Multiple calibration decomposition analysis:

Energy use and carbon dioxide emissions in the Japanese economy, 1970-1995

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Abstract

The purpose of this paper is to present a new approach to evaluating structural change of the economy in a multisector general equilibrium framework. The multiple calibration technique is applied to an *ex post* decomposition analysis of structural change between periods, enabling the distinction between price substitution and technological change to be made for each sector. This approach has the advantage of sounder microtheoretical underpinnings when compared with conventional decomposition methods. The proposed technique is empirically applied to changes in energy use and carbon dioxide (CO_2) emissions in the Japanese economy from 1970 to 1995. The results show that technological change is of great importance for curtailing energy use and CO_2 emissions in Japan. Total CO_2 emissions increased during this period primarily because of economic growth, which is represented by final demand effects. On the other hand, the effects such as technological change for labor or energy mitigated the increase in CO_2 emissions.

1. Introduction

Ever since the oil crises in the 1970s, a large amount of research has been conducted in energy demand studies, including seminal works such as Hudson and Jorgenson (1974), Berndt and Wood (1975), Manne (1976), Borges and Goulder (1984), and Solow (1987). Furthermore, it is well known that there has been renewal of interest in the energy analysis, driven by the recent escalation in energy prices.

Economic analyses such as these studies often focus on price changes, which lead to the price substitution effect affecting the overall economy. In fact, price changes have dramatically altered energy usage patterns during the past few decades. On the other hand, it is clear that the changes in the patterns of energy use are caused by a multitude of factors, including autonomous technological development. Accordingly, decomposition methods are necessary if we want to understand the contribution of these various explanatory factors to structural change in the economy or changes in energy use.

The purpose of this paper is to suggest a new approach to such decomposition, the Multiple Calibration Decomposition Analysis (MCDA). Many decomposition methods have already been proposed to disentangle and quantify the impacts of causal factors. Of these, one of the more well-known methods is the Total Factor Productivity or Growth Accounting approach put forward by Solow (1957), which decomposes output growth into measured increases in factor inputs and technical change (see, e.g., Denison, 1967; Jorgenson and Griliches, 1967). This method is of great significance with regard to the explicit integration of economic theory into such decomposition (Griliches, 1996). This paper is motivated by Solow's idea. The 'new wrinkle' we wish to describe is a way of separating structural change due to price substitution from that due to technological change by capturing the interdependence among economic sectors or factor inputs in a

general equilibrium framework. The multiple calibration technique enables us to decompose structural change in such a manner.[1]

The MCDA also takes over the inheritance of Input-Output (I-O) analysis. In the I-O framework, Structural Decomposition Analysis (SDA) has recently developed into a major tool for decomposition, as it surmounts the static characteristics of I-O analysis and enables the examination of structural change (Rose and Casler, 1996; Rose, 1999; Hoekstra and van den Bergh, 2002; Hoekstra, 2005). However, "a rigorous grounding in economic theory is lacking for SDA", as pointed out by Rose and Casler (1996). The MCDA may then provide some additional microtheoretical underpinnings to conventional decomposition methods such as SDA. In addition, the MCDA has an advantage in terms of data availability or efficiency. Although the attempt to conduct econometric studies often suffers from data insufficiency, the approach requires only a two-period dataset. It therefore may provide a practical alternative to econometric approaches.

This paper applies the proposed methodology to the Japanese economy during 1970-1995 to evaluate the factors responsible for changes in energy use and carbon dioxide (CO_2) emissions. The period includes two oil crises, the first in 1973 and the second in 1979, when the oil price escalation had a tremendous impact on the Japanese economy. The experience serves to illustrate the methodology's forte, which is to provide a better understanding of how much the economy was affected by price substitution or technological change. On top of this, this kind of analysis may have some implications for current Japanese environmental policy. The empirical results quantitatively show that technological change is the principal factor in diminishing energy use and CO_2 emissions in that period while total CO_2 emissions increased primarily because of final demand effects reflecting economic growth.

The remainder of the paper is structured as follows. Section 2 explains the methodology. Section 3 applies the methodology to the Japanese economy in the period

1970-1995. Section 4 identifies the causal factors to change in CO_2 emissions in Japan with the methodology. The final section includes some concluding remarks.

2. Decomposition technique

This paper suggests a new methodology for decomposing structural change in a multisector general equilibrium framework, namely the Multiple Calibration Decomposition Analysis (MCDA). The distinguishing feature of the MCDA technique is that it explicitly defines two-tier CES production functions to separate price substitution effects (hereafter, PS) from other types of technological change (hereafter, TC). In other words, the MCDA decomposes structural change in the economy, shown by the change in factor inputs per unit of output between periods, into one part attributable to price substitution and another attributable to technological change. As in the relevant literature, structural change (total change) in this paper is defined as the change in factor inputs per unit of output (hereafter, CFI); this is identical to the change in input coefficients in I-O tables.

The MCDA technique itself is described as follows. The model structure is assumed in Fig. 1. The production functions are given by two-tier constant-returns-to-scale CES functions. The model is composed of capital K, labor L, energy aggregate E, and material aggregate M, as well as energy and material subaggregates. Capital K and labor L are the primary factors of production. Industries are assumed to act to maximize their profits in competitive markets. The factor inputs per unit (hereafter, factor inputs) in the top tier in the initial period ($t-1$) are derived by Equation (1):

$$A_{Ij}^{t-1} = \frac{X_{I(j)}^{t-1}}{X_j^{t-1}} = \lambda_{Ij}^{t-1} \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^{t-1}}{p_{I(j)}^{t-1}} \right)^{\sigma}, I = K, L, E, M , \qquad (1)$$

where A_{Ij}^{t-1} is the factor input (input coefficient) of I per unit output by the sector j in $t-1$,

$X_{I(j)}^{t-1}$ is the aggregate or input of I by the sector j in $t-1$, X_{j}^{t-1} is the output of the sector j

in $t-1$, p_{j}^{t-1} is the price of the good j in $t-1$, $p_{I(j)}^{t-1}$ is the price of I in the sector j in $t-1$,

σ is the elasticity of substitution, α_{Ij} is the share parameter ($\sum_{I}\alpha_{Ij}=1$), and β_{j} is the scale

parameter of the CES functions. λ_{Ij}^{t-1} is the TC parameter in the top tier, as explained

below, and is set at unity in $t-1$. p_{j}^{t-1} and $p_{I(j)}^{t-1}$ are also as one because they are from the

actual price data, which are normalized so that the prices in the initial period are in unity.

When the values of $X_{I(j)}^{t-1}$ and X_{j}^{t-1} are obtained from the dataset, and the substitution

parameters σ are exogenously given, all parameters of the production functions, α_{Ij} and

β_{j}, are determined so as to reproduce the actual economic structure in $t-1$ as an

equilibrium. This is the same procedure followed under conventional single calibration

techniques (Mansur and Whalley, 1984; Shoven and Whalley, 1984, 1992; Dawkins et al.,

2001). The production functions are thus specified. The parameters, α_{Ij}, β_{j}, and σ, are

assumed to be time invariant.

The factor inputs of capital and labor are expressed as in Equation (2), which is the

same as in Equation (1), because there is no bottom tier with regard to capital K and labor

L:

$$a_{ij}^{t-1} = A_{Ij}^{t-1} = \frac{X_{I(j)}^{t-1}}{X_{j}^{t-1}} = \lambda_{Ij}^{t-1}\beta_{j}^{\sigma-1}\left(\alpha_{Ij}\frac{p_{j}^{t-1}}{p_{I(j)}^{t-1}}\right)^{\sigma}, I = K, L; i = K, L.$$

(2)

Next, the bottom tier will be explained. As in Fig. 1, energy aggregate E and material

aggregate M are assumed to be weakly separable. The factor inputs of energy $\mathbf{e}$ (=

$\{e_1,...,e_4\}$) and material $\mathbf{m}$ (= $\{m_1,...,m_5\}$) in the bottom tier in the initial period are given

by Equation (3):

$$a_{I(ij)}^{t-1} = \frac{x_{ij}^{t-1}}{X_{I(j)}^{t-1}} = \lambda_{I(ij)}^{t-1} \beta_{I(j)}^{\sigma_I - 1} \left(\alpha_{I(ij)} \frac{p_{I(j)}^{t-1}}{p_i^{t-1}} \right)^{\sigma_I} , I = E, M ; i = \mathbf{e}, \mathbf{m} , \qquad (3)$$

where $a_{I(ij)}^{t-1}$ is the factor input (input coefficient) of energy $\mathbf{e}$ and material $\mathbf{m}$ per the corresponding aggregate by the sector j in $t-1$, x_{ij}^{t-1} is the input of energy $\mathbf{e}$ and material $\mathbf{m}$ by the sector j in $t-1$, p_i^{t-1} is the price of energy $\mathbf{e}$ and material $\mathbf{m}$ in $t-1$, σ_I is the elasticity of substitution, $\alpha_{I(ij)}$ is the share parameter ($\sum_i \alpha_{I(ij)} = 1$), and $\beta_{I(j)}$ is the scale parameter of the CES functions. $\lambda_{I(ij)}^{t-1}$ is the TC parameter in the bottom tier. $\lambda_{I(ij)}^{t-1}$ and p_i^{t-1} are set at unity in $t-1$. The parameters $\alpha_{I(ij)}$ and $\beta_{I(j)}$ in the bottom tier are then specified by using the same procedure as in Equation (1) in the top tier. The parameters, $\alpha_{I(ij)}$, $\beta_{I(j)}$, and σ_I, are also assumed to be time invariant.

Therefore, the factor inputs of energy $\mathbf{e}$ and material $\mathbf{m}$ per unit output in the initial period are expressed as in Equation (4):

$$a_{ij}^{t-1} = \frac{X_{I(j)}^{t-1}}{X_j^{t-1}} \cdot \frac{x_{ij}^{t-1}}{X_{I(j)}^{t-1}} = \lambda_{Ij}^{t-1} \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^{t-1}}{p_{I(j)}^{t-1}} \right)^{\sigma} \cdot \lambda_{I(ij)}^{t-1} \beta_{I(j)}^{\sigma_I - 1} \left(\alpha_{I(ij)} \frac{p_{I(j)}^{t-1}}{p_i^{t-1}} \right)^{\sigma_I} , I = E, M ; i = \mathbf{e}, \mathbf{m}$$
$$. \qquad (4)$$

One notable characteristic of the MCDA at this point is that another period's dataset is used to specify the TC parameters λ^t. The factor inputs in the terminal period (t) are given by:

$$a_{ij}^t = \frac{X_{I(j)}^t}{X_j^t} = \lambda_{Ij}^t \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^t}{p_{I(j)}^t} \right)^{\sigma} , I = K, L ; i = K, L , \qquad (5)$$

$$a_{ij}^t = \frac{X_{I(j)}^t}{X_j^t} \cdot \frac{x_{ij}^t}{X_{I(j)}^t} = \lambda_{Ij}^t \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^t}{p_{I(j)}^t} \right)^{\sigma} \cdot \lambda_{I(ij)}^t \beta_{I(j)}^{\sigma_I - 1} \left(\alpha_{I(ij)} \frac{p_{I(j)}^t}{p_i^t} \right)^{\sigma_I} , I = E, M ; i = \mathbf{e}, \mathbf{m}$$
$$. \qquad (6)$$

As in the initial period ($t-1$), the values of x^t_{ij}, X^t_j, and $p^t_i (= p^t_j)$ are obtained from the dataset. The prices of capital and labor $p^t_{I(j)}$ ($I = K, L$) are the same as p^t_i ($i = K, L$), while the prices of energy and material aggregate $p^t_{I(j)}$ ($I = E, M$) in the terminal period are represented by the CES cost functions in the bottom tier of the model:

$$p^t_{I(j)} = \frac{1}{\beta_{I(j)}} \left(\sum_i \alpha_{I(ij)}{}^{\sigma_I} p^{t1-\sigma_I}_i \right)^{1/(1-\sigma_I)} , I = E, M ; i = \mathbf{e}, \mathbf{m} . \tag{7}$$

Therefore, the TC parameters $\lambda^t_{ij} (= \lambda^t_{Ij}$ for $I = K, L$, or $= \lambda^t_{Ij} \cdot \lambda^t_{I(ij)}$ for $I = E, M$) are endogenously determined to replicate the economic structure in the terminal period as another equilibrium. In other words, λ^t_{ij} are chosen to fill the gap between the counterfactual point associated with the price change under the specified production functions and the actual equilibrium in the terminal period.

In the MCDA, as shown in Equation (8), the change in factor inputs (CFI) can be decomposed into TC and PS in additive form: [2]

$$a^t_{ij} - a^{t-1}_{ij} = \left(a^t_{ij} - a^c_{ij} \right) + \left(a^c_{ij} - a^{t-1}_{ij} \right), i = K, L, \mathbf{e}, \mathbf{m} ,$$

$$\Leftrightarrow \mathrm{CFI} = \mathrm{TC} + \mathrm{PS} . \tag{8}$$

a^c_{ij} is the counterfactual point, created as:

$$a^c_{ij} = \lambda^{t-1}_{Ij} \beta_j{}^{\sigma-1} \left(\alpha_{Ij} \frac{p^t_j}{p^t_{I(j)}} \right)^{\sigma} , I = K, L ; i = K, L , \tag{9}$$

$$a^c_{ij} = \lambda^{t-1}_{Ij} \beta_j{}^{\sigma-1} \left(\alpha_{Ij} \frac{p^t_j}{p^t_{I(j)}} \right)^{\sigma} \cdot \lambda^{t-1}_{I(ij)} \beta_{I(j)}{}^{\sigma_I-1} \left(\alpha_{I(ij)} \frac{p^t_{I(j)}}{p^t_i} \right)^{\sigma_I} , I = E, M ; i = \mathbf{e}, \mathbf{m} . \tag{10}$$

In decomposition analysis, it is important to make counterfactual points and indicate what the counterfactual points actually mean. The counterfactual points work as the juncture or separation of the step-by-step transition from the initial to the terminal period. The counterfactual points of the MCDA are constructed by incorporating the effect of relative price change between the initial and terminal periods. As shown in Equation (8), the change in the factor input between the initial and terminal periods is represented as CFI, with the difference between the counterfactual point and the initial period as PS and the difference between the terminal period and the counterfactual point as TC. Thus, the MCDA can exactly decompose CFI into PS and TC. PS, which depends upon the elasticity of substitution and the change in relative prices over the periods, embodies the price substitution effects. On the other hand, TC embodies those parts of the factor input change that cannot be explained by the price substitution effects, including autonomous technological change.

From a theoretical viewpoint, PS represents the change in factor inputs along the production function while TC represents shifts in the production function. [3] The decomposition of the MCDA provided is then consistent with the production theory in microeconomics. The prominent feature of the method is that it has clear theoretical underpinnings, and allows the decomposition components to be interpreted in a theoretically meaningful way.

A final and important point is as follows. In this paper, the elasticities of substitution are assumed to be constant in all sectors and zero or unity between inputs (see Fig. 1). As described later, this is for the purposes of simplicity. However, this production structure resembles that inferred from the existing literature that econometrically estimates the parameters using historical Japanese data (see, e.g., Tokutsu, 1994; Okushima and Goto, 2001). The MCDA methodology essentially could be applied to a more delicate production structure, for example, where elasticities are different in each sector and

between inputs, or employ a more complicated production function. In the paper, a sensitivity analysis with regard to the substitution elasticities is included in the appendix so as to look into this assumption.

[*Insert Fig. 1 here*]

3. Decomposing the change in energy use

This section applies the methodology to the Japanese economy to decompose the changes in energy use during 1970-1995. The period includes two oil crises: the first in 1973 and the second in 1979. It is generally recognized that skyrocketing oil prices greatly influenced the Japanese economy during this time and structural changes have had an important impact on manufacturing energy use (IEA, 2004). However, economic structure is known to be influenced by a multitude of factors other than price change. This situation then offers a typical context upon which to apply our methodology, which can specifically evaluate how much the Japanese economy was influenced by the price substitution or technological change.

This paper focuses on the analysis of energy as has been explained in section 1. [4] In the beginning, it gives an outline for the circumstances of Japan's energy use in advance of the result of the MCDA. Fig. 2 indicates the primary energy supply and final energy consumption in 1970-1995. Energy consumption in Japan has been a consistent rising trend in volume, still the rate of growth in the early 1980s, i.e., after the two oil crises, is lower than in other periods. It is said that Japan accomplished energy conservation and substitution from oil through the lessons of the oil crises. Evidently, the share of oil has declined on both primary supply and final consumption after the oil crises meanwhile those of gas and electricity have increased mainly due to use of natural gas and nuclear

power. The primary supply of coal such as power generation is gradually increasing while the final consumption of coal remains almost at the same level and the share of coal in the final consumption is declining.

Next, this paper analyzes the change in energy use in the Japanese economy with the MCDA methodology. Data from 1970 to 1995 are used in the analysis. Nominal outputs (factor inputs) are obtained from the 1970-75-80 and 1985-90-95 Linked Input-Output Tables (Management and Coordination Agency). Real outputs (factor inputs) are obtained by deflating the nominal values by the corresponding prices. Prices of goods and services are from the Domestic Wholesale Price Index (Bank of Japan) or Deflators on Outputs of National Accounts (Economic Planning Agency). Capital and labor prices are estimated following Ito and Murota (1984). In the MCDA, these prices are normalized such that the prices in the initial period are at unity. This units convention, originally proposed by Harberger (1962) and widely adopted since (Shoven and Whalley, 1984, 1992; Dawkins et al., 2001), permits the analysis of consistent units across time. The sectors are classified into five industries and four energy inputs as in Fig. 1. The elasticities of substitution are assumed, for the purposes of simplicity, to be $\sigma = 0$ and $\sigma_E, \sigma_M = 1$; nevertheless, these estimates are not so different from those in the previous literature that econometrically estimates these elasticities for the Japanese economy (e.g., Tokutsu, 1994; Okushima and Goto, 2001).[5]

Table 1 shows the decomposition of the changes in energy inputs in the Japanese economy. The sectors are classified into five industries and four energy inputs (see the notes accompanying Table 1 for more details). In relation to the final energy consumption in Fig. 2, changes in factor inputs (CFIs) for coal and oil are mainly negative while those for gas and electricity are positive in most cases. CFIs should be produced by substitution effects due to price changes or other effects such as technological change.

The MCDA methodology can divide the CFIs in Table 1 into technological change (TC) and price substitution (PS), as explained in section 2. The PSs for oil are negative in all sectors during the 1970s. This means that the rise in oil prices decreased the factor inputs of oil. On the other hand, the TCs for oil in EII and OMF are positive. This is theoretically explained by the fact that the price substitution effects were expected to induce a larger decrease in the factor inputs of oil whereas they did not decrease to the extent that was expected from these effects in these sectors. Meanwhile, the TCs for oil in the other sectors, i.e., AGM, MAC, and SER are all negative. This implies the opposite; that is, the CFIs for these had decreased more than the extent that was expected from the price substitution.

The PSs for oil turn positive after the 1980s, reflecting the fall in the price of oil. By contrast, the TCs for oil are negative in all sectors. This indicates that oil-diminishing technological change had occurred in the Japanese economy after the 1980s. This would reflect various technological innovations taken place in these days, such as the continuous casting or waste heat recovery in the iron and steel industry, and waste heat recovery equipment of plants in the chemical industry (see, e.g., MITI, 1985).[6]

The PSs for coal are positive in the 1970s while both CFIs and TCs for coal are mainly negative, regardless of the period or industry. This implies that coal-diminishing technological change has continued after the 1970s. There may be some kinds of alternation or innovation in that period as the backgrounds. For instance, the rationalization of production process and waste heat recovery such as coke dry quenching in the iron and steel industry, and new suspension preheater kilns in the ceramic industry were developed. However, although the coal-diminishing technological change was expected to induce a larger decrease in the factor inputs of coal they did not decrease to the extent that was expected. The CFIs did not decrease as much as suggested by the TCs, possibly because of an offsetting effect whereby coal was demanded as an alternative to

oil, especially during the 1970s. Hence, the PSs for coal make a good contrast with those for oil.

For gas, the CFIs and PSs are positive in most cases. The industries had continuously expanded the use of gas, which has a price advantage, after the oil crises, as also inferred from Fig. 2. Moreover, the CFIs for gas in 1990-1995 are positive in all sectors even when the corresponding PSs are all negative. This implies that the factor inputs of gas had increased in that period, notwithstanding the disadvantage in relative prices; that is the price substitution from gas to other types of energy. This is because the increase in CFIs for gas that could not be explained by the price substitution had occurred in 1990-1995, then the TCs for gas are largely positive in all sectors.

The trends in electricity depend on the sectors. Interestingly, the CFI and TC in MAC are positive in 1980-85 while those in the other sectors are negative. This reflects the growth in sectors such as the processing assembly and precision machinery industries, which use large amounts of electricity, in the Japanese economy after the second oil crisis. In turn, electricity-augmenting technological change had occurred in AGM and SER, as the CFIs and TCs in those sectors turn positive after 1985. This is evidenced by the well-known electrification of the service industry.

When arranging the result in this section, the PSs for oil are negative in all sectors while those for the other types of energy are mostly positive in the 1970s. On the contrary, in the 1980s, the PSs for oil turn to positive while the PSs for coal change to negative. The MCDA has the advantage of quantitatively capturing such interrelationship caused by price substitution effects, in consistent with the production theory in microeconomics. In addition, the TCs for oil are largely negative from the 1980s; this means that oil-diminishing technological change had mainly occurred in the 1980s rather than in the 1970s. The TCs for coal are mostly negative over the periods, and those for gas are substantially positive in recent years. These results show that technological change is

important for the change in energy use. Another strength of the MCDA is that it can evaluate such technological change in types of energy, sectors, or periods, respectively.

[*Insert Fig. 2 here*]

[*Insert Table 1 here*]

4. Decomposing the change in CO₂ emissions

4.1 Methodology

This section decomposes the change in carbon dioxide (CO_2) emissions in the Japanese economy during the period 1970-1995. This analysis would be regarded as an extension of Structural Decomposition Analysis (SDA) in the meaning that it deals with the decomposition of both a factor input matrix (input coefficient matrix) and a final demand vector (Rose and Casler, 1996; Rose, 1999; Hoekstra and van den Bergh, 2002; Hoekstra, 2005). One of the advantages is that it can allow the evaluation in volume considering both direct and indirect effects.[7] This paper practices the decomposition of a factor input matrix (input coefficient matrix) based on the MCDA methodology, by utilizing the results of the analysis in section 3. From a historical point of view, many applications of SDA have been used in environmentally relevant physical flows (see, Hoekstra and van den Bergh, 2002; Hoekstra, 2005). For Japan, while there are some studies on energy intensity or energy use (e.g., Han and Lakshmanan, 1994; Kagawa and Inamura, 2001), little SDA literature has been in the context of CO_2 emissions.[8] Furthermore, there are no studies concerning the decomposition analysis for the Japanese economy using the full-fledged KLEM model that includes all factor inputs (capital, labor, energy, and material). The KLEM model gives a circumstantial account of the interdependent relationship in the economy.

The formulation of the analysis is based on Casler and Rose (1998). CO_2 emissions are expressed as:

$$\mathbf{\Pi}_{TOT} = \mathbf{C}\left(\mathbf{I} - \mathbf{A}\right)^{-1}\mathbf{Y}, \tag{11}$$

where $\mathbf{\Pi}_{TOT}$ is the CO_2 emission vector [carbon metric tons; t-C], $\mathbf{C}$ is the CO_2 emission coefficient matrix [t-C/Yen], $\mathbf{I}$ is an identity matrix, $\mathbf{A}$ is the factor input matrix (input coefficient matrix), $(\mathbf{I}-\mathbf{A})^{-1}(\equiv \overline{\overline{\mathbf{\Pi}}})$ is the Leontief inverse matrix, and $\mathbf{Y}$ is the final demand vector. The emission intensity matrix is defined as $\mathbf{\Pi} \equiv \mathbf{C}(\mathbf{I}-\mathbf{A})^{-1}$.

The change in CO_2 emissions over periods is given by:

$$\Delta\mathbf{\Pi}_{TOT} = \Delta\mathbf{\Pi}\mathbf{Y} + \mathbf{\Pi}\Delta\mathbf{Y} + \varepsilon, \tag{12}$$

where Δ is the derivative between periods and ε is an interaction term. Each source of the change represents a comparative static result, while controlling the other factors constant. From Equation (12), the change in CO_2 emissions is decomposed into three major components: a Leontief inverse effect (KLEM effects) due to changes in the factor input matrix (input coefficient matrix), a final demand effect attributable to changes in a final demand vector, and an interaction effect (see, e.g., Casler and Rose, 1998; Hoekstra and van den Bergh, 2002; Hoekstra, 2005).

The Leontief inverse effect is further subdivided into the various types of KLEM effects. The change in emission intensity matrix can be approximately written as $\Delta\mathbf{\Pi} \cong \mathbf{\Pi}^{t-1}\Delta\mathbf{A}\overline{\overline{\mathbf{\Pi}}}^{t-1}$ (see, Casler and Rose, 1998; Rose, 1999); hence the change in CO_2 emissions due to the KLEM effects is given by:

$$\Delta\mathbf{\Pi}_{TOT,KLEM} \cong \left(\mathbf{\Pi}^{t-1}\Delta\mathbf{A}\overline{\overline{\mathbf{\Pi}}}^{t-1}\right)\mathbf{Y}. \tag{13}$$

The MCDA can divide the change in the factor input matrix (the ijth element is $a_{ij}^{t} - a_{ij}^{t-1}$) into the matrices reflecting the various effects by extending the individual elements obtained from the result in section 3 into the corresponding matrices with zeros elsewhere:

$$\Delta \mathbf{A} = \Delta \mathbf{A}_K^{TC} + \Delta \mathbf{A}_K^{PS} + \Delta \mathbf{A}_L^{TC} + \Delta \mathbf{A}_L^{PS} + \Delta \mathbf{A}_E^{TC} + \Delta \mathbf{A}_E^{PS} + \Delta \mathbf{A}_M^{TC} + \Delta \mathbf{A}_M^{PS}, \qquad (14)$$

where $\Delta \mathbf{A}_I^{TC}$ ($I = K$, L, E, M) represents the technological change (TC), and $\Delta \mathbf{A}_I^{PS}$ ($I = K$, L, E, M) does the price substitution (PS), as has been explained in the previous section. Here, $\Delta \mathbf{A}_K^{PS}$ and $\Delta \mathbf{A}_L^{PS}$ no exist because the elasticity of substitution in the top tier is zero. The KLEM effects for the change in CO_2 emissions are given by inserting Equation (14) into Equation (13), and decomposed into the effects derived from price substitution and technological change.

In addition, Equation (15) decomposes the changes in a final demand vector into its 'level' and 'mix' components:

$$\Delta \mathbf{Y} = \left(\mathbf{Y}^t - \mathbf{Y}^t \frac{\sum_i \mathbf{Y}_i^{t-1}}{\sum_i \mathbf{Y}_i^t} \right) + \left(\mathbf{Y}^t \frac{\sum_i \mathbf{Y}_i^{t-1}}{\sum_i \mathbf{Y}_i^t} - \mathbf{Y}^{t-1} \right). \qquad (15)$$

The first term of the right side of the equation is referred to as the final demand level effect, which represents the effect of total level change in final demand. The second term is referred to as the final demand mix effect, which represents the effect of changes in the mix of final demand while controlling the total level of final demand.

4.2   Empirical results

Japan is the fourth largest CO_2 emitting country in the world, after the United States, China, and Russia. Fig. 3 depicts that CO_2 emissions in the Japanese economy, obtained by multiplying the energy consumption by their respective emission coefficients (IEA, 1999), increased in total by 119 [millions of carbon metric tons; Mt-C] (204 to 323[Mt-C]): a 58% increase between 1970 and 1995.

The data sources and classifications in this section are the same as earlier. The CO_2 emission is calculated by multiplying the CO_2 emission coefficient matrix by the standard monetary I-O transactions. The energy inputs that lead to CO_2 emissions are coal, oil, and gas while the use of electricity does not directly generate CO_2. Following Rose and Chen (1991), a Leontief inverse closed with respect to capital and labor is used for the decomposition of a Leontief inverse effect (KLEM effects) while a regular open inverse and a full final demand vector are used for the decomposition of a final demand effect. This is because the part related to input coefficients and that related to final demand are separable (see, Rose and Chen, 1991, p.9; Rose and Casler, 1996, p.49).

Table 2 shows the decomposition of the changes in CO_2 emissions between 1970 and 1995. In each column, the sum of the entries equals to the total, excluding minor rounding errors. As for a final demand effect, the final demand level effect is the major contributor to the increase in CO_2 emissions. It represents the expansion of the economy. This result is usually observed in the continuously growing economy, and is consistent with the results of empirical studies on energy use in the Japanese economy (e.g., Kagawa and Inamura, 2001).[9] Furthermore, the final demand mix effect has a positive impact on the increase in the period. This indicates that the change in the mix of final demand also contributes to the increase. As a result, the final demand effect is the primary cause of the increase in CO_2 emissions in Japan during 1970-1995.

Next, some of the KLEM effects serve as negative sources to the increase in emissions. In particular, the negative contribution of the labor TC stands out. This is due to the increase in labor productivity. On the contrary, the capital TC contributes substantially to the increase in CO_2 emissions. This reflects the continuously increasing trend in capital intensity in the Japanese economy. These results can be inferred by other empirical results on structural change in the Japanese economy (see, e.g., Tokutsu, 1998). With

regard to materials, the PSs and TCs for all types of energy have positive effects on emissions during the period.

As seen in Table 2, the energy PS for oil is negative while those for coal and gas are positive. This reflects the price substitution from oil to the other types of energy following the oil crises. Notably, the influence on CO_2 emissions stemming from the price substitution effect is mutually canceled out. Accordingly, as in Table 2, the energy PSs have positive influence on the emissions overall. The MCDA enables to produce this kind of information by considering the interrelationship between inputs that is caused by the price substitution effect.

The energy TCs for coal and oil are negative, and the former has the large negative impact on emissions. This is implied by the result in section 3, which shows that the energy TCs for coal are mainly negative regardless of the period or industry, in addition to the fact that coal is the most carbon intensive. In contrast, the energy TC for gas is positive, reflecting that the TCs for gas are largely positive in recent period as seen in section 3. On the whole, the energy TCs contribute to the downward impact on emissions. This analysis shows that the energy TC played a key part in cutting off CO_2 emissions.

This section decomposes the change in CO_2 emissions in Japan between 1970 and 1995. Among the effects, the final demand level effect and capital TC are the major contributors to the emission increase. The energy PS for oil is a negative cause of emissions; however, the negative effect is offset by the corresponding positive effects of the other energy PSs. Consequently, the energy PS is totally a positive contributor to the increase. On the other hand, the labor and energy TCs are the primary negative sources and then mitigate the increase in CO_2 emissions. This result shows that technological change is of much importance in the context of reducing CO_2 emissions.

[*Insert Fig.3 here*]

[*Insert Table 2 here*]

5.   Conclusions

This paper develops a new decomposition methodology, the Multiple Calibration Decomposition Analysis (MCDA). It is an *ex post* decomposition analysis of structural change between periods, enabling the distinction between price substitution and technological change to be made for each sector in consistent with the production theory. The MCDA serves as an elementary but powerful tool for empirical studies. In the paper, the approach is applied to the evaluation of changes in energy use and carbon dioxide (CO_2) emissions in the Japanese economy since the 1970s.

The empirical result in section 3 sheds light on how the factor inputs of energy were affected by relative price change between energy inputs or technological change through the experience of the two oil crises. It shows that the price substitution from oil to the other types of energy had occurred in the 1970s; on the contrary, the opposite had in the 1980s. In spite of such an adverse effect, the factor inputs of oil had fallen off in all sectors in the 1980s. It is because that oil-diminishing technological change had occurred, primarily in the 1980s. As for coal, technological change has continuously been a diminishing source on the factor inputs. The factor inputs of gas a lot increased in 1990-1995 despite the negative price substitution effect in all sectors; gas-augmenting technological change had taken place in that period. Thus, the analysis by the MCDA depicts that technological change played a significant role for change in energy use in Japan.

Section 4 decomposes the change in CO_2 emissions in the Japanese economy during 1970-1995 using the result in section 3. The CO_2 emissions from energy use in Japan

increased by 58% in that period. The analysis shows that the final demand level effect, which reflects the expansion of the economy, is the primary cause to the increase in CO_2 emissions. This indicates that economic growth is an overwhelming driver behind the CO_2 emission hike. On the other hand, technological change for labor or energy mitigates such increase. As for price substitution effects, energy PS for oil is a negative contributor to the emission increase, which reflects the price substitution from oil to the other types of energy after the oil crises; nevertheless, the overall influence ascribed to energy PS had increased the CO_2 emissions. This is because the negative effect of oil is offset by the corresponding positive price substitution effects of the other types of energy, namely, coal and gas. The results show that technological change, rather than price substitution, mitigated the increase in CO_2 emissions in Japan. In that context, technological change is essential for reducing CO_2 emissions.

Before closing, it is necessary to make clear the assumptions upon which our methodology depends. The first is that the MCDA assumes that the economy is in equilibrium in each period. The MCDA compares two periods of the economy as two equilibria, although the economy is, in fact, constantly changing. Many researchers suggest that this assumption should be regarded as a weakness prevailing in economic methods. However, as Hicks (1963) argues, the error resulting from this assumption will generally be within some permissible range, if the two periods compared are separated by a substantial time span.

The second is that the MCDA has defects similar to applied general equilibrium analysis. That is, it employs a deterministic procedure and the reliability of empirical results depends on the empirical validity of elasticity parameters. [10] Despite the importance of elasticity parameters, there are still few estimates of elasticities in the literature (see, e.g., Shoven and Whalley, 1984, 1992). The method could be more fruitful if used complementarily with econometric methods.

Acknowledgements

Appendix A. Sensitivity analysis

The reliability of the results in this paper depends on the validity of elasticity parameters as previously mentioned. The elasticities of substitution are generally pivotal parameters for general equilibrium analysis, although such exogenous parameter values are ineluctably subject to uncertainties (see, e.g., Dawkins et al., 2001). To shed light upon this issue, this appendix undertakes a sensitivity analysis to evaluate the influence of the substitution parameter values on the results in the paper. In the analysis, the values of substitution elasticities are varied from those in the reference case—the very results of this paper illustrated by Table 1 and Table 2.

To start with, the appendix addresses the sensitivity of the result in section 3 to the substitution parameters. Section 3 decomposes the changes in factor/energy inputs (CFI) into price substitution (PS) and technological change (TC). This analysis is well qualified as a first step in understanding how the change in substitution elasticity affects the decomposition results.

The following tables show the relationship between the substitution parameter for energy (σ_E) and the decomposed result in section 3. Table A.1, Table A.2, and Table A.3 illustrate the results when σ_E is set to 1.0, 0.7, and 1.3, respectively. Table A.1 shows the reference case: the same as in Table 1.

These tables demonstrate the PS variation with the change in substitution parameters. The more the substitution elasticity increases, the more PSs explain. This indicates that the values of PSs and TCs vary in response to the change in the substitution parameters while their signs are almost identical in these cases. As the definition suggests, the directions of PSs are decided by the relative price changes and are independent of the substitution parameters. Therefore, the signs of PSs are identical in all tables.

On the other hand, TCs are determined in conjunction with both CFIs and PSs. The change in substitution elasticities alters the volumes of PSs, which have a ripple effect on the values of TCs. Hence, TCs are sensitive to the substitution parameter values rather than PSs in terms of the sign. Nonetheless, the result shows the robustness of the TC signs in the simulation. The analysis shows that the decomposed result in section 3 is qualitatively robust with respect to the change in substitution elasticity for energy in the bottom tier.

[*Insert Table A.1 here*]

[*Insert Table A.2 here*]

[*Insert Table A.3 here*]

Next, the appendix implements a more rigorous sensitivity analysis of the decomposed result in section 4. The analysis makes a thorough investigation into the influence of substitution parameter values on the decomposition. We focus here on the results for total CO_2 emissions because the implications are similar for each type of energy. The representative methodologies for evaluating elasticity sensitivity in general equilibrium analysis are the conditional systematic sensitivity analysis (CSSA) and the unconditional systematic sensitivity analysis (USSA) (see, e.g., Dawkins et al., 2001). The CSSA performs a series of simulations in which each elasticity parameter is perturbed holding

the other parameters constant, while the USSA does this for all configurations of the elasticity parameters. This appendix performs a sensitivity analysis in line with these procedures.

There are three types of substitution parameters in Fig. 1, namely, σ_E, σ_M, and σ in the model. First, the influence of the substitution parameter for energy (σ_E) is explored holding the other substitution parameters fixed. This substitution elasticity is considered to be one of the most important parameters in the energy analysis. The analysis fluctuates σ_E by 30% downwards and upwards, that is, in the range from 0.7 to 1.3 with a 0.1 point interval. Fig. A.1 depicts the results for the decomposition of CO_2 emission change. In the following figures, only the KLEM effects are presented because the remaining effects are immutable to the elasticity changes.

Fig. A.1 shows the range of each effect by the sensitivity analysis. The low case (Low) is where σ_E is 0.7, the reference case (Ref.) is where σ_E is 1.0, while the high case (High) is where σ_E is 1.3. The extreme cases correspond to the upper and lower bounds of the results. The figure demonstrates that the decomposed result is almost unaltered with the change in the substitution parameter for energy. As explained, the greater the value of elasticity is, the more PSs account for. Nonetheless, the result is little sensitive to the change in the substitution parameter for energy. A sensitivity analysis with respect to the substitution parameter for material (σ_M) is also performed; the result is insensitive as with σ_E. These analyses prove the robustness of the results with regard to the change in the substitution parameters in the bottom tier.

Then, each and every substitution parameter (σ_E, σ_M, and σ) is under simultaneous fluctuation by examining all configurations in these parameters. Fig. A.2 depicts the range of each effect by the sensitivity analysis. In the result, σ_E and σ_M are perturbed

from 0.7 to 1.3 and σ is from 0 to 0.3 with a 0.1 point interval. The low case (Low) is when $\sigma_E, \sigma_M = 0.7$ and $\sigma = 0$ while the high case (High) is when $\sigma_E, \sigma_M = 1.3$ and $\sigma = 0.3$. These extreme cases almost correspond to the upper and lower bounds of the results.

Fig. A.2 describes more variation than Fig. A.1. It indicates that the decomposition result in this paper is more sensitive to the substitution elasticity in the top tier (σ). The substitution elasticity in the bottom tier, for example σ_E, only affects the substitution within energy inputs, which results in little effect on the aggregated contribution to the change in CO_2 emissions represented by energy TC and PS. In contrast, the substitution elasticity in the top tier σ determines the substitution between aggregates (capital, labor, energy, and material), which ends in a direct and overall impact on the effects. When case σ is fluctuated by holding the elasticities in the bottom tier constant, the result is practically the same.

Fig. A.2 shows that there stands out a price substitution from labor and energy to capital reflecting their relative price changes in the period. As formally examined in Tables A.1-A.3, there is a mechanism such that the increase in substitution elasticities makes the contribution of PSs larger and vice versa. The result exactly shows this relationship, which suggests that the price substitution has much influence on the change in CO_2 emissions in the neighborhood of the high case. In addition, the direction of energy PS changes with the σ increased because the substitution effect between aggregates overweighs that within energy inputs. Nevertheless, it should be emphasized that the signs of the effects, especially those of TCs, are rather stable with plausible changes in substitution elasticities.

The key issue of this appendix is how robust the results in this paper are to the assumption about the substitution parameter values. This sensitivity analysis shows that

most of the results in this paper are qualitatively robust with regard to a plausible amount of elasticity fluctuation, but also that much attention is needed given that there is much uncertainty concerning the substitution parameter σ. The analysis provides a fundamental understanding of the elasticity sensitivity; nevertheless, it could never by itself replace better data, and, as Shoven and Whalley (1984, 1992) says, better elasticity estimates are crucial to the advancement of the field. This appendix exemplifies the appropriateness of this statement.

[*Insert Fig.A.1 here*]

[*Insert Fig.A.2 here*]

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Table 1

Decomposition of the changes in energy inputs in the Japanese economy

Input	Sector	AGM			EII			MAC			OMF			SER		
		CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS
COAL	1970-75	-59.5%	-89.7%	30.2%	29.6%	22.9%	6.7%	-70.1%	-77.6%	7.5%	-43.6%	-50.8%	7.1%	-5.2%	-22.6%	17.4%
	1975-80	-23.6%	-67.4%	43.8%	-31.7%	-54.3%	22.6%	-19.2%	-52.6%	33.4%	-14.1%	-49.1%	35.0%	-0.3%	-36.4%	36.0%
	1980-85	-68.5%	-59.4%	-9.1%	-36.1%	-29.9%	-6.2%	-60.1%	-52.7%	-7.4%	-36.8%	-29.4%	-7.4%	-32.7%	-24.8%	-7.8%
	1985-90	32.2%	57.8%	-25.6%	-25.4%	-6.4%	-19.0%	-3.6%	18.1%	-21.7%	-22.5%	-0.4%	-22.1%	-19.3%	3.9%	–23.2%
	1990-95	-62.7%	-67.4%	4.7%	-41.2%	-48.8%	7.6%	-39.4%	-51.6%	12.2%	-52.8%	-64.3%	11.5%	6.3%	-2.2%	8.5%
OIL	1970-75	-9.2%	-5.2%	-4.0%	0.6%	21.9%	-21.3%	-51.0%	-30.3%	-20.7%	-6.6%	14.4%	-21.0%	-22.0%	-8.5%	–13.4%
	1975-80	-1.5%	-0.5%	-1.1%	-8.2%	7.4%	-15.7%	-36.8%	-28.6%	-8.2%	7.6%	14.8%	-7.1%	-23.2%	-16.8%	–6.4%
	1980-85	-43.2%	-43.6%	0.3%	-23.9%	-27.5%	3.5%	-28.0%	-30.2%	2.2%	-38.8%	-41.0%	2.1%	-15.2%	-16.9%	1.7%
	1985-90	-4.1%	-5.2%	1.1%	-32.0%	-41.9%	9.9%	-41.8%	-48.2%	6.3%	-31.1%	-36.9%	5.8%	-22.9%	-27.2%	4.4%
	1990-95	0.6%	-1.2%	1.8%	-15.2%	-19.9%	4.6%	-19.0%	-28.1%	9.2%	2.1%	-6.3%	8.5%	1.2%	-4.3%	5.5%
GAS	1970-75	14.3%	-33.0%	47.3%	2.8%	-17.9%	20.7%	-36.3%	-57.9%	21.6%	-13.2%	-34.4%	21.2%	49.1%	16.3%	32.8%
	1975-80	30.6%	2.6%	27.9%	34.0%	25.0%	9.0%	-13.4%	-32.0%	18.7%	62.0%	41.9%	20.1%	15.4%	-5.6%	21.0%
	1980-85	-24.7%	-23.8%	-0.9%	-51.0%	-53.3%	2.3%	-42.8%	-43.8%	1.0%	84.7%	83.8%	0.9%	-17.8%	-18.3%	0.5%
	1985-90	-40.2%	-43.6%	3.4%	88.3%	75.8%	12.4%	-41.9%	-50.6%	8.8%	19.0%	10.8%	8.2%	-15.5%	-22.2%	6.7%
	1990-95	23.8%	32.0%	-8.2%	17.5%	23.1%	-5.6%	19.5%	21.1%	-1.6%	35.8%	38.0%	-2.2%	57.2%	62.1%	–4.8%
ELC	1970-75	7.5%	-32.8%	40.3%	12.9%	-2.1%	15.0%	-17.9%	-33.8%	15.9%	20.9%	5.5%	15.5%	21.0%	-5.5%	26.5%
	1975-80	23.3%	12.4%	10.9%	-9.1%	-3.6%	-5.4%	-16.4%	-19.3%	2.9%	19.2%	15.1%	4.1%	1.3%	-3.6%	4.9%
	1980-85	-24.5%	-21.2%	-3.2%	-7.7%	-7.5%	-0.1%	37.0%	38.4%	-1.4%	-6.3%	-4.9%	-1.5%	-2.9%	-1.0%	–1.9%
	1985-90	25.8%	33.0%	-7.2%	0.5%	-0.4%	0.9%	-24.0%	-21.7%	-2.4%	-6.1%	-3.3%	-2.8%	8.3%	12.5%	–4.2%
	1990-95	14.0%	22.6%	-8.6%	-7.8%	-1.8%	-6.0%	-0.3%	1.7%	-1.9%	9.4%	12.0%	-2.6%	7.7%	12.9%	–5.2%

Note: (1) The values are percentage changes.

(2) Classifications are as follows.

AGM: Agriculture, forestry, fishery, and mining; EII: Energy intensive industry (paper and pulp, chemical, ceramics, and iron and steel);

MAC: Machinery; OMF: Other manufacturing; SER: Services and others (including Construction);

COAL: Coal and coal products; OIL: Oil and oil products; GAS: Gas; ELC: Electricity.

Table 2

Decomposition of the changes in CO_2 emissions, 1970-1995 (millions of carbon metric tons)

	COAL	OIL	GAS	TOTAL
KLEM effects				
Capital TC	33.1	83.2	16.4	132.8
Labor TC	-8.6	-23.4	-5.6	-37.5
Energy TC	-17.0	-8.2	9.2	-16.1
Energy PS	3.0	-4.8	4.9	3.1
Material TC	9.3	36.9	7.4	53.5
Material PS	6.8	9.9	2.4	19.0
Final demand effects				
Final demand level	33.7	87.9	23.6	145.2
Final demand mix	5.9	13.1	2.7	21.7
Interaction effects	-41.1	-128.2	-33.0	-202.4
Total	25.0	66.4	27.9	119.2

Table A.1

Decomposition of the changes in energy inputs in the Japanese economy when $\sigma_E = 1.0$ (reference case)

Input	Sector	AGM			EII			MAC			OMF			SER		
		CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS
COAL	1970-75	-59.5%	-89.7%	30.2%	29.6%	22.9%	6.7%	-70.1%	-77.6%	7.5%	-43.6%	-50.8%	7.1%	-5.2%	-22.6%	17.4%
	1975-80	-23.6%	-67.4%	43.8%	-31.7%	-54.3%	22.6%	-19.2%	-52.6%	33.4%	-14.1%	-49.1%	35.0%	-0.3%	-36.4%	36.0%
	1980-85	-68.5%	-59.4%	-9.1%	-36.1%	-29.9%	-6.2%	-60.1%	-52.7%	-7.4%	-36.8%	-29.4%	-7.4%	-32.7%	-24.8%	-7.8%
	1985-90	32.2%	57.8%	-25.6%	-25.4%	-6.4%	-19.0%	-3.6%	18.1%	-21.7%	-22.5%	-0.4%	-22.1%	-19.3%	3.9%	-23.2%
	1990-95	-62.7%	-67.4%	4.7%	-41.2%	-48.8%	7.6%	-39.4%	-51.6%	12.2%	-52.8%	-64.3%	11.5%	6.3%	-2.2%	8.5%
OIL	1970-75	-9.2%	-5.2%	-4.0%	0.6%	21.9%	-21.3%	-51.0%	-30.3%	-20.7%	-6.6%	14.4%	-21.0%	-22.0%	-8.5%	-13.4%
	1975-80	-1.5%	-0.5%	-1.1%	-8.2%	7.4%	-15.7%	-36.8%	-28.6%	-8.2%	7.6%	14.8%	-7.1%	-23.2%	-16.8%	-6.4%
	1980-85	-43.2%	-43.6%	0.3%	-23.9%	-27.5%	3.5%	-28.0%	-30.2%	2.2%	-38.8%	-41.0%	2.1%	-15.2%	-16.9%	1.7%
	1985-90	-4.1%	-5.2%	1.1%	-32.0%	-41.9%	9.9%	-41.8%	-48.2%	6.3%	-31.1%	-36.9%	5.8%	-22.9%	-27.2%	4.4%
	1990-95	0.6%	-1.2%	1.8%	-15.2%	-19.9%	4.6%	-19.0%	-28.1%	9.2%	2.1%	-6.3%	8.5%	1.2%	-4.3%	5.5%
GAS	1970-75	14.3%	-33.0%	47.3%	2.8%	-17.9%	20.7%	-36.3%	-57.9%	21.6%	-13.2%	-34.4%	21.2%	49.1%	16.3%	32.8%
	1975-80	30.6%	2.6%	27.9%	34.0%	25.0%	9.0%	-13.4%	-32.0%	18.7%	62.0%	41.9%	20.1%	15.4%	-5.6%	21.0%
	1980-85	-24.7%	-23.8%	-0.9%	-51.0%	-53.3%	2.3%	-42.8%	-43.8%	1.0%	84.7%	83.8%	0.9%	-17.8%	-18.3%	0.5%
	1985-90	-40.2%	-43.6%	3.4%	88.3%	75.8%	12.4%	-41.9%	-50.6%	8.8%	19.0%	10.8%	8.2%	-15.5%	-22.2%	6.7%
	1990-95	23.8%	32.0%	-8.2%	17.5%	23.1%	-5.6%	19.5%	21.1%	-1.6%	35.8%	38.0%	-2.2%	57.2%	62.1%	-4.8%
ELC	1970-75	7.5%	-32.8%	40.3%	12.9%	-2.1%	15.0%	-17.9%	-33.8%	15.9%	20.9%	5.5%	15.5%	21.0%	-5.5%	26.5%
	1975-80	23.3%	12.4%	10.9%	-9.1%	-3.6%	-5.4%	-16.4%	-19.3%	2.9%	19.2%	15.1%	4.1%	1.3%	-3.6%	4.9%
	1980-85	-24.5%	-21.2%	-3.2%	-7.7%	-7.5%	-0.1%	37.0%	38.4%	-1.4%	-6.3%	-4.9%	-1.5%	-2.9%	-1.0%	-1.9%
	1985-90	25.8%	33.0%	-7.2%	0.5%	-0.4%	0.9%	-24.0%	-21.7%	-2.4%	-6.1%	-3.3%	-2.8%	8.3%	12.5%	-4.2%
	1990-95	14.0%	22.6%	-8.6%	-7.8%	-1.8%	-6.0%	-0.3%	1.7%	-1.9%	9.4%	12.0%	-2.6%	7.7%	12.9%	-5.2%

Note: Table A.1 is the same as Table 1.

Table A.2

Decomposition of the changes in energy inputs in the Japanese economy when $\sigma_E = 0.7$

Input	Sector	AGM			EII			MAC			OMF			SER		
		CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS
COAL	1970-75	-59.5%	-80.0%	20.5%	29.6%	24.7%	4.9%	-70.1%	-75.7%	5.6%	-43.6%	-48.9%	5.3%	-5.2%	-17.4%	12.3%
	1975-80	-23.6%	-52.5%	29.0%	-31.7%	-47.3%	15.6%	-19.2%	-41.6%	22.4%	-14.1%	-37.5%	23.4%	-0.3%	-24.5%	24.2%
	1980-85	-68.5%	-62.0%	-6.4%	-36.1%	-31.8%	-4.3%	-60.1%	-54.8%	-5.2%	-36.8%	-31.6%	-5.3%	-32.7%	-27.1%	-5.5%
	1985-90	32.2%	50.9%	-18.7%	-25.4%	-11.8%	-13.6%	-3.6%	12.1%	-15.7%	-22.5%	-6.5%	-16.0%	-19.3%	-2.5%	-16.8%
	1990-95	-62.7%	-66.0%	3.3%	-41.2%	-46.5%	5.3%	-39.4%	-47.8%	8.4%	-52.8%	-60.8%	8.0%	6.3%	0.3%	5.9%
OIL	1970-75	-9.2%	-6.6%	-2.7%	0.6%	15.8%	-15.2%	-51.0%	-36.4%	-14.7%	-6.6%	8.3%	-14.9%	-22.0%	-12.7%	-9.3%
	1975-80	-1.5%	-0.8%	-0.7%	-8.2%	2.8%	-11.0%	-36.8%	-31.0%	-5.8%	7.6%	12.6%	-5.0%	-23.2%	-18.8%	-4.4%
	1980-85	-43.2%	-43.5%	0.2%	-23.9%	-26.4%	2.5%	-28.0%	-29.6%	1.5%	-38.8%	-40.3%	1.5%	-15.2%	-16.4%	1.2%
	1985-90	-4.1%	-4.8%	0.8%	-32.0%	-39.0%	7.0%	-41.8%	-46.3%	4.4%	-31.1%	-35.2%	4.1%	-22.9%	-25.9%	3.1%
	1990-95	0.6%	-0.7%	1.3%	-15.2%	-18.5%	3.3%	-19.0%	-25.3%	6.4%	2.1%	-3.7%	5.9%	1.2%	-2.6%	3.9%
GAS	1970-75	14.3%	-17.0%	31.3%	2.8%	-11.6%	14.4%	-36.3%	-51.4%	15.1%	-13.2%	-28.0%	14.8%	49.1%	26.7%	22.4%
	1975-80	30.6%	11.7%	18.8%	34.0%	27.5%	6.5%	-13.4%	-26.2%	12.8%	62.0%	48.2%	13.7%	15.4%	1.0%	14.4%
	1980-85	-24.7%	-24.1%	-0.6%	-51.0%	-52.7%	1.6%	-42.8%	-43.5%	0.7%	84.7%	84.1%	0.6%	-17.8%	-18.1%	0.4%
	1985-90	-40.2%	-42.6%	2.4%	88.3%	79.6%	8.7%	-41.9%	-47.9%	6.1%	19.0%	13.3%	5.7%	-15.5%	-20.2%	4.7%
	1990-95	23.8%	29.6%	-5.8%	17.5%	21.4%	-3.9%	19.5%	20.6%	-1.1%	35.8%	37.3%	-1.5%	57.2%	60.6%	-3.4%
ELC	1970-75	7.5%	-19.4%	26.9%	12.9%	2.3%	10.6%	-17.9%	-29.2%	11.3%	20.9%	10.0%	11.0%	21.0%	2.7%	18.3%
	1975-80	23.3%	15.8%	7.6%	-9.1%	-5.5%	-3.6%	-16.4%	-18.5%	2.1%	19.2%	16.3%	2.9%	1.3%	-2.3%	3.5%
	1980-85	-24.5%	-22.2%	-2.3%	-7.7%	-7.6%	-0.1%	37.0%	38.0%	-1.0%	-6.3%	-5.3%	-1.0%	-2.9%	-1.6%	-1.3%
	1985-90	25.8%	30.9%	-5.1%	0.5%	-0.3%	0.8%	-24.0%	-22.4%	-1.6%	-6.1%	-4.1%	-2.0%	8.3%	11.2%	-2.9%
	1990-95	14.0%	20.1%	-6.1%	-7.8%	-3.6%	-4.2%	-0.3%	1.1%	-1.3%	9.4%	11.2%	-1.8%	7.7%	11.4%	-3.7%

Note: Classifications are the same as in Table 1.

Table A.3

Decomposition of the changes in energy inputs in the Japanese economy when $\sigma_E = 1.3$

Input		AGM			EII			MAC			OMF			SER		
	Sector	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS
COAL	1970-75	-59.5%	-100.1%	40.6%	29.6%	21.3%	8.3%	-70.1%	-79.2%	9.1%	-43.6%	-52.3%	8.7%	-5.2%	-27.6%	22.4%
	1975-80	-23.6%	-83.9%	60.3%	-31.7%	-61.4%	29.6%	-19.2%	-64.4%	45.2%	-14.1%	-61.6%	47.5%	-0.3%	-49.2%	48.9%
	1980-85	-68.5%	-56.8%	-11.6%	-36.1%	-28.1%	-8.0%	-60.1%	-50.5%	-9.5%	-36.8%	-27.3%	-9.6%	-32.7%	-22.6%	-10.1%
	1985-90	32.2%	64.1%	-31.9%	-25.4%	-1.2%	-24.2%	-3.6%	23.6%	-27.3%	-22.5%	5.2%	-27.7%	-19.3%	9.8%	-29.1%
	1990-95	-62.7%	-68.8%	6.1%	-41.2%	-51.1%	9.9%	-39.4%	-55.5%	16.2%	-52.8%	-68.0%	15.2%	6.3%	-4.9%	11.1%
OIL	1970-75	-9.2%	-3.8%	-5.4%	0.6%	27.7%	-27.2%	-51.0%	-24.5%	-26.6%	-6.6%	20.3%	-26.9%	-22.0%	-4.3%	-17.7%
	1975-80	-1.5%	-0.1%	-1.4%	-8.2%	12.0%	-20.3%	-36.8%	-26.1%	-10.7%	7.6%	16.9%	-9.3%	-23.2%	-14.8%	-8.4%
	1980-85	-43.2%	-43.7%	0.5%	-23.9%	-28.5%	4.6%	-28.0%	-30.9%	2.9%	-38.8%	-41.6%	2.8%	-15.2%	-17.4%	2.3%
	1985-90	-4.1%	-5.5%	1.4%	-32.0%	-44.8%	12.8%	-41.8%	-50.1%	8.3%	-31.1%	-38.7%	7.6%	-22.9%	-28.5%	5.6%
	1990-95	0.6%	-1.7%	2.3%	-15.2%	-21.2%	6.0%	-19.0%	-31.0%	12.1%	2.1%	-9.0%	11.1%	1.2%	-6.0%	7.2%
GAS	1970-75	14.3%	-50.7%	65.0%	2.8%	-24.3%	27.1%	-36.3%	-64.4%	28.1%	-13.2%	-40.8%	27.6%	49.1%	5.5%	43.6%
	1975-80	30.6%	-7.1%	37.7%	34.0%	22.7%	11.4%	-13.4%	-38.1%	24.7%	62.0%	35.3%	26.7%	15.4%	-12.5%	27.9%
	1980-85	-24.7%	-23.6%	-1.1%	-51.0%	-54.0%	3.0%	-42.8%	-44.0%	1.2%	84.7%	83.5%	1.2%	-17.8%	-18.4%	0.6%
	1985-90	-40.2%	-44.6%	4.4%	88.3%	72.1%	16.2%	-41.9%	-53.4%	11.5%	19.0%	8.2%	10.8%	-15.5%	-24.2%	8.8%
	1990-95	23.8%	34.3%	-10.6%	17.5%	24.8%	-7.3%	19.5%	21.6%	-2.1%	35.8%	38.7%	-2.9%	57.2%	63.5%	-6.3%
ELC	1970-75	7.5%	-47.4%	54.9%	12.9%	-6.4%	19.3%	-17.9%	-38.2%	20.3%	20.9%	1.2%	19.8%	21.0%	-13.8%	34.9%
	1975-80	23.3%	8.9%	14.4%	-9.1%	-1.6%	-7.5%	-16.4%	-20.1%	3.6%	19.2%	13.9%	5.3%	1.3%	-5.0%	6.2%
	1980-85	-24.5%	-20.3%	-4.2%	-7.7%	-7.5%	-0.2%	37.0%	38.8%	-1.8%	-6.3%	-4.4%	-1.9%	-2.9%	-0.5%	-2.4%
	1985-90	25.8%	35.1%	-9.3%	0.5%	-0.4%	1.0%	-24.0%	-20.9%	-3.1%	-6.1%	-2.4%	-3.7%	8.3%	13.8%	-5.5%
	1990-95	14.0%	25.0%	-11.0%	-7.8%	0.0%	-7.8%	-0.3%	2.3%	-2.6%	9.4%	12.8%	-3.4%	7.7%	14.5%	-6.8%

Note: Classifications are the same as in Table 1.
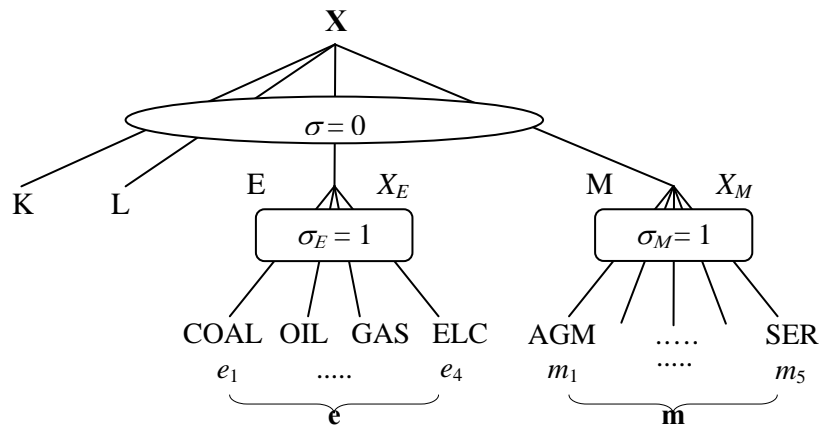
Fig. 1. The model.

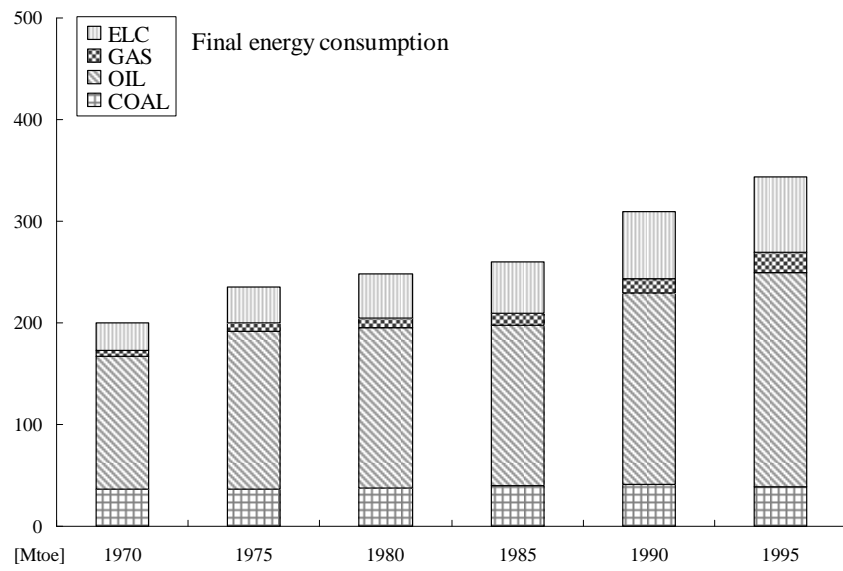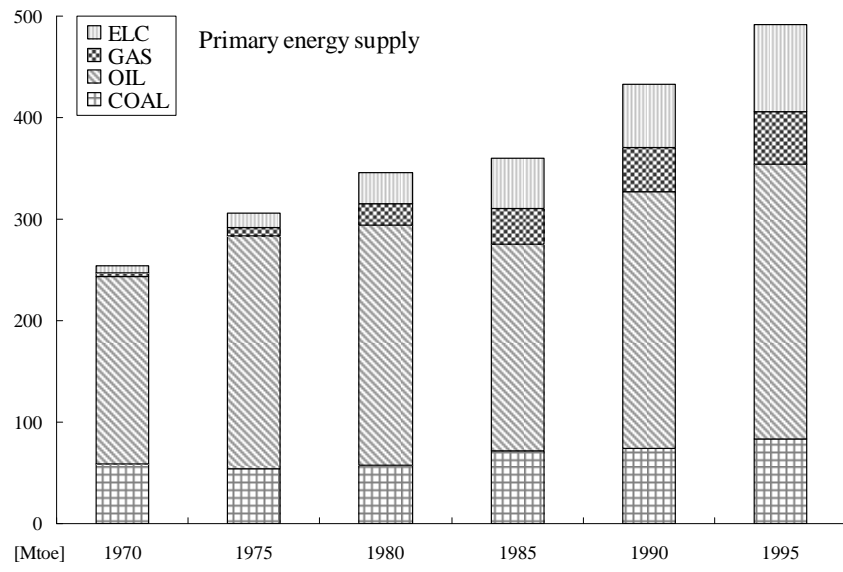**Fig. 2. Primary energy supply and final energy consumption in Japan, 1970-1995.**
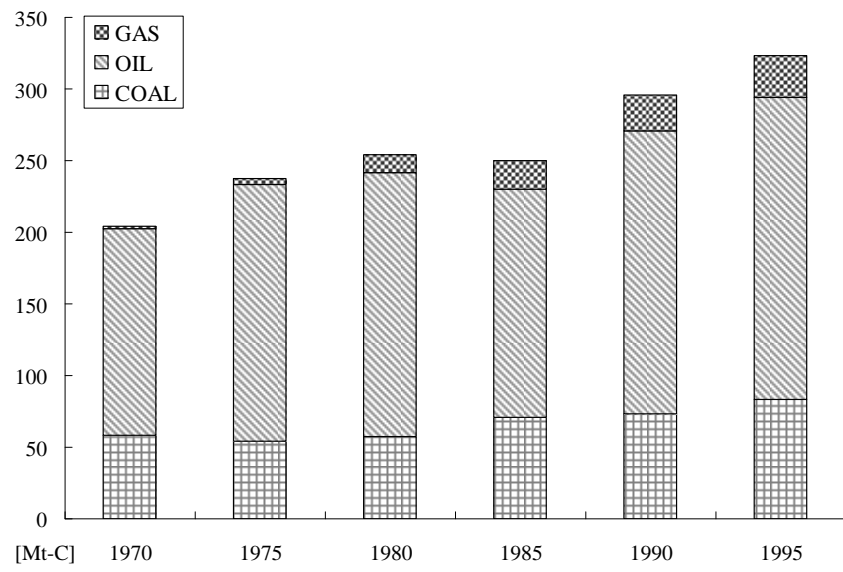
Source: IEA (1999)

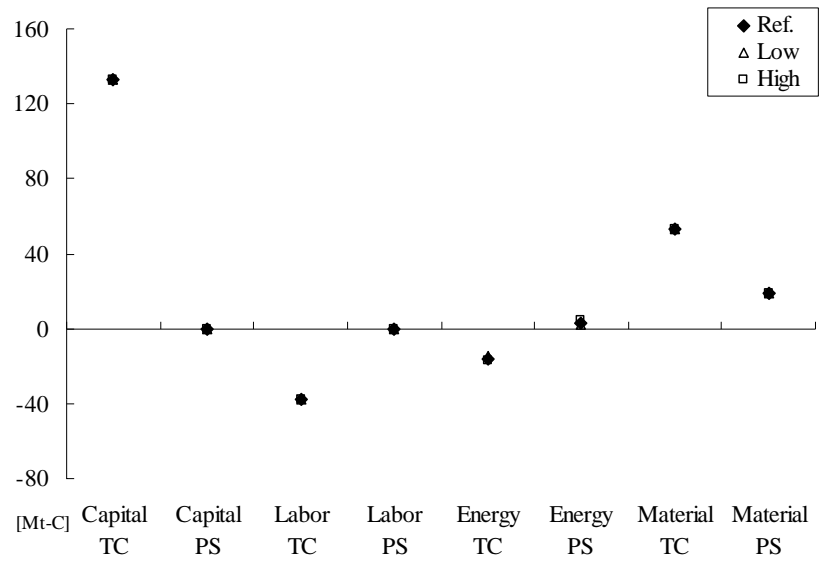**Fig. 3. CO$_2$ emissions in Japan, 1970-1995.**

Fig.A.1. Decomposition of the change in CO$_2$ emissions 1970-1995 when varying the substitution parameter for energy.
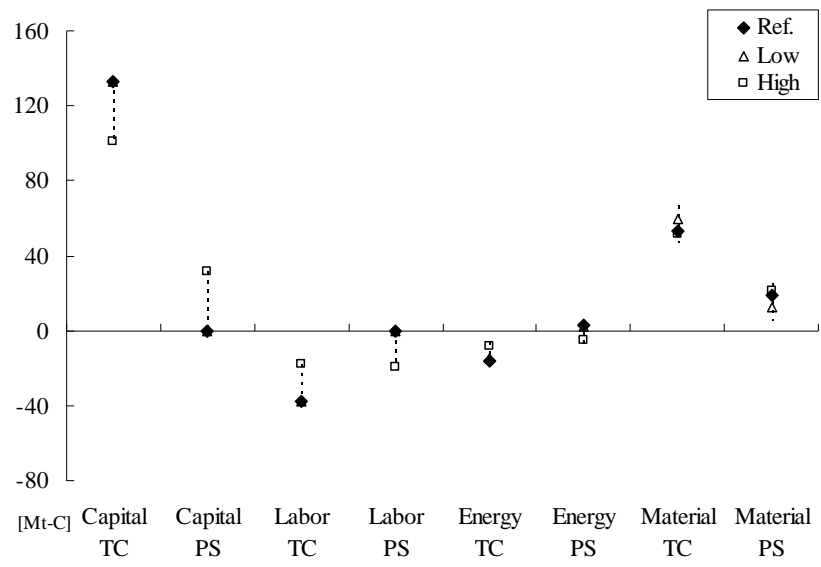

Fig.A.2. Decomposition of the change in CO$_2$ emissions 1970-1995 when varying all substitution parameters.

X

$\sigma = 0$

K L

E X_E

$\sigma_E = 1$

M X_M

$\sigma_M = 1$

COAL OIL GAS ELC

AGM ..... SER

e_1 ..... e_4

m_1 ..... m_5

e **m**

Primary energy supply

500

400

300

200

100

0

[Mtoe]   1970   1975   1980   1985   1990   1995

ELC
GAS
OIL
COAL

Final energy consumption

500

400

300

200

100

0

[Mtoe]   1970   1975   1980   1985   1990   1995

ELC
GAS
OIL
COAL

Section 1

[1] For more information on the calibration technique, see Mansur and Whalley (1984), Shoven and Whalley (1984, 1992), and Dawkins et al. (2001). Only a few studies are known to incorporate the multiple calibration technique: Piggott and Whalley (2001) analyzes the effects of Canadian tax reform and Abrego and Whalley (2005) decomposes the wage inequality change in the UK. However, to the authors' best knowledge, no studies have attempted to apply the multiple calibration technique to the decomposition of structural change as in the present paper.

Section 2

[2] Equation (8) can be rewritten in another way as:

$$\Delta\mathbf{A} = \left\{ f(\mathbf{p}^{t}, \boldsymbol{\lambda}^{t}) - f(\mathbf{p}^{t}, \boldsymbol{\lambda}^{t-1}) \right\} + \left\{ (f(\mathbf{p}^{t}, \boldsymbol{\lambda}^{t-1}) - f(\mathbf{p}^{t-1}, \boldsymbol{\lambda}^{t-1})) \right\}$$

$$\Leftrightarrow \mathrm{CFI} = \mathrm{TC} + \mathrm{PS},$$

where $\Delta\mathbf{A} = \left(\Delta a_{ij} \right)$ is the CFI, Δa_{ij} is the element of $\Delta\mathbf{A}$, $f(.)$ is the underlying model (the CES production functions), $\mathbf{p}$ is prices, and $\boldsymbol{\lambda}$ is the TC parameters. The decomposition is additive and uses both initial and terminal period weights.

This decomposition form is simple, exact, and microtheoretically meaningful. Nonetheless, various splitting procedures are possible. For instance, this paper uses the additive decomposition form while the MCDA itself can perform both additive and multiplicative splitting. In fact, Okushima and Tamura (2006) employs a multiplicative decomposition. The choice of decomposition scheme depends on the research objective. For more information on this topic, see, e.g., Dietzenbacher and Los (1998), Ang and Zhang (2000), Hoekstra and van den Bergh (2003), and Hoekstra (2005).

[3] With regard to terminology, Carter (1970, p.10) mentions the same distinction between 'substitution' and 'technological change', namely, between 'choice within the context of a given production function' and 'changes in production function itself'.

Section 3

[4] The results other than energy inputs are upon request.

[5] Also see the last paragraph in section 2.

[6] It is noteworthy that some of these technologies would reduce not only the use of oil but also those of the other types of energy (especially, coal).

Section 4

[7] Another decomposition technique is Index Number Analysis (INA) or Index Decomposition (ID). Although ID requires less data than SDA, it cannot distinguish direct effects from indirect effects. See Ang and Zhang (2000), Hoekstra and van den Bergh (2003), and Hoekstra (2005) for more detail.

[8] One of the exceptions known is Chung (1998).

[9] If one wants to avoid the level effect of final demand or the effect of economic growth that does not cause any structural changes, see Skolka (1989), which suggests a method for removing it.

Section 5

[10] The appendix evaluates the elasticity sensitivity.