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A HIGH PRODUCTIVITY AND FLEXIBILITY MODELING METHODOLOGY FOR ENERGY AND ENVIRONMENT SYSTEMS

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Abstract Recent remarkable progresses of computer technology and solving algorisms have enabled to solve large-scale optimization problems rather easily. Correspondingly, many large-scale models of energy and environment systems have been developed. However, it has become more difficult for modelers on one side to construct, modify and upgrade the models due to their complexity and large size, and for decision-makers on the other to understand the analyses results of the complicated models. Analysis of energy and environment systems usually requires large-scale models, and constructed models occasionally need to be modified or upgraded to meet changes in assumed data and in analysis purpose or to enjoy the progress of computer technology and of solving algorithms. Thus, a new methodology is wanted to provide a high productivity in model construction and a high flexibility to model modification or upgrading. This paper presents such a new methodology to construct mathematical programming models for energy and environment systems analysis. To acquire intended productivity and flexibility, the model is divided, at first, into three kinds of modules: a database system, a matrix generator and a report generator. Secondly, all the model elements are grouped into four categories and then the equations to express inter-element relationships are also categorized: "Flow" "Conversion Process", "Stock" and "Inter-regional Transportation". In order to verify the effectiveness of the new methodology, two kinds of sample models have been developed by the new methodology and their results are shown in this article. The new methodology helps attain high productivity in modeling systems of energy and environment and also of other areas. It also facilitates for the related people such as policy analysts or policy makers to interpret the model analysis results more accurately because the model structure is more clearly understood thanks to the categorization of model elements and equations.

Keywords: Mathematical modeling, model generator, energy and environment, linear programming model, categorization, productivity

1. Introduction

Development of large-scale mathematical programming models, especially linear programming models, for energy and environment systems analyses has become practical by progresses of computer technology and of solving algorisms. Correspondingly, the effective modeling is crucial under such recent circumstances for large-scale systems. Among other things, the effective management of the model assumption data, which are great in number and various in kind, is an important matter. In addition, these assumption data must be changed in many situations; new knowledge acquisition and new findings, sensitivity analyses, etc. Even the model framework such as regional division or interval between the representative time points must sometimes be changed when the focus of analysis is varied. This paper presents a new methodology of large-scale model construction to provide a high construction productivity and also a high flexibility to model parameter and framework changes, especially for energy and environment systems analyses. The gap between modelers and model result users, e.g., policymakers and policy analysts, is another issue to be solved. Generally speaking, simple models are not useful to support the actual decision-making and large-scale complicated models, on the other hand, are inclined to be discarded by policy makers. Analysis of energy and environment systems usually requires large-scale models and yet the gap between the two must be filled. The new methodology developed in this paper also categorizes all the model elements and inter-element relationships and helps fill this gap because the model structure is clarified with the categorization and is therefore understood easily.

To ease the modelers burden, several computer languages to describe mathematical programming models, e.g., GAMS (GAMS [5]), OPL (for the solver of CPLEX (ILOG [6])), Xpress-Mosel (for the solver of Xpress-MP), SIMPLE (for the solver of NUOPT), have been developed. These modeling languages are very helpful to model various types of the systems, and the productivity of the modeling has certainly been increased. Especially GAMS has a remarkable feature, whose language is independent on the solvers. Many models of energy and environment systems have been described in GAMS language, e.g., MERGE (Manne and Richels [8]), DICE (Nordhaus [12]), RICE (Nordhaus and Boyer [13]), MARIA (Mori and Takahashi [11]), GRAPE (Kurosawa et al. [7]). However, these types of languages including GAMS are just description languages and not more than that. They cannot manage effectively model parameter data, which are usually large in amount. Therefore, it is not easy for model users to understand and run the models or to interpret model analysis results. On the other hand, the developed methodology in this paper is to provide a high construction productivity through the categorization of model elements and consequent model structure simplification and to provide a high flexibility to model parameter and framework changes through the introduction of a data management system.

The new methodology is powerful for the modeling of intertemporal linear programming or mixed integer programming models. Existing energy and environment models, such as, MARKAL (Fishbone et al. [3]), MESSAGE (Messner et al. [9, 10]), DNE21 (Fujii et al. [4]), LDNE21 (Yamaji et al. [14]), are of these types of models and the developed methodology can easily be applied to models of these kinds.

This paper also presents two sample models of energy and environment systems which were constructed based on the new methodology.

2. Outline of Methodology

In order to acquire intended high productivity of construction and also high flexibility to data modification and updating, a model is divided into three kinds of modules in the new methodology: a database system based on Microsoft Access, a matrix generator and a report generator all of which are written in C language. C language is superior to the languages designed specifically for mathematical programming models, e.g., GAMS, from the viewpoint of the generality, the dynamic memory allocations, etc. The matrix generator having the dynamic memory allocations can be independent on the numbers of optimization time points, divided model regions, technologies to be evaluated, etc., which are generated by the database system, and no change in the matrix generator is required for changes in these items. The generated file having MPS (Mathematical Programming System) format will be solved by LP (Linear Programming) or MIP (Mixed Integer Programming) solvers (depending on their formulation) which are available on the market, e.g., CPLEX, Xpress-MP, NUOPT. The flow of the model construction and calculation is shown in Figure 1. By constructing the model in this way, such model change as described above can be made only within the database system, which has user-friendly interfaces, without any change in the matrix generator or the report generator.

Another gimmick used for efficient model construction and easy modification is a modeling structure as shown in Figure 2. The model elements are grouped into four categories: “Flow”, “Conversion Process”, “Stock” and “Inter-regional Transportation”. “Conversion Process” represents conversion between different types of “Flow”s, “Stock” represents “Flow” difference between two time points, and “Inter-regional Transportation” represents “Flow” difference between two regions. For example, annual coal production, annual input of coal fuel to coal fired power plant, annual output of electricity generated by coal fired power plant, etc. can be modeled as “Flow”, electricity generation, oil refinery, CO_2 recovery, etc. can be modeled as “Conversion Process”, fossil fuel resources, sequestered CO_2, electricity storage, etc. can be modeled as “Stock”, and energy and CO_2 transportations between divided model regions can be modeled as “Inter-regional Transportation”. In addition, the facilities of “Conversion Process”, “Stock” and “Inter-regional Transportation” can be modeled explicitly when they are needed. By categorizing all the elements in this way, the formulations of inter-element relationships are also categorized, avoiding a large number of various equations which, otherwise, are to be individually written down.

Thanks to this model structure of separated modules, the usage of database system and the element categorization, models are constructed without any change in the matrix generator, the report generator and the structure of database system, but only by change in the contents of the database. In addition, the new modeling methodology simplifies not only the formulation of the optimization model but also the construction of database system, assuring easy change in representative time points, region division, technology characteristics, etc. which can be implemented through the user-friendly interfaces of the database system module.

The report generator of model results is also supported by the database system. Obtained results are reported according to the format defined in the database system; the format is determined by the model element group such as primary energy, final energy, electricity, etc. in case of “Flow”.

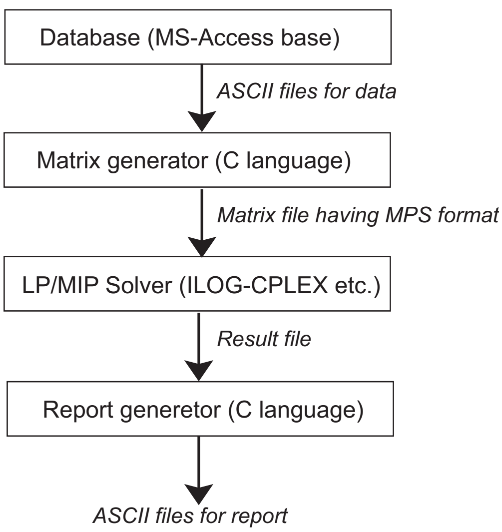

Figure 1: Model construction and calculation flow

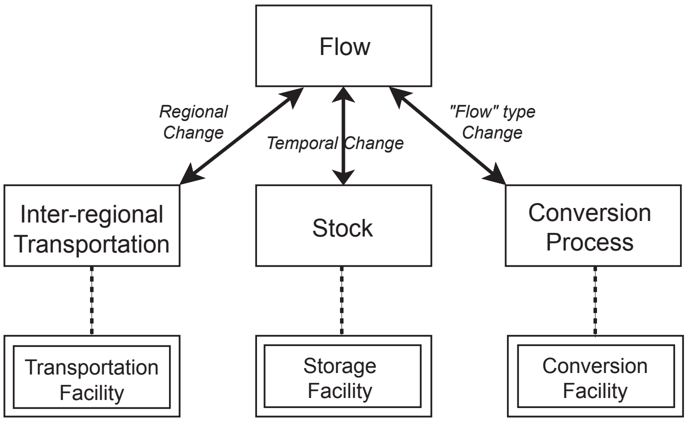

Figure 2: Model structure simplification based on categorization

3. Formulations

Inter-elemental relationships are categorized and formulated in the following generalized fashion. The following equations comprise the matrix generator module, but all of them are not always modeled in the actual model; some of the constraints are modeled only when necessary. The equations are relatively simple, and when a user-friendly database system is used in cooperation, various models of energy and environment systems can be constructed rather easily. As for time between successive two of the representative time points is interpolated by a linear function in the objective function, and this way of interpolation yields flexibility of the interval setting between the optimization time points, which is usually regarded as fixed in regular modeling.

The following symbols are introduced;

t subscript for a representative time point for optimization

z subscript for a separated time zone in a representative time point

r subscript for a divided model region

x subscript for an inter-regional connection among divided model regions

i subscript for category of flow (="Flow"), conversion process (="Conv"), stock (="Stock") and inter-regional transportation (="Trans": an inter-regional transportation, "Trans-F": inter-regional transportation of flow from region A to B, "Trans-R": inter-regional transportation of flow from region B to A, "Trans-Imp": import in a divided region, "Trans-Exp": export in a divided region)

n subscript for a type of flow, conversion process, stock or inter-regional transportation

The mathematical model contains the following equations. The decision variables are as follows;

C cost

V amount of flow, stock and inter-regional transportation

F capacity of facilities of conversion, storage and inter-regional transportation

FN capacity of new installation facilities of conversion, storage and inter-regional transportation

All decision variables are non-negative.

- Objective Function
  The objective function is the sum of the discounted energy and environment systems

costs interpolated by the linearization between the representative time points.

$$Minimize \sum_{t=1}^{T} \left\{ \int_{Year_{t-1}}^{Year_t} \frac{C_{t-1} \times (Year_t - \tau) + C_t \times (\tau - Year_{t-1})}{Year_t - Year_{t-1}} e^{-\gamma(\tau - Year_0)} d\tau \right\} \tag{3.1}$$

where γ : discount rate, C_t : total system cost in t-th time point, $Year_t$: year in t-th time point

- Cost Balance

$$C_t = \sum_{r=1}^{R} (C_{Flow,r,t} + C_{Stock,r,t} + CF_{Conv,r,t} + CF_{Stock,r,t} + C_{Saving,r,t}) + C_{Trans,t} + CF_{Trans,t} \tag{3.2}$$

where $C_{Flow,r,t}$: cost of flow, $C_{stock,r,t}$: cost of stock, $CF_{Conv,r,t}$: cost of conversion facility, $CF_{Stock,r,t}$: cost of stock facility, $C_{Saving,r,t}$: cost of saving, $C_{Trans,t}$: cost of inter-regional transportion, $CF_{Trans,t}$: cost of inter-regional transportion facility

- Flow and Stock Cost

The cost of flow and stock is represented as the following equation.

$$C_{Flow,r,t} = \sum_{n=1}^{N} \left(P_{Flow,n,r,t} \times \sum_{z=1}^{Z} V_{Flow,n,r,t,z} \right) \tag{3.3}$$

$$C_{Stock,r,t} = \sum_{n=1}^{N} (P_{Stock,n,r,t} \times V_{Stock,n,r,t}) \tag{3.4}$$

where $P_{Flow,n,r,t}$: unit cost of flow, $P_{Stock,n,r,t}$: unit cost of stock

- Cost of Conversion and Stock Facilities

The cost of conversion and stock facilities is represented as the following equation.

$$CF_{i,r,t} = \sum_{n=1}^{N} (PF_{i,n,r,t} \times \eta_{i,n,r} \times F_{i,n,r,t}) \qquad (i = "Conv", "Stock") \tag{3.5}$$

where $\eta_{Conv,n,r}$: annual expense rate of conversion facility, $PF_{Conv,n,r,t}$: unit cost of conversion facility, $\eta_{Stock,n,r}$: annual expense rate of stock facility, $PF_{Stock,n,r,t}$: unit cost of stock facility

- Flow Saving Cost

The new methodology is useful for bottom-up modeling of energy and environment technologies, but the top-down approach is partially conducted in the bottom-up models. "Flow", e.g., energy demand, can be saved by increases in the price, and the effect is represented using long-term price elasticity as shown in the following equation. The saving cost is taken into account only in the non-reference case, i.e., under additional policies inducing reductions in the amount of assumed flows, e.g., CO_2 tax, regulation policies.

$$\begin{aligned} C_{Saving,r,t} = & \sum_{n=1}^{N} \left\{ \sum_{k=1}^{Step_{n,r}} \Big((SP_{n,r,t} + (RP_{n,r} - SP_{n,r,0})) \right. \\ & \left. \times \Big(1 - {}^{Flow_{n,r,t} \times MaxSave_{n,r} \times (k-1)} / {}_{Step_{n,r}} \Big)^{-\frac{1}{\alpha}} \times V_{Saving,n,r,t,k} \Big) \right\} \end{aligned} \tag{3.6}$$

where $-\alpha$: long-term price elasticity ($\alpha > 0$), $Flow_{n,r,t}$: flow in Reference case (corresponds to the lower limit of flow), $MaxSave_{n,r}$: maximum flow saving (ratio to the flow in Reference case), $Step_n, r$: number of steps of the step function for flow saving cost linearization, $RP_{n,r}$: actual price in the base year, $SP_{n,r,t}$: shadow price in Reference case

- Inter-regional Transportation Cost

$$C_{Trans,t}=\sum_{x=1}^{X}\sum_{n=1}^{N}\left(P_{Trans,n,x,t}\times\sum_{z=1}^{Z}V_{Trans,n,x,t,z}\right)$$
$$+\sum_{r=1}^{R}\sum_{n=1}^{N}\left\{\left(P_{Trans-Exp,n,r,t}\times\sum_{z=1}^{Z}V_{Trans-Exp,n,r,t,z}\right)+\left(P_{Trans-Imp,n,r,t}\times\sum_{z=1}^{Z}V_{Trans-Imp,n,r,t,z}\right)\right\} \quad (3.7)$$

where $P_{Trans,n,x,t}$: unit cost of inter-regional transportation of the connection x, $P_{Trans-Exp,n,r,t}$: unit cost of export of inter-regional transportation, $P_{Trans-Imp,n,r,t}$: unit cost of import of inter-regional transportation

- Inter-regional Transportation Facility Cost
  The cost balances for inter-regional transportation facilities are formulated by the following equation.

$$CF_{Trans,t}=\sum_{x=1}^{X}\sum_{n=1}^{N}(PF_{Trans,n,r,t}\times\eta_{Trans,n,x}\times F_{Trans,n,x,t}) \quad (3.8)$$

where $\eta_{Trans,n,x}$: annual expense rate of inter-regional transportation facility, $PF_{Trans,n,x,t}$: unit cost of inter-regional transportation facility

- Flow Balance
  The balances of the internal flow and the inter-regional transportation of flow are formulated as shown in Eq. (3.9). In addition, the maximum and minimum shares are modeled as shown in Eqs. (3.10)-(3.13); they are useful, for example, to model the maximum/minimum shares among oil products.

$$\sum_{n\in InB_j}V_{Flow,n,r,t,z}+V_{Trans-Imp,w,r,t,z}=\sum_{n\in OutB_j}V_{Flow,n,r,t,z}+V_{Trans-Exp,w,r,t,z} \quad (3.9)$$

(w is the related transportation item of the flow balance j)

$$V_{Flow,n,r,t,z}\le MaxShare_n\times\sum_{n\in InB_j}V_{Flow,n,r,t,z} \quad (3.10)$$

$$V_{Flow,m,r,t,z}\le MaxShare_n\times\sum_{n\in OutB_j}V_{Flow,n,r,t,z} \quad (3.11)$$

$$V_{Flow,n,r,t,z}\ge MinShare_n\times\sum_{n\in InB_j}V_{Flow,n,r,t,z} \quad (3.12)$$

$$V_{Flow,m,r,t,z}\ge MinShare_n\times\sum_{n\in OutB_j}V_{Flow,n,r,t,z} \quad (3.13)$$

where InB_j: a set of flows into flow balance j, $OutB_j$: a set of flows from flow balance j

- Inter-regional Transportation Balance
  The inter-regional transportation balances are formulated by the following equation.

$$V_{Trans,n,x,t,z}=V_{Trans-F,n,x,t,z}+V_{Trans-R,n,x,t,z} \quad (3.14)$$

$$V_{Trans-Imp,n,r,t,z}=\sum_{x\in Imp_r}V_{Trans-F,n,x,t,z}+\sum_{x\in Imp_r}V_{Trans-R,n,x,t,z} \quad (3.15)$$

$$V_{Trans-Exp,n,r,t,z}=\sum_{x\in Exp_r}V_{Trans-F,n,x,t,z}+\sum_{x\in Exp_r}V_{Trans-R,n,x,t,z} \quad (3.16)$$

where Imp_r : a set of inter-regional transportation connections imported in r-th region, Exp_r : a set of inter-regional transportation connections exported in r-th region

- Conversion Balance
  The conversion processes are formulated as in Eq. (3.17).

$$V_{Flow,k,r,t,z}=Conv_{n,m,k,r,t}\times V_{Flow,m,r,t,z} \quad (3.17)$$

where $Conv_{i,n,m,t}$: conversion coefficient from n-th flow to m-th flow on i-th conversion process

- Stock Balance
  The stock is represented by the accumulation of the input/output of flow.

$$V_{Stock,n,r,t} = V_{Stock,n,r,t-1} \pm \sum_{m \in R_{Stock,n}} \left\{ \frac{1}{2} \times \left(\sum_{z=1}^{Z} V_{Flow,m,r,t-1,z} + \sum_{z=1}^{Z} V_{Flow,m,r,t,z} \right) \times (Year_t - Year_{t-1}) \right\} \quad (3.18)$$

where R_{Stock} : a set of flows into/from stock

- Facility Vintage Constraints
  The facility vintages of conversion, stock and inter-regional transportation are modeled as shown in the following equation, when the facilities are explicitly modeled.

$$F_{i,n,r,t} = \int_{Year_t - Life_{i,n}}^{Year_t} \frac{FN_{i,n,r,k-1} \times (Year_k - \tau) + FN_{i,n,r,k} \times (\tau - Year_{k-1})}{Year_k - Year_{k-1}} d\tau$$
$$(Year_{k-1} \le \tau \le Year_k) \;, \quad (i = \text{"}Conv\text{"}, \text{"}Stock\text{"}) \quad (3.19)$$

$$F_{i,n,x,t} = \int_{Year_t - Life_{i,n}}^{Year_t} \frac{FN_{i,n,x,k-1} \times (Year_k - \tau) + FN_{i,n,x,k} \times (\tau - Year_{k-1})}{Year_k - Year_{k-1}} d\tau$$
$$(Year_{k-1} \le \tau \le Year_k) \;, \quad (i = \text{"}Trans\text{"}) \quad (3.20)$$

where $Life_{i,n}$: lifetime of facility [years], $F_{i,n,r,t}$: total capacity of n-th facility in r-th region, $FN_{i,n,r,t}$: new installation capacity of n-th facility in r-th region, $F_{i,n,x,t}$: total capacity of n-th facility in x-th inter-regional transportation connection, $FN_{i,n,x,t}$: new installation capacity of n-th facility in x-th inter-regional transportation connection

- Required Capacity of Conversion, Inter-regional Transportation and Stock Facility
  The required capacities of conversion, stock and inter-regional transportation are constrained by the amount of the main flow relating conversion process, stock and inter-regional transportation, respectively.

$$V_{Flow,n,r,t,z} \le \nu_{Conv,m,r,t} \times F_{Conv,m,r,t} \times T_z \qquad (Flow\ n \text{ is the base flow in } Conv\ m.) \quad (3.21)$$

$$V_{Stock,n,r,t} \le \nu_{Stock,n,r,t} \times F_{Stock,n,r,t} \quad (3.22)$$

$$V_{Trans,n,x,t,z} \le \nu_{Trans,n,x,t} \times F_{Trans,n,x,t} \times T_z \quad (3.23)$$

where T_z : the length of the time which a year is divided into, $\nu_{i,n,r,t}$: usage rate

- Maximum and Minimum Flow, Stock and Inter-regional Transportation Constraints
  The constraints on the maximum and minimum flow, stock and inter-regional transportation are shown in Eqs. (3.24)-(3.27). For example, the exogenous energy demand constraints can be represented by the minimum flow constraints.

$$\sum_{z=1}^{Z} V_{Flow,n,r,t,z} \le MaxV_{Flow,n,r,t} \quad (3.24)$$

$$\sum_{z=1}^{Z} V_{Flow,n,r,t,z} \ge MinV_{Flow,n,r,t} - \sum_{k=1}^{Step_{m,r}} V_{Saving,m,r,t,k} \quad (Flow\ n \text{ is the target of the } Saving\ m) \quad (3.25)$$

$$V_{i,n,r,t} \le MaxV_{i,n,r,t} \qquad (i = \text{"}Stock\text{"}, \text{"}Trans\text{"}) \quad (3.26)$$

$$V_{i,n,r,t} \ge MinV_{i,n,r,t} \qquad (i = \text{"}Stock\text{"}, \text{"}Trans\text{"}) \quad (3.27)$$

where $MaxV_{i,n,r,t}$: upper limit of flow, stock and transportation, $MinV_{i,n,r,t}$: lower limit of flow, stock and transportation

- Maximum and Minimum Capacity Constraints for New Installation Facility
  The maximum and minimum constraints in the conversion, storage and inter-regional

transportation new installation facilities are shown in Eqs. (3.28) and (3.29).

$$\frac{1}{2} \times (FN_{i,n,r,t} + FN_{i,n,r,t-1}) \times (Year_t - Year_{t-1}) \leq MaxFN_{i,n,r,t} \tag{3.28}$$

$$\frac{1}{2} \times (FN_{i,n,r,t} + FN_{i,n,r,t-1}) \times (Year_t - Year_{t-1}) \geq MinFN_{i,n,r,t} \tag{3.29}$$

where $MaxFN_{i,n,r,t}$: upper limit for conversion, stock and inter-regional transportation new installation facilities, $MinFN_{i,n,r,t}$: lower limit for conversion, stock and inter-regional transportation new installation facilities

- Maximum and Minimum Capacity Constraints of Facility
  The maximum and minimum constraints in the conversion, storage and inter-regional transportation facilities are shown in Eqs. (3.30) and (3.31).

$$F_{i,n,r,t} \leq MaxF_{i,n,r,t} \tag{3.30}$$

$$F_{i,n,r,t} \geq MinF_{i,n,r,t} \tag{3.31}$$

where $MaxF_{i,n,r,t}$: upper limit for conversion, stock and inter-regional transportation facilities, $MinF_{i,n,r,t}$: lower limit for conversion, stock and inter-regional transportation facilities

- Maximum Increase and Decrease Constraints of Flow, Stock and Inter-regional Transportation
  The constraints of the maximum annual increase and decrease of flow, stock and inter-regional transportation are shown in Eqs. (3.32) and (3.33).

$$\sum_{z=1}^{Z} V_{i,n,r,t,z} \leq (1 + MaxVI_{i,n,r,t})^{Year_t - Year_{t-r}} \times \sum_{z=1}^{Z} V_{i,n,r,t-1,z} \tag{3.32}$$

$$\sum_{z=1}^{Z} V_{i,n,r,t,z} \geq (1 - MaxVD_{i,n,r,t})^{Year_t - Year_{t-1}} \times \sum_{z=1}^{Z} V_{i,n,r,t-1,z} \tag{3.33}$$

where $MaxVI_{i,n,r,t}$: maximum annual increase rate of flow, stock and inter-regional transportation, $MaxVD_{i,n,r,t}$: maximum annual decrease rate of flow, stock and inter-regional transportation

- Maximum Increase and Decrease Constraints of Capacity Constraints of Facility
  The constraints of the maximum annual increase and decrease of conversion, storage and inter-regional transportation facilities are shown in Eqs. (3.34) and (3.35).

$$F_{i,n,r,t} \leq (1 + MaxFI_{i,n,r,t})^{Year_t - Year_{t-1}} \times F_{i,n,r,t-1} \tag{3.34}$$

$$F_{i,n,r,t} \geq (1 - MaxFD_{i,n,r,t})^{Year_t - Year_{t-1}} \times F_{i,n,r,t-1} \tag{3.35}$$

where $MaxFI_{i,n,r,t}$: maximum annual increase rate of conversion, stock and inter-regional transportation facilities, $MaxFD_{i,n,r,t}$: maximum annual decrease rate of conversion, stock and inter-regional transportation facilities

4. User Interface for Modeling

As for the model assumption data, they usually appear at several places of the ASCII format files, and therefore, the change of model data requires consistent changes at all the places where they exist. A relational database management system (DBMS) is very helpful for this matter, because one datum appear/exists only in one place in the DBMS and the data change is necessary only in one place.

For example, if a conversion process is to be added to the constructed model to evaluate the effect of a technology, all the required change is only to add the data records of the

"Conversion Process" and related "Flow" and to define the relationship between them, and then, to provide the value of conversion coefficient, e.g., energy efficiency, in the database system.

In addition, prohibition concerning assumption data such as, minus values for lifetime of facility, can be easily maintained and the user-friendly interface which manages the database enables the easy modeling. Thus, a high productivity of the modeling is achieved.

Figures 3, 4 and 5 show sample interfaces of the DBMS; Figure 3 shows the interface for the connection of "Flow", Figure 4 shows that for the parameters of "Flow", and Figure 5 shows that for the parameters of "Flow" saving with a top-down approach using the long-term price elasticity.

As for regional data, although historical data are usually available by country, prefecture etc., the region division is rough in the model because of the limited capability of the computer and the historical data are aggregated. The advance of the computer capability in the future would allow a larger number of model regions (e.g., 30 regions) and in such an occasion the database system automatically generates the new data set for the expanded model regions.

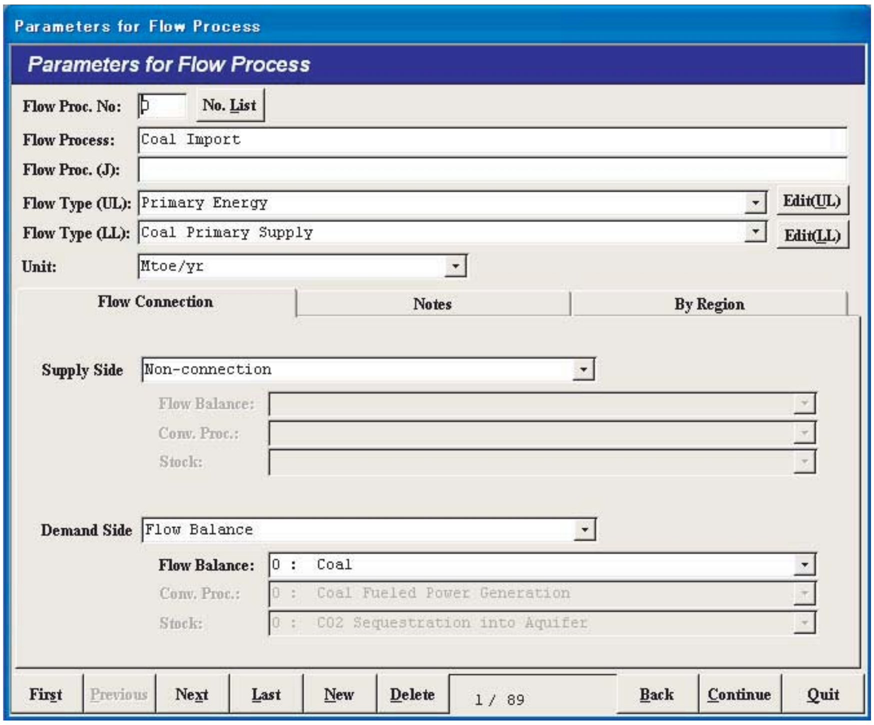

Figure 3: Sample 1 of the modeling interfaces: connection of "Flow"

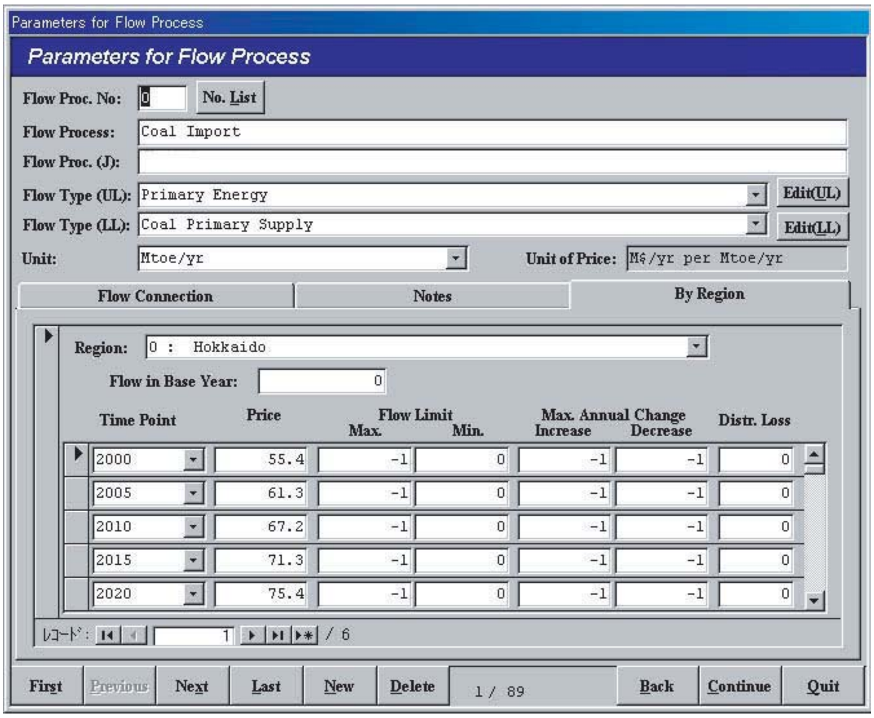

Figure 4: Sample 2 of the modeling interfaces: parameters of "Flow"

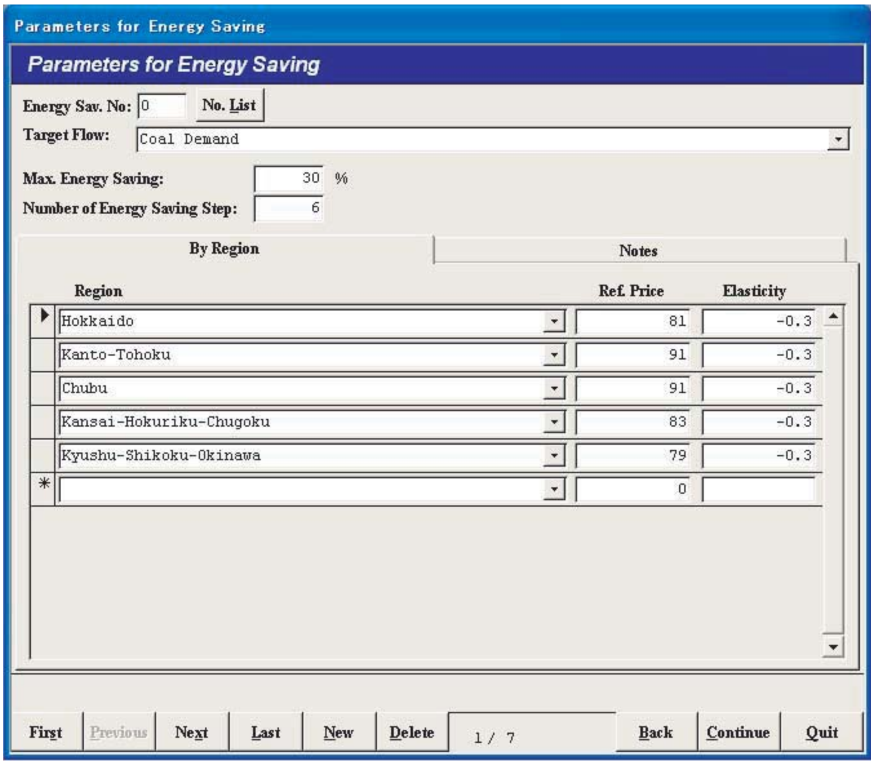

Figure 5: Sample 3 of the modeling interfaces: parameters of "Flow" saving with a top-down approach using long-term price elasticity

5. Example Model and Simulation Using the Developed Modeling System

Two sample models which were constructed for evaluations of Japanese energy and environment systems using the new methodology are presented: a first model has 40 regions and 8 representative time points for optimization, and the second one is a one-region model having 25 representative time points. The main objective of the former model is the evaluation of CO_2 recovery and sequestration in Japan (Akimoto et al. [2]), and that of the latter is the evaluation of electric power generation systems expansion including their R & D processes in Japan (Akimoto et al. [1]).

5.1. Example 1: 40 region model

The first example is a domestic model for the analysis of energy and global warming issue. CO_2 capture and the sequestration into aquifer are taken into account as one of the CO_2 emission reduction technologies. In order to evaluate the technologies, the land area of Japan is divided into 20 regions and the offshore area also into 20 regions in the model because the economics of the technologies depend strongly on the sites. The representative time points in this model are 2000, 2005, 2010, 2015, 2020, 2025, 2030, 2040 and 2050. The total cost of energy systems and CO_2 sequestrations in Japan between the years of 2000 and 2050 is minimized to meet the given final energy demand by fuel.

The land regions have various kinds of electric power plants, e.g., coal fueled, oil fueled, natural gas fueled power plants, IGCC with CO_2 recovery unit, hydro, geothermal, nuclear, wind power and photovoltaics. They also have CO_2 chemical recoveries and other energy systems, e.g., oil refinery, water electrolysis, etc. They are modeled as the “Conversion Process” and “Conversion Facility”. On the other hand, the offshore regions have aquifers for CO_2 sequestration. The aquifers for CO_2 sequestration are modeled as the “Stock” of the modeling system. In addition, CO_2 sequestration into ocean is taken into account. These model regions are inter-linked each other to evaluate CO_2 transportation between the CO_2 sources and the reservoirs, using the “Inter-regional Transportation” in the methodology.

Electricity demand is expressed by annual load duration curves having four kinds of time periods: instantaneous peak, peak, intermediate and off-peak. Energy saving in end-use sectors is modeled by top-down approach using linearization approximations having 8 steps of long-term price elasticity of energy demands.

For sample results, the resulting primary energy supply and the CO_2 emissions from fossil fueled power plants and recoveries by land region in 2020 are shown in Figures 6 and 7. These are the results of minimization of the total cost of energy systems and CO_2 sequestrations in Japan between the years of 2000 and 2050 under the constraint of CO_2 emissions reduction of 0.5 %/yr.

5.2. Example 2: 25 representative time point model

The second example is a domestic one-region model between 2000 and 2050 having 25 representative time points for optimization. This model was developed for the evaluation of electric power generation systems expansion including their R&D processes. The small intervals of the representative time points were required because of the intended optimization of the power generation plus the technology developments. The module of the R&D processes represented in the model is based on GERT (Graphical Evaluation and Review Technique). In the module, the R&D target technology of power generation is broken down into a number of elemental technologies, some of which are substitutional for each other, and the sequential processes of the technology development are explicitly modeled with GERT

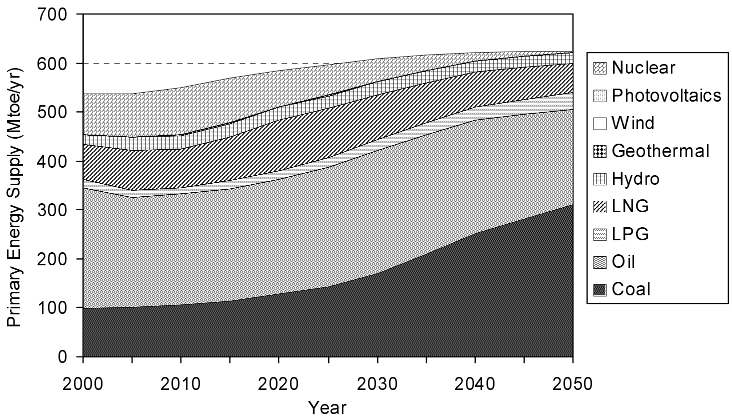

Figure 6: Resulting primary energy supply with the model of the Example 1 (Source: Akimoto et al. [2])

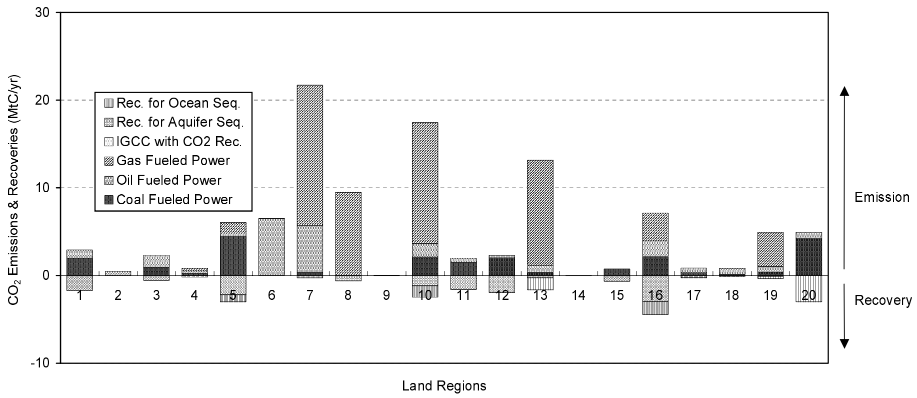

Figure 7: Resulting CO_2 emissions from fossil fueled power plants and recoveries by region in 2020 with the model of the Example 1 (Source: Akimoto et al. [2])

logic of "Exclusive-OR", "Inclusive-OR", "AND", etc. The model is formulated as an mixed integer programming model, and the objective function is the sum of expenditures on both R&D of the advanced combined cycle power systems technologies and the electric power generation cost. The module for power expansion planning in the model can be also modeled by the new methodology presented in this article, though some additional equations for the module of the R&D processes are required to write down in the matrix generator.

The following major electric power generation technologies are considered in this model: conventional coal fired, IGCCs (Integrated coal Gasification Combined Cycles), LNG and coal-gas used MCFC (Molten Carbonate Fuel Cell) and SOFC (Solid Oxide Fuel Cell) combined cycles, conventional LNG fueled, LNG combined cycle, advanced LNG combined cycles, conventional oil fired, wind power, photovoltaics, nuclear power, hydro & geothermal power, and electricity storage (pumping-up). They are modeled as the "Conversion Process" and "Conversion Facility". Future electricity demands are exogenously given to the model, and the constraints are modeled by the minimum flows. The total cost of electric power systems in Japan between the years of 2000 and 2050 is minimized. The cost-effective installation of electric power plants and the generation pattern including the effect of R&D expenditures are obtained with the model.

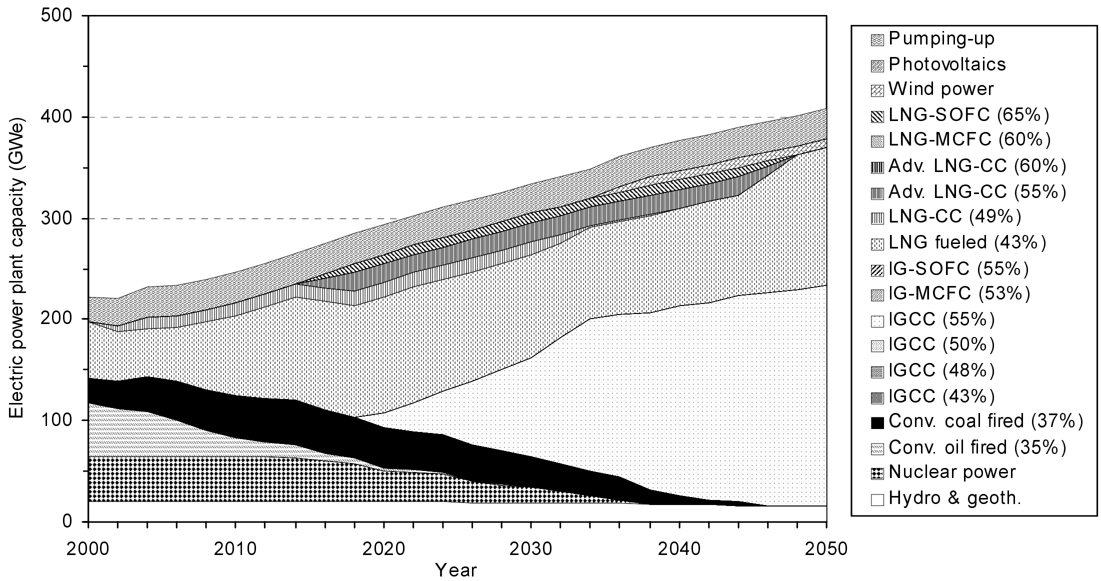

Figure 8: Resulting cost-effective capacities of electric power plants including the effects of R&D expenditures by the model of the Example 2 (Source: Akimoto et al. [1])

This model was constructed using the model presented in Section 5.1 and there is a large amount of common data between these models, e.g., vintage of electric power plants, and therefore, it took only a short time to construct this model. Although the two models appear to be very different, the second model is considered to be an extension of the first one and the construction of the second model was carried out very easily by so considering.

Figure 8 shows the resulting capacities of electric power plants including the acceleration effect of the development time by the R&D expenditures.

6. Conclusion

We developed a new methodology for a high productivity in model construction and also a high flexibility to model modification or upgrading of mathematical programming models for energy and environment systems analysis. The high productivity and flexibility have been achieved by constructing the model with four modules, a database system, a matrix generator, a solver and a report generator, and by categorizing all the elements into "Flow", "Conversion Process", "Stock" and "Inter-regional Transportation". In addition, the database system having user-friendly interfaces makes the model construction easy in cooperation with the new methodology.

In order to verify the effectiveness of the new methodology, two kinds of sample models was developed by the new methodology and their results are shown in this article. These models was constructed for a short time thanks to the developed modeling methodology. The developed new methodology will bring out high productivity and flexibility in modeling energy and environment systems. In addition, the authors believe that the modeling system based on the new methodology makes gaps smaller between modelers and model users, e.g., policymakers, because of the user-friendly and highly flexible interface and model structure simplification by the element categorization.

Finally remarking, the new methodology would also be useful to other systems having flow and stock types, although we showed the methodology effectiveness only for the modeling of energy and environment systems in this study.

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