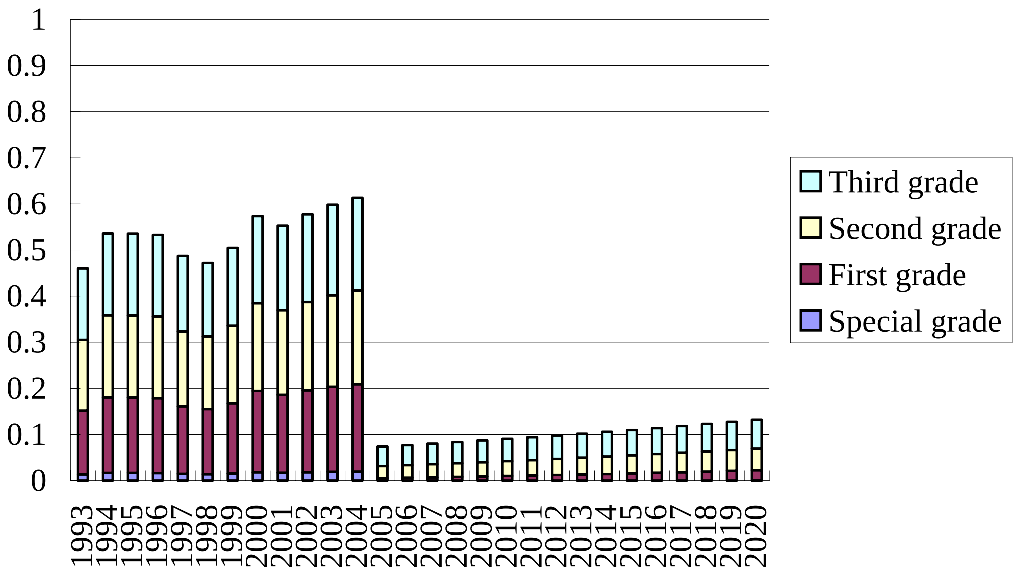


Figure 14: Changing Symptoms of Patients (simulation [2], scenario 4)

Scenario 5

Generated patients 10 thousand persons



Patients at the term end 10 thousand persons

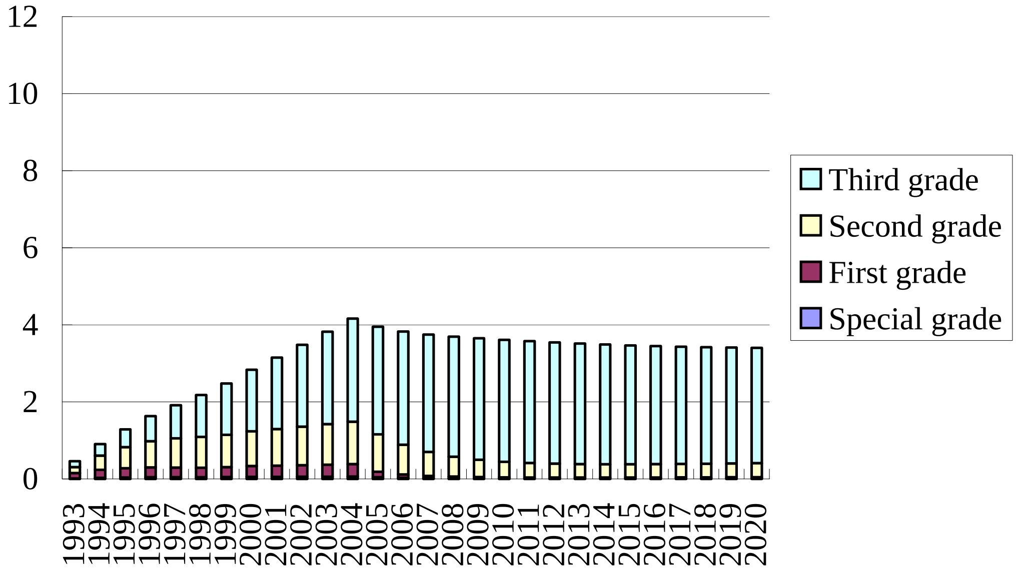


Figure 15: Changing Symptoms of Patients (simulation [2], scenario 5)

Chart 1:Equation System for the Economic and Environmental Model of Liaoning

< Economic Variables >		
Composite Price of Goods	$\ln p_{oi} = [s_i, (1-s_i)] \begin{bmatrix} \ln p_i \\ \ln p_{\bar{M}i} \end{bmatrix}$	$i = 1, \cdots, 52$
Short − term Supply Function	$p_j = \sum_i p_{oi} a_{ij} + \frac{\partial L_j}{\partial x_j} w_j$	$j = 2, \cdots, 52$
Domestic Supply	$\mathbf{x} = [\mathbf{P} - \mathbf{P_o}(\mathbf{I} - \boldsymbol{\Delta})\mathbf{A}]^{-1}[(\mathbf{I} - \boldsymbol{\Delta})\mathbf{P_o}(\mathbf{C} + \mathbf{I} + \bar{\mathbf{G}}) + \mathbf{P} \cdot \mathbf{E}\bar{\mathbf{X}}]$	52×1 *Vector*
Induced Import	$\mathbf{IM} = \mathbf{P_M^{-1}} \boldsymbol{\Delta} \mathbf{P_o}[\mathbf{Ax} + \mathbf{C} + \mathbf{I} + \bar{\mathbf{G}}]$	52×1 *Vector*
Production by Sector		$j = 1, \cdots, 52$
Value Added by Region and Sector	$v_j^k = p_j x_j^k - \sum_i p_{oi} a_{ij} x_j^k$	$j = 1, \cdots, 52$
Macroeconomic Consumption Function	$C_e = \alpha^c + \beta^c v$	
Account Description Aggregation of Composite Price of Goods	$p_{ohl} = \Pi_i \; Conv_{il}^h p_{oi}$	$l = 1, \cdots, 5$
Consumption Demand Function by 5 Account Descriptions	$p_{ohl} c_l = \alpha_l^h p_{ohl} + \beta_l^h (C_e - \sum_m p_{ohm} \alpha_m^h)$	$l, m = 1, \cdots, 5$
Conversion between Account Description and Item	$c_{jl} = Conv_{jl}^c p_{ohl} c_l$	$l = 1, \cdots, 5$ $j = 1, \cdots, 52$
Consumption Demand by Account Description(for Environmental Analysis)	$c_l = \sum_j c_{jl} / p_j$	$l = 1 \cdots, 5$
Aggregation of Consumption Demand	$C_j = \sum_l c_{jl} / p_{oj}$	$j = 1, \cdots, 52$
Aggregation of Composite Price of Goods (for Investment Function)	$p_{oI} = \Pi_i \; Conv_i^I p_{oi}$	$i = 1, \cdots, 52$
Investment Function	$\ln I = \alpha^I + \beta^I \ln \bar{Y}_{real-1} + \gamma^I (r - \frac{\Delta p_{oI}}{p_{oI}})$	
Investment Demand by Item	$I_{nom,j} = Conv_j^I I p_{oI}$ $I_j = I_{nom,j} / p_{oj}$	$j = 1, \cdots, 52$
Labor Demand Function	$L_j = \delta_j^{-\frac{1}{\beta_j^L}} x_j^{\frac{1}{\beta_j^L}} \bar{K}_{j,-1}^{1-\frac{1}{\beta_j^L}}$	$j = 2, \cdots, 52$
Labor Supply of Agricultural Sector	$L_1 = \bar{L} - \sum_{j=2} L_j$	
Wage of Agricultural Sector	$w_1 = \frac{x_1 - \sum_i p_{oi} a_{i1} x_1 - p_{k1} \bar{K}_{1,-1}}{L_1}$	
Wage Differetials	$w_j = \alpha_j^w w_1$	$j = 2, \cdots, 52$
Nominal GDP	$Y = \sum_j v_j$	
Real GDP	$Y_{real} = \sum_j (p_j x_j / p_j - \sum_i p_{oi} a_{ij} x_j / p_{oi})$	
GDP Deflator	$GDPdef = Y / Y_{real}$	

i and j indicate Industrial Sector$(i, j = 1, \cdots, 52)$
l indicates Consumption Account Description$(l = 1, \cdots, 5)$

$$\Delta = \begin{bmatrix} (1-s_1) & & \\ & \ddots & \\ & & (1-s_n) \end{bmatrix}$$

Chart 1:Equation System for the Economic and Environmental Model of Liaoning(Cont.)

< *Environmental Variables* >

Fuel Input by and Sector	$E_{ju} = coe_{ju}x_j$	$j = 1, \cdots, 52$ $u = 1, \cdots, 8$
Fuel Input of Household Consumption	$EC_u = \sum_l c_l coec_u$	$u = 1, \cdots, 8$
SO_x Emission by Sector and Fuel	$SO_{ju} = ((1 - d_{ju})so_{ju}E_{ju})(64/32)$	$j = 1, \cdots, 52$ $u = 1, \cdots, 8$
SO_x Emission from Households by Fuel (Direct Combustion)	$SOC_u = ((1 - dc_u)soc_u EC_u)(64/32)$	$u = 1, \cdots, 8$
SO_x Emission by Sector	$SO_j = \sum_u SO_{ju}$	$j = 1, \cdots, 52$
SO_x Emission from Household Consumption(Direct Combustion)	$SOC = \sum_u SOC_u$	
SO_x Emission	$SO = \sum_u \sum_j SO_{ju} + \sum_u SOC_u$	
CO_2 Emission by Sector and Fuel	$CO_{ju} = (ci_{ju}E_{ju})(44/12)$	$j = 1, \cdots, 52$ $u = 1, \cdots, 8$
CO_2 Emission from Households by Fuel (Direct Combustion)	$COC_u = (cc_u EC_u)(44/12)$	$u = 1, \cdots, 8$
CO_2 Emission by Sector	$CO_j = \sum_u CO_{ju}$	$j = 1, \cdots, 52$
CO_2 Emission from Household Consumption(Direct Combustion)	$COC = \sum_u COC_u$	
CO_2 Emission	$CO = \sum_u \sum_j CO_{ju} + \sum_u COC_u$	

j indicates Industrial Sector$(j = 1, \cdots, 52)$
u indicates Energy$(l = 1, \cdots, 8)$

Chart 2 :Endogenous Variables of the Economic and Environmental Model of Liaoning

$< Economic\ Variables >$			
C_e			$Nominal\ Consumption$
C_j	$j = 1, \cdots, 52$		$Real\ Consumption$
c_l	$l = 1 \cdots, 5$		$Real\ Consumption\ Demand\ by\ Account\ Description$
c_{jl}	$j = 1, \cdots, 52$	$l = 1 \cdots, 5$	$Nominal\ Consumption\ Demand\ by\ Account\ Description\ and\ Item$
p_{oi}	$i = 1, \cdots, 52$		$Composite\ Price\ of\ Goods$
p_{ohl}	$l = 1, \cdots, 5$		$Composite\ Price\ of\ Goods\ by\ Account\ Description$
p_{oI}			$Composite\ Price\ of\ Goods\ (Aggregation\ for\ Investment\ Function)$
p_j	$j = 2, \cdots, 52$		$Domestic\ Price\ of\ Goods$
IM	$52 \times 1\ Vector$		$Induced\ Import$
x_j	$j = 1, \cdots, 52$		$Real\ Production\ by\ Sector$
v_j	$j = 1, \cdots, 52$		$Value\ Added\ by\ Sector$
I	$52 \times 1\ Vector$		$Real\ Investment$
Y			$Nominal\ GDP$
Y_{real}			$Real\ GDP$
L_j	$j = 2, \cdots, 52$		$Labor\ Demand(Non-agricultural\ Sector)$
L_1			$Labor\ Supply(Agricultural\ Sector)$
w_1			$Average\ Wage\ per\ capita(Agricultural\ Sector)$
w_j	$j = 2, \cdots, 52$		$Wage(Non-agricultural\ Sector)$
$< Environmental\ Variables >$			
E_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	$Fuel\ Input\ by\ Sector$
EC_u	$u = 1, \cdots, 8$		$Fuel\ Input\ of\ Household\ Consumption$
SO_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	$SO_x\ Emission\ by\ Sector\ and\ Fuel$
SOC_u	$u = 1, \cdots, 8$		$SO_x Emission\ from\ Households\ by\ Fuel\ (Direct\ Combustion)$
SO_j	$j = 1, \cdots, 52$		$SO_x\ Emission\ by\ Sector$
SOC			$SO_x\ Emission\ from\ Household\ Consumption\ (Direct\ Combustion)$
SO			$SO_x\ Emission$
CO_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	$CO_2\ Emission\ by\ Sector\ and\ Fuel$
COC_u	$u = 1, \cdots, 8$		$CO_2\ Emission\ from\ Households\ by\ Fuel\ (Direct\ Combustion)$
CO_j	$j = 1, \cdots, 52$		$CO_2\ Emission\ by\ Sector$
COC			$CO_2\ Emission\ from\ Household\ Consumption\ (Direct\ Combustion)$
CO			$CO_2\ Emission$

Chart 3 :Exogenous Variables and Parameters of the Economic and Environmental Model of Liaoning

$\bar{G}$	52×1 *Vector*		*Real Government Consumption*
$\bar{EX}$	52×1 *Vector*		*Real Export*
a_{ij}	$i, j = 1, \cdots, 52$		*Input Coefficient*(A *indicates Vector*)
$\bar{p_{Mi}}$	$i = 1, \cdots, 52$		*Import Price of Goods*
$\bar{p_{o1}}$			*Price of Agricultural Goods*(*Composite Goods*)
$\bar{p}_1$			*Price of Agricultural Goods*(*Domestic Goods*)
$\bar{p}_{k1}$			*Rental Cost of Capital*(*Agricultural Sector*)
$\bar{Y}_{real-1}$			*Real GDP in the previous term* (*Predetermined Endogenous Variable*)
$\bar{L}$			*Total Labor Supply*
$\bar{K}_{j,-1}$	$j = 1, \cdots, 43$		*Capital Stock*(*Predetermined Endogenous Variable*)
$\bar{M}$			*Money Supply*
r			*Nominal Interest Rate*
s_i	$i = 1, \cdots, 52$		*Share of Domestic and Import Goods*
$Conv^h_{il}$	$i = 1, \cdots, 52$	$l = 1, \cdots, 5$	*Converter between Account Description and Item for Composite Price of Goods*
$Conv^c_{jl}$	$j = 1, \cdots, 52$	$l = 1, \cdots, 5$	*Converter between Account Description and Item for Consumption Demand*
$Conv^I_i$	$i = 1, \cdots, 52$		*Item Aggregation Converter of Composite Price of Goods*(*for Investment Function*)
α^c, β^c			*Parameter of Macroecnomic Consumption Function*
α^h, β^h			*Parameter of Consumption Demand Fuction by* 5 *Account Descriptions*
$\alpha^I, \beta^I, \gamma^I$			*Parameter of Investment Fuction*
δ_j	$j = 1, \cdots, 52$		*Parameter of Labor Demand Function*
β^L_j	$j = 1, \cdots, 52$		*Distribution Rate of Labor*
α^w_j	$j = 1, \cdots, 52$		*Coefficient of Wage Differetials*
coe_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	*Input Coefficient of Fuel by Industry*(*by Sector*)
$coec_u$	$u = 1, \cdots, 8$		*Input Coefficient of Fuel by Household*
d_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	*Desulfurization Rate*(*by Sector*)
dC_u	$u = 1, \cdots, 8$		*Desulfurization Rate of Household Consumption*
so_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	*Sulfur Contents*(*by Sector and Fuel*)
soc_u	$u = 1, \cdots, 8$		*Sulfur Contents for Household Consumption* (*by Fuel*)
ci_{ju}	$j = 1, \cdots, 52$	$u = 1, \cdots, 8$	*Carbon Contents*(*by Sector and Fuel*)
cc_u	$u = 1, \cdots, 8$		*Carbon Contents for Household Consumption* (*by Fuel*)