Department of Social Systems and Management

Discussion Paper Series

No.1216

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Multiple Calibration Decomposition Analysis and Structural Decomposition Analysis

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September 2008

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JAPAN

How Can We Gauge the Sources of Energy Use Change?

Multiple Calibration Decomposition Analysis and Structural Decomposition Analysis

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Abstract. Decomposition methodologies are requisite to gauge the sources of changes in energy use or carbon dioxide emissions. This paper is intended as an inquiry into the theoretical properties of such decomposition methodologies. The paper first presents our new decomposition methodology -the Multiple Calibration Decomposition Analysis (MCDA)- as a tool for the investigation. Then, the paper theoretically reexamines an established decomposition method -Structural Decomposition Analysis proposed by Casler and Rose (Environmental and Resource Economics 11(3-4): 349-363). Subsequently, the paper empirically investigates the properties of both methodologies, applying them to an actual case: the changes in energy use and carbon dioxide emissions in Japan during the oil crises period, when the oil price had a significant influence on the economy. The result shows that understanding the theoretical properties of decomposition methodologies is essential for a precise interpretation of empirical results.

Keywords: calibration, carbon dioxide emissions, decomposition, energy use, structural decomposition analysis

JEL classification: C67, D57, D58, Q40, Q50

1. Introduction

What are the sources of energy use change in the economy? The oil crises in the 1970s have given much 'energy' to the conduct of energy demand analyses. Since then, a large amount of research has been conducted on energy demand, including seminal works by Hudson and Jorgenson (1974), Berndt and Wood (1975), Manne (1976), Borges and Goulder (1984), and Solow (1987). A recent rise in oil prices, as well as the problem of climate change, is driving new interest in such analyses, as shown by studies by Dowlatabadi and Oravetz (2006), Metcalf (2008), and Sue Wing (2008).

Economic analyses such as these often focus on price changes, which lead to price substitution effects influencing the overall economy. This approach is justified by the thought that the energy price escalation could largely explain the structural change of the economy in that era; in fact, it has dramatically changed the energy use pattern over the past decades.

On the other hand, it is clear that changes in patterns of energy use are caused by a multitude of factors, including autonomous technological development. Determining the importance of the various factors on energy use change is a troublesome but necessary task.

Consequently, decomposition methodologies are required to assess the contribution of these various explanatory factors to the structural change of the economy or changes in energy use. In this context, it is quite natural that many types of decomposition methodologies have been proposed to disentangle and quantify the impacts of such causal factors.

In terms of energy analysis, Structural Decomposition Analysis (hereafter, SDA) has developed into a major tool for undertaking such decomposition analyses (see Rose and Casler 1996; Rose 1999; Hoekstra and van den Bergh 2002; Hoekstra 2005). Rose (1999) notes that there have been more than fifty SDA studies over the past decade and more than half of them have been applied to energy issues. Although we could trace the antecedents of SDA back to Leontief (1941), Carter (1970), and Leontief and Ford (1972), it is entirely fair to say that important works such as Skolka (1989), Rose and Miernyk (1989), and Rose and Chen (1991) developed the idea and formally established the methodology. The SDA methodology surmounts the static features of input-output (I-O) analysis and enables us to examine structural changes between periods.

Notably, the pioneering study by Rose and Chen (1991) -a decomposition analysis of energy use change in the United States, 1972-1982- and a follow-on study by Casler and Rose (1998) -a decomposition analysis of carbon dioxide (CO_2) emission change in the United States, 1972-1982- addressed the properties of SDA with the intention of comparing it with microeconomic production theory, and constructed one of the most sophisticated SDA models (hereafter, the CRSDA), which is an extended version of SDA, equivalent to the two-tier KLEM model. The KLEM model that includes all inputs (capital, K; labor, L; energy, E; and materials, M) has been widely used within the neoclassical approach since Hudson and Jorgenson (1974). Hudson and Jorgenson (1974) econometrically estimates the KLEM model and demonstrates how the input coefficients change in relation to price changes. Although many accept that their approach is well suited to the analysis of price substitution effects in response to relative price changes, attempts to estimate the KLEM model econometrically often suffer from data insufficiency. By contrast, as Casler and Rose (1998) stresses, the SDA requires only a two-period dataset and can analyze at the same level of detail. Its extensive use provides clear confirmation of the contribution of SDA to the decomposition analysis in the fields of energy and environmental issues.

However, problems arise in the SDA methodology. Most importantly, the contribution assigned to each component is not clearly interpretable in all cases. Conceptual ambiguity hinders the precise interpretation given to factors in the empirical studies. Rose and Casler (1996) points out that this is because SDA has a limited robust grounding in economic theory, and also comments (p. 34), "most important is the need for conceptual work on the theoretical foundation of SDA. This is important in its own right and to facilitate comparisons with more conventional neoclassical approaches."

Given this context, two motives have combined to make us write this paper. The first one is to present our methodology for decomposing structural change of the economy in a multisector general equilibrium framework, namely the Multiple Calibration Decomposition Analysis (MCDA), proposed by Okushima and Tamura (2007). The MCDA methodology applies multiple calibration technique to a decomposition analysis of structural change between periods, enabling a theoretically rigorous distinction to be made between price substitution and technological changes for each sector.[1] The second purpose of this paper is to reconsider the SDA methodology, especially the most theoretically motivated version of SDA, the CRSDA by Casler and Rose (1998), in the MCDA framework. Here, the MCDA is used as a beneficial tool for the investigation of its theoretical properties. Then, this paper compares both methodologies theoretically and empirically, and attempts to provide deeper insights into them. The analysis points out that a detailed understanding of the theoretical properties is a prerequisite for accurate interpretation of decomposition results.

The remainder of the paper is organized as follows. Section 2 presents our MCDA methodology and then reexamines the CRSDA in the MCDA framework. Section 3 practically applies these two methodologies to an empirical case, the energy use change in the Japanese economy from 1970 to 1990, and discusses their results theoretically and empirically. Section 4 applies the two methodologies to the causal factors behind increasing carbon dioxide emissions in Japan. The final section provides concluding remarks.

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[1] See Mansur and Whalley (1984), Shoven and Whalley (1984, 1992), Dawkins et al. (2001), and Okushima and Tamura (2008) for more information on the calibration technique. Only a few studies are known to utilize the multiple calibration technique.

2. Decomposition Methodologies

This section explains the theoretical properties of the two methodologies, the Multiple Calibration Decomposition Analysis (MCDA) and Structural Decomposition Analysis (SDA).

Let Ψ represent explained variables and ξ_k (k = 1, 2,…, n) denote a set of explanatory factors. A function $\Phi(.)$ describes the underlying model:

$$\Psi = \Phi(\xi_1, \xi_2, ..., \xi_n) . \tag{1}$$

In general, any types of decomposition methodologies assign a contribution C_k to each explanatory factor ξ_k. In the case of exact decomposition, Ψ in the above equation can be explained as the sum of the contributions C_k. In a decomposition analysis of structural change of the economy, for example, Ψ is the change in factor inputs per unit of output (change in input coefficients) and ξ_k are the causal factors such as price changes.[2]

2.1. *MULTIPLE CALIBRATION DECOMPOSITION ANALYSIS: MCDA*

This section presents a new methodology, the Multiple Calibration Decomposition Analysis (MCDA). The distinguishing feature of the MCDA methodology is that it explicitly defines two-tier CES production functions as the underlying model $\Phi(.)$ in order to separate price substitution effects (hereafter, PS) from other types of technological change (hereafter, TC^{MC}). In this case, Equation (1) is rewritten as:

$$\Delta \mathbf{A} = f(\Delta \mathbf{p}, \Delta \boldsymbol{\lambda}) , \tag{2}$$

where $\Delta \mathbf{A}$ is the change in factor inputs per unit of output (change in input coefficients), $\Delta \mathbf{p}$ is the change in relative prices, $\Delta \boldsymbol{\lambda}$ is the technological change, and $f(.)$ is the underlying model (the two-tier CES production functions). In other words, the MCDA decomposes the structural change of the economy, shown by the change in factor inputs per unit of output between periods, into two parts, one attributable to price substitution and the other attributable to technological change.

The MCDA methodology itself is described as follows. This paper assumes the model structure shown in Fig. 1. The production functions are given by two-tier constant-returns-to-scale CES functions.[3] The model is composed of capital K, labor L, energy aggregate E, and material

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[2] In the paper, as in other literature on this subject, structural change (total change) is defined as the change in factor inputs per unit of output, which is identical to the change in input coefficients in I-O tables. This definition is a purely economic one.

[3] In this paper, the production structure is given by two-tier constant-returns-to-scale CES functions, and the elasticities of substitution are assumed to be constant in all sectors and to be zero or unity between inputs. As described later, this is for the purpose of simplicity, and this production structure resembles the one inferred from the existing literature that econometrically estimates the parameters using historical Japanese data (see, e.g., Okushima and Goto 2001). Essentially, however, the MCDA methodology could be applied to a more delicate production structure, e.g., where elasticities are different in each sector and between inputs, or using more complicated production functions. For some discussion on the sensitivity of substitution elasticity, see Okushima and Tamura (2007).

aggregate *M*, as well as energy and material inputs. 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 of output (hereafter, factor inputs) in the top tier in the initial period $(t-1)$ are derived by Equation (3):

$$A_{Ij}^{t-1} = \frac{X_{I(j)}^{t-1}}{X_j^{t-1}} = \lambda_{Ij}^{t-1} \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^{t-1}}{p_{I(j)}^{t-1}} \right)^{\sigma}, \ I = K, L, E, M \ , \tag{3}$$

where A_{Ij}^{t-1} is the factor input (input coefficient) of *I* per unit of 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$^{\text{MC}}$ parameter in the top tier, as explained below, and is set at unity in $t-1$. In addition, p_j^{t-1} and $p_{I(j)}^{t-1}$ are set at one because they are obtained from the actual price dataset, which is normalized so that the prices in the initial period are at 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 the initial period 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). Then, the production functions in the top tier are 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 (4), which is the same as in Equation (3), owing to the fact that there is no bottom tier for capital *K* and labor *L*:

$$a_{ij}^{t-1} = A_{Ij}^{t-1} = \frac{X_{I(j)}^{t-1}}{X_j^{t-1}} = \lambda_{Ij}^{t-1} \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^{t-1}}{p_{I(j)}^{t-1}} \right)^{\sigma}, \ I = K, L; i = K, L \ . \tag{4}$$

Next, the bottom tier will be illustrated. As in Fig. 1, the energy aggregate *E* and the material aggregate *M* are assumed to be weakly separable. The factor inputs of energy **e** (= {$e_1,\ldots,e_4$}) and material **m** (= {$m_1,\ldots,m_5$}) in the bottom tier in the initial period are given by Equation (5):

$$a_{I(ij)}^{t-1} = \frac{x_{ij}^{t-1}}{X_{I(j)}^{t-1}} = \lambda_{I(ij)}^{t-1} \beta_{I(j)}^{\sigma_I - 1} \left(\alpha_{I(ij)} \frac{p_{I(j)}^{t-1}}{p_i^{t-1}} \right)^{\sigma_I}, \ I = E, M; i = \mathbf{e}, \mathbf{m} \ , \tag{5}$$

where $a_{I(ij)}^{t-1}$ is the factor input (input coefficient) of energy **e** and material **m** per the corresponding aggregate by the sector *j* in $t-1$, x_{ij}^{t-1} is the input of energy **e** and material **m** by the sector *j* in $t-1$, p_i^{t-1} is the price of energy **e** and material **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$^{\text{MC}}$ 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 $\beta_{I(j)}$ of the production functions in the bottom tier are then specified by using the same procedure as in Equation (3) for the top tier. The parameters, $\alpha_{I(ij)}$, $\beta_{I(j)}$, and σ_I, are also assumed to be time invariant.

Hence, the factor inputs of energy **e** and material **m** per unit of output in the initial period are given by Equation (6):

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

Then, let us move on from the initial period ($t-1$) to the terminal period (t). It is remarkable that the MCDA utilizes another period's dataset to specify the TC$^{\text{MC}}$ parameters λ^t. The factor inputs in the terminal period (t) are expressed as:

$$a_{ij}^{t} = \frac{X_{I(j)}^{t}}{X_j^{t}} = \lambda_{Ij}^{t} \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^{t}}{p_{I(j)}^{t}} \right)^{\sigma}, I = K, L; i = K, L, \qquad (7)$$

$$a_{ij}^{t} = \frac{X_{I(j)}^{t}}{X_j^{t}} \cdot \frac{x_{ij}^{t}}{X_{I(j)}^{t}} = \lambda_{Ij}^{t} \beta_j^{\sigma-1} \left(\alpha_{Ij} \frac{p_j^{t}}{p_{I(j)}^{t}} \right)^{\sigma} \cdot \lambda_{I(ij)}^{t} \beta_{I(j)}^{\sigma_I - 1} \left(\alpha_{I(ij)} \frac{p_{I(j)}^{t}}{p_i^{t}} \right)^{\sigma_I}, \qquad (8)$$
$$I = E, M; i = \mathbf{e}, \mathbf{m}.$$

The values of x_{ij}^t, X_j^t, and $p_i^t (= p_j^t)$ are obtained from the dataset as in the initial period. The prices of capital and labor $p_{I(j)}^t$ (I = K, L) are the same as p_i^t (i = K, L), whereas the prices of energy and material aggregates $p_{I(j)}^t$ (I = E, M) in the terminal period are represented by the CES cost functions in the bottom tier of the model:

$$p_{I(j)}^{t} = \frac{1}{\beta_{I(j)}} \left(\sum_i \alpha_{I(ij)}^{\sigma_I} p_i^{t\,1-\sigma_I} \right)^{1/(1-\sigma_I)}, I = E, M; i = \mathbf{e}, \mathbf{m}. \qquad (9)$$

Therefore, the TC$^{\text{MC}}$ parameters $\lambda_{ij}^t (= \lambda_{Ij}^t$ for I = K, L, or $= \lambda_{Ij}^t \cdot \lambda_{I(ij)}^t$ for I = E, M) are endogenously determined to replicate the economic structure in the terminal period as another equilibrium. In other words, λ_{ij}^t 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.

From the above equations, the change in factor inputs (CFI) is decomposed as:

$$\Delta\mathbf{A} = \left\{ f(\mathbf{p}^t, \boldsymbol{\lambda}^t) - f(\mathbf{p}^t, \boldsymbol{\lambda}^{t-1}) \right\} + \left\{ (f(\mathbf{p}^t, \boldsymbol{\lambda}^{t-1}) - f(\mathbf{p}^{t-1}, \boldsymbol{\lambda}^{t-1}) \right\}, \qquad (10)$$

where $\Delta\mathbf{A}$ consists of the elements Δa_{ij}: $\Delta\mathbf{A} = \left(\Delta a_{ij}\right)$. In the MCDA, the contributions to the CFI are assigned to the two explanatory components attributed to the changes in the TC$^{\text{MC}}$ parameters and relative prices.

In other words, the CFI can be decomposed into TC$^{\mathrm{MC}}$ and PS in additive form:[4]

$$a_{ij}^{t} - a_{ij}^{t-1} = \left(a_{ij}^{t} - a_{ij}^{c}\right) + \left(a_{ij}^{c} - a_{ij}^{t-1}\right),\ i = K, L, \mathbf{e}, \mathbf{m}\,,$$

$$\Leftrightarrow \mathrm{CFI} = \mathrm{TC}^{\mathrm{MC}} + \mathrm{PS}\,. \tag{11}$$

a_{ij}^{c} is the counterfactual point, created as follows:

$$a_{ij}^{c} = \lambda_{Ij}^{t-1} \beta_{j}^{\sigma-1} \left(\alpha_{Ij} \frac{p_{j}^{t}}{p_{I(j)}^{t}} \right)^{\sigma},\ I = K, L; i = K, L\,, \tag{12}$$

$$a_{ij}^{c} = \lambda_{Ij}^{t-1} \beta_{j}^{\sigma-1} \left(\alpha_{Ij} \frac{p_{j}^{t}}{p_{I(j)}^{t}} \right)^{\sigma} \cdot \lambda_{I(ij)}^{t-1} \beta_{I(j)}^{\sigma_I - 1} \left(\alpha_{I(ij)} \frac{p_{I(j)}^{t}}{p_{i}^{t}} \right)^{\sigma_I},\ I = E, M; i = \mathbf{e}, \mathbf{m}\,. \tag{13}$$

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 the relative price change between the initial and terminal periods. As shown in Equation (11), the change in factor inputs 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$^{\mathrm{MC}}$. Thus, the MCDA can exactly decompose the CFI into PS and TC$^{\mathrm{MC}}$. 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$^{\mathrm{MC}}$ 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, whereas TC$^{\mathrm{MC}}$ represents shifts in the production function.[5] Thus, the decomposition of the MCDA provided is consistent with production theory in microeconomics. The prominent feature of the methodology is that it has clear theoretical underpinnings, and allows the decomposition components to be interpreted in a theoretically meaningful way.

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[4] This decomposition form is simple, exact, and micro-theoretically meaningful. Nonetheless, various alternative splitting procedures are possible. For instance, this paper uses the additive decomposition form, whereas the MCDA itself can perform both additive and multiplicative splitting. 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).

[5] 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 the production function itself’.

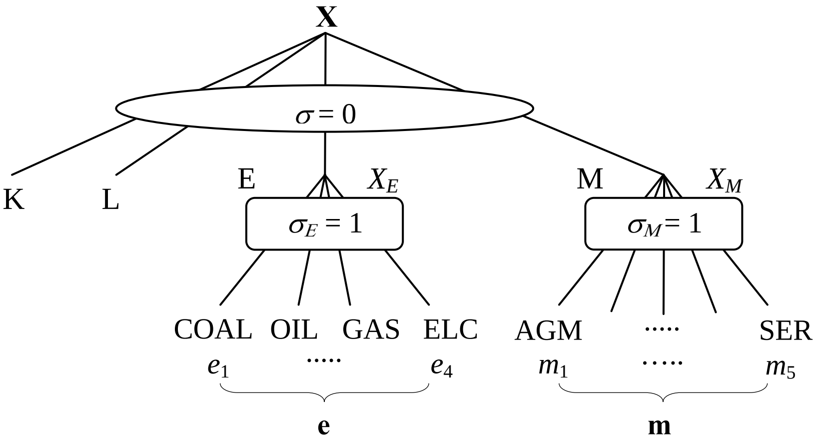

Fig. 1 The model

2.2. STRUCTURAL DECOMPOSITION ANALYSIS: SDA

This section explains Structural Decomposition Analysis (SDA), and attempts to reexamine the SDA methodology in comparison with the MCDA. Skolka (1989) summarizes that the SDA methodology transforms the input-output table for the initial period into the table for the terminal period on a step-by-step basis. There are many SDA studies (see, e.g., Rose and Casler 1996; Rose 1999; Hoekstra and van den Bergh 2002; Hoekstra 2005). However, only a few attempts have been made at examining the theoretical background of SDA. Rose and Chen (1991) and the follow-on study by Casler and Rose (1998) are the epoch-making studies in this respect. They offered an extensive formulation of the SDA equivalent to the two-tier KLEM model for the purpose of comparing SDA with the neoclassical approach. Their studies are innovative and unquestionably serve to strengthen the theoretical properties of SDA. Hence, this paper reconsiders their model as a representative of theoretically motivated SDA approaches and refers to it as the CRSDA in the following.

This paper reexamines the CRSDA in the MCDA framework for comparison purposes. In the context, this section attempts to reformulate the CRSDA from the perspective of the counterfactual points. In a decomposition analysis, whether intentionally or otherwise, the counterfactual points need to be created to separate structural change into some causal components. Therefore, the notation below is different from the original one by Rose and Chen (1991) or Casler and Rose (1998), as it is aligned with the MCDA terminology.

The CRSDA decomposes the change in factor inputs into the effects of substitution and technological change regarding the energy and material aggregates, as well as the effects of substitution and technological change regarding the KLEM aggregates. The components for energy and material differ from those for capital and labor, as there is only one constituent for capital and labor.

In the beginning, the factor inputs of energy **e** and material **m** in the initial and terminal periods are given by Equations (14) and (15):

$$a_{ij}^{t-1} \equiv \frac{x_{ij}^{t-1}}{X_j^{t-1}} = A_{Ij}^{t-1} \frac{x_{ij}^{t-1}}{X_{I(j)}^{t-1}}, I = E, M; i = \mathbf{e}, \mathbf{m}, \tag{14}$$

$$a_{ij}^{t} \equiv \frac{x_{ij}^{t}}{X_j^{t}} = A_{Ij}^{t} \frac{x_{ij}^{t}}{X_{I(j)}^{t}}, I = E, M; i = \mathbf{e}, \mathbf{m}, \tag{15}$$

where a_{ij} is the factor input (input coefficient) of energy **e** and material **m** per unit of output by the sector *j*, x_{ij} is the input of energy **e** and material **m** by the sector *j*, X_j is the output of the sector *j*, $A_{Ij}\left(\equiv X_{I(j)}/X_j, I = E, M\right)$ is the factor input (input coefficient) of energy and material aggregates per unit of output by the sector *j*, and $X_{I(j)}\left(=\sum_i x_{ij}, I = E, M; i = \mathbf{e}, \mathbf{m}\right)$ is the energy and material aggregates. The superscript refers to each period. Owing to the fact that there is no bottom tier for capital and labor, the factor inputs of capital and labor per unit of output are given by $a_{ij}\left(\equiv x_{ij}/X_j, i = K, L\right)$.

This paper attempts to define the counterfactual points in the CRSDA and reconsider the CRSDA's characteristics as a decomposition methodology, with reference to the MCDA framework. In the CRSDA, several ratios counted by the 'unit costs' are essential for decomposition. The unit costs are defined by the column sum of input coefficients for the individual aggregates or KLEM aggregates in each sector. First, $c_{Ij}^{t(t-1)}$ in Equation (16) is the ratio of the sum of the input coefficients for the energy or material aggregate in the initial period to the sum in the terminal period:

$$c_{Ij}^{t(t-1)} \equiv \frac{\sum_i \left(x_{ij}^{t-1}/X_j^{t-1}\right)}{\sum_i \left(x_{ij}^{t}/X_j^{t}\right)} = \frac{X_{I(j)}^{t-1}/X_j^{t-1}}{X_{I(j)}^{t}/X_j^{t}} = \frac{A_{Ij}^{t-1}}{A_{Ij}^{t}}, I = E, M; i = \mathbf{e}, \mathbf{m}. \tag{16}$$

This ratio denotes the unit cost change between periods regarding the bottom tier (for the energy or material aggregate). Second, $c_{KLEMj}^{t(t-1)}$ in Equation (17) is the ratio of the column sum of the input coefficients for KLEM aggregates in the initial period to the sum in the terminal period:

$$c_{KLEMj}^{t(t-1)} \equiv \frac{\sum_i \left(x_{ij}^{t-1}/X_j^{t-1}\right)}{\sum_i \left(x_{ij}^{t}/X_j^{t}\right)} = \frac{A_{KLEMj}^{t-1}}{A_{KLEMj}^{t}}, i = K, L, \mathbf{e}, \mathbf{m}. \tag{17}$$

This ratio denotes the unit cost change between periods regarding the top tier (for the KLEM aggregates). $c_{Ij}^{t(t-1)}$ and $c_{KLEMj}^{t(t-1)}$ are not usually valued at one because the factor inputs in both periods are in real terms.

Now, this paper sets up the counterfactual points of the CRSDA (a_{ij}^{c1} and a_{ij}^{c2}) by using two ratios, as shown in Equations (18) and (19):

$$a_{ij}^{c1} \equiv c_{Ij}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}}, I = E, M; i = \mathbf{e}, \mathbf{m}, \tag{18}$$

$$a_{ij}^{c2} \equiv c_{KLEMj}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}}, i = K, L, \mathbf{e}, \mathbf{m}. \tag{19}$$

a_{ij}^{c1} is the factor input per unit of output (input coefficient) in the terminal period multiplied by the unit cost ratio for the energy or material aggregate, whereas a_{ij}^{c2} is the one multiplied by the unit cost ratio for the KLEM aggregates. This means that the input coefficients in the terminal period are rescaled by the unit cost ratios, $c_{Ij}^{t(t-1)}$ and $c_{KLEMj}^{t(t-1)}$, respectively. These counterfactual points operate as the juncture or separation of the step-by-step transition from the initial to the terminal period.

Thus, the change in factor inputs (CFI) of energy **e** or material **m** is decomposed into three components, as shown in Equation (20):

$$a_{ij}^{t} - a_{ij}^{t-1} = \left(a_{ij}^{t} - a_{ij}^{c2}\right) + \left(a_{ij}^{c2} - a_{ij}^{c1}\right) + \left(a_{ij}^{c1} - a_{ij}^{t-1}\right), i = \mathbf{e}, \mathbf{m}, \tag{20}$$

$$\Leftrightarrow \mathrm{CFI} = \mathrm{TC}^{\mathrm{SD}} + \mathrm{KLEMSUB} + \mathrm{IF[IM]SUB},$$

where the first difference to the right of the equality is defined as the technological change ($\mathrm{TC}^{\mathrm{SD}}$) for energy or material in the CRSDA, and the second one as the KLEM substitution (KLEMSUB), which measures substitution between KLEM aggregates with regard to energy or material. The third one is defined as the interfuel substitution (IFSUB), which measures substitution between energy inputs, or the intermaterial substitution (IMSUB), which measures substitution between material inputs. Rose and Chen (1991) and Casler and Rose (1998) regard technological change in their model as improvement in efficiency or autonomous conservation, and interpret substitution as the effect reflecting the change in relative prices.

With respect to the substitution effects for energy or material, KLEMSUB and IF[IM]SUB are written as:

$$\begin{aligned} \mathrm{KLEMSUB} &\equiv a_{ij}^{c2} - a_{ij}^{c1} \\ &= c_{KLEMj}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}} - c_{Ij}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}} = \left(c_{KLEMj}^{t(t-1)} - c_{Ij}^{t(t-1)}\right) \frac{x_{ij}^{t}}{X_{j}^{t}}, I = E, M; i = \mathbf{e}, \mathbf{m}, \\ \mathrm{IF[IM]SUB} &\equiv a_{ij}^{c1} - a_{ij}^{t-1} \\ &= c_{Ij}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}} - \frac{x_{ij}^{t-1}}{X_{j}^{t-1}}, I = E, M; i = \mathbf{e}, \mathbf{m}. \end{aligned} \tag{21}$$

The substitution effect is represented by the changes in input coefficients and unit cost ratios. The unit cost ratios play roles in rescaling the input coefficients to be equal regarding the total of input coefficients for the corresponding aggregates (the energy or material aggregate, or KLEM aggregates) between periods. To sum up, the substitution effect in the CRSDA refers to the change in the rescaled input coefficients. IF[IM]SUB is defined as the difference between the rescaled input coefficients for energy or material in the terminal period and the input coefficients in the initial period, whereas KLEMSUB is defined as the difference between the rescaled input coefficients for KLEM aggregates and the ones for the energy or material aggregate.

In this paper, the substitution effects for energy or material inputs are aggregated in the top and bottom tiers so that they can be compared with those of the MCDA. In other words, the substitution (SUB) for each type of energy or material is defined as the summation of the KLEMSUB and the IFSUB or the IMSUB, which is given by:

$$\begin{aligned} \mathrm{SUB} &\equiv \mathrm{KLEMSUB} + \mathrm{IF[IM]SUB} \\ &= a_{ij}^{c2} - a_{ij}^{t-1} = c_{KLEMj}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}} - \frac{x_{ij}^{t-1}}{X_{j}^{t-1}}, i = \mathbf{e}, \mathbf{m}. \end{aligned} \tag{21'}$$

Similar equations apply to capital and labor inputs. Their counterfactual points are only a_{ij}^{c2} in Equation (19), as there is no bottom tier for capital and labor. The CFI of capital or labor is decomposed as shown in Equation (22):

$$a_{ij}^{t} - a_{ij}^{t-1} = \left(a_{ij}^{t} - a_{ij}^{c2}\right) + \left(a_{ij}^{c2} - a_{ij}^{t-1}\right), i = K, L, \tag{22}$$

$$\Leftrightarrow \mathrm{CFI} = \mathrm{TC}^{\mathrm{SD}} + \mathrm{SUB},$$

where the first difference to the right of the equality is defined as the technological change ($\mathrm{TC}^{\mathrm{SD}}$) for capital or labor in the CRSDA, and the second one as the substitution (SUB) for capital or labor.

From Equations (19) and (20), $\mathrm{TC}^{\mathrm{SD}}$ is represented by the unit cost change for the overall KLEM aggregates and the input coefficient in the terminal period:

$$\begin{aligned} \mathrm{TC}^{\mathrm{SD}} &\equiv a_{ij}^{t} - a_{ij}^{c2} \\ &= \frac{x_{ij}^{t}}{X_{j}^{t}} - c_{KLEMj}^{t(t-1)} \frac{x_{ij}^{t}}{X_{j}^{t}} = \left(1 - c_{KLEMj}^{t(t-1)}\right) \frac{x_{ij}^{t}}{X_{j}^{t}}, i = K, L, \mathbf{e}, \mathbf{m}. \end{aligned} \tag{23}$$

It is notable from the equation that $\mathrm{TC}^{\mathrm{SD}}$ for all inputs is identical with regard to the signs because $a_{ij}^{t} \geq 0$ and the unit cost change $c_{KLEMj}^{t(t-1)}$ is uniform in each sector.

As shown in the above equations, it is the two counterfactual points that are the keys to understanding the characteristics and components of the CRSDA methodology. Casler and Rose (1998) regards technological change as the effect that reflects the change in efficiency, and substitution as the effect that primarily captures the change in relative prices. However, the counterfactual points of the SDA methodology are not clearly derived from microeconomic production theory. Hence, the contributions assigned to the explanatory factors are not thoroughly interpretable from the microeconomic perspective. This will be illustrated further by the empirical results in the following sections.

3. Comparison of the Methodologies: Energy Use in Japan

This section attempts to compare the two decomposition methodologies, the MCDA and CRSDA, by means of applying them to the change in energy use that occurred in the Japanese economy during 1970-1990. This period includes two oil crises: one in 1973 and a second one in 1979. It is widely recognized that skyrocketing oil prices greatly influenced the Japanese economy during this time, and that the structural changes have had a huge impact on manufacturing energy use (IEA 2004). This situation offers a typical context in which to use the decomposition methodologies, which can specifically evaluate, for example, how much the Japanese economy was influenced by the resulting price substitution and, by the same token, by technological change.

This section focuses on the change in energy use, using data from 1970 to 1990.[6] The sectors are classified into five industries and four energy inputs (see the notes accompanying Table 1 for more details). Nominal outputs (factor inputs) are obtained from the 1970-75-80 and 1985-90-95 Linked Input-Output Tables (Management and Coordination Agency).[7] 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 elasticities of substitution are assumed, for the purposes of simplicity, to be $\sigma = 0$ and $\sigma_E, \sigma_M = 1$ as in Fig. 1; nevertheless, these estimates are not significantly different from those in the previous literature that econometrically estimates these elasticities for the Japanese economy (see, e.g., Okushima and Goto 2001).[8]

First, let us provide a summary of the trends in Japan's energy use (see, e.g., IEA 2004). Energy use in Japan has steadily increased in volume since the 1970s, although the growth rate in the early 1980s, following the oil crises, was lower than in other periods. It is said that Japan succeeded in the field of energy conservation and substitution from oil as a result of the lessons of the oil crises. In fact, the share of oil in both primary supply and final consumption has decreased following the oil crises, whereas the shares of gas and electricity have increased, mainly owing to use of natural gas and nuclear power. The primary supply of coal such as power generation is gradually increasing,

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

[7] Casler and Rose (1998) uses hybrid energy/value tables, the energy inputs rows of which are represented in physical units, whereas the former version of their SDA (Rose and Chen 1991) uses standard value tables. Our analysis chooses the standard value tables as the dataset because the MCDA necessitates reliable monetary-balanced data. In any case, the issue of which type of tables is used is irrelevant to the purpose of this paper, which is to make a comparison of the methodologies. Furthermore, from a theoretical perspective, Dietzenbacher and Stage (2006) criticizes the straightforward application of SDA to hybrid tables, as it may induce arbitrary results depending on the choice of units.

[8] See also footnote 3.

whereas its final consumption has remained almost constant, and its share in final consumption is declining. Following the trend of final energy consumption, the changes in factor/energy inputs (CFIs), which will be analyzed in Table 1 and Table 2, also reflect the experience. The Tables show that the CFIs for coal and oil are mainly negative, whereas those for gas and electricity are positive. The CFIs should be caused by various effects such as price substitution or technological change.

Table 1 illustrates the decomposition of the CFIs in the Japanese economy by the MCDA methodology. The MCDA can divide the CFIs into the technological change ($\mathrm{TC}^{\mathrm{MC}}$) and the price substitution (PS). As explained in Section 2, the MCDA is consistent with microeconomic production theory and allows the decomposition components to be interpreted in a theoretically meaningful way. The PS is determined by the change in relative prices over the periods. PS represents the change in factor inputs along the production function. As in Table 1, in the 1970s, the PSs for oil are negative in all sectors, whereas those for the other types of energy are mostly positive. In contrast, the PSs for oil turn to positive in the 1980s, whereas those for coal change to negative. The PSs for coal make a good contrast with those for oil. The PSs for gas are positive in most cases. This is because the industries had continuously expanded their use of gas, which has a price advantage, after the oil crises. The MCDA can thus evidently exhibit the price substitution effect; that is, it shows the substitution that occurs from the inputs with relatively higher prices to those that have relatively lower prices. This confirms that the MCDA is a decomposition methodology that is based on production theory.

Another strength of the MCDA is that it can evaluate technological change in terms of types of energy, sectors, or periods. The preceding section mentions that the $\mathrm{TC}^{\mathrm{MC}}$ is defined by the difference between CFI and PS, which represents shifts in the production function. Table 1 shows that the $\mathrm{TC}^{\mathrm{MC}}$s for oil are largely negative in the 1980s. In other words, theoretically, the CFIs for oil had decreased by more than was expected from the price substitution effect (PS). The result indicates that oil-diminishing technological change had occurred mainly in the 1980s rather than in the 1970s. The $\mathrm{TC}^{\mathrm{MC}}$s for coal are mostly negative over the periods in question. The MCDA explains that technological change is important for curtailing energy use.

Next, Table 2 shows the decomposition of the CFIs by the CRSDA. The CFIs are the same as in Table 1. The CRSDA can divide the CFIs into various effects between and within KLEM aggregates. In Table 2, the substitution effects regarding energy inputs in the top and bottom tiers are integrated so that they can be compared with those of the MCDA; substitution (SUB) for each type of energy is the summation of the KLEM substitution (KLEMSUB) and the interfuel substitution (IFSUB). This treatment relates to the aim of this paper, which is the comparison of the two methodologies; on this account, the components are aggregated in a different way from those in Casler and Rose (1998).

Technological change in the CRSDA ($\mathrm{TC}^{\mathrm{SD}}$) is defined by $\mathrm{TC}^{\mathrm{SD}} = \left(1 - c_{KLEMj}^{t(t-1)}\right)\left(x_{ij}^{t} / X_{j}^{t}\right)$, as in Equation (23). That is, $\mathrm{TC}^{\mathrm{SD}}$ is determined by the unit cost ratio $c_{KLEMj}^{t(t-1)}$, which refers to the change in the sum of the input coefficients for overall KLEM aggregates between periods, and the input coefficient in the terminal period. Table 2 empirically shows that the values of $\mathrm{TC}^{\mathrm{SD}}$s are relatively small in most cases and that the signs in each sector are wholly identical in each period. This is because, by definition, the unit cost ratio $c_{KLEMj}^{t(t-1)}$ is identical for any kinds of inputs in a sector. Hence, without negative input coefficients in the terminal period, the signs of the $\mathrm{TC}^{\mathrm{SD}}$s are identical for all inputs. In practice, Table 2 demonstrates that $\mathrm{TC}^{\mathrm{SD}}$s are fully negative in EII and MAC regardless of the types of energy in the entire periods, while the opposite applies in SER. The CRSDA explains that the trend of technological change is completely identical in each sector without regard to the types of energy.

On the other hand, the substitution effect in the CRSDA (SUB) is defined by the changes in the rescaled input coefficients, as shown in Equation (21’). Table 2 illustrates that the SUBs have multifarious signs and large absolute values, in contrast to the $\mathrm{TC}^{\mathrm{SD}}$s. In consequence, the SUBs account for the larger part of the corresponding CFIs. Again, this result is well grounded, given the definition. As in Equation (20), SUB is resulted from CFI and $\mathrm{TC}^{\mathrm{SD}}$. Again, $\mathrm{TC}^{\mathrm{SD}}$ is determined by $\left(1-c_{KLEMj}^{t(t-1)}\right)\left(x_{ij}^{t}/X_{j}^{t}\right)$, in which $c_{KLEMj}^{t(t-1)}$ is the unit cost ratio. Suppose that the sum of the input coefficients for KLEM aggregates in a sector changes little between the initial and terminal periods ($A_{KLEMj}^{t-1} \simeq A_{KLEMj}^{t}$). Then, the unit cost ratio $c_{KLEMj}^{t(t-1)}$ will be close to one. As a result, $\mathrm{TC}^{\mathrm{SD}}$ is in the neighborhood of zero and SUB is almost equal to the CFI itself. In general, $\mathrm{TC}^{\mathrm{SD}}$ is not so large because of the empirical fact that the unit cost does not greatly change between neighboring periods. Table 2 empirically shows, for instance, that all $\mathrm{TC}^{\mathrm{SD}}$s in AGM and EII are less than 1% in 1975-1980 and their SUBs are almost identical to their CFIs. Additionally, Table 2 illustrates that the SUBs for coal and oil are mostly negative over the periods in question. In consequence, the CRSDA concludes that substitution effects are essential for cutting off energy use.

Thus, there is much variation between the results of the decomposition methodologies. The MCDA and the CRSDA provide insights into the determinants of energy use change from their methodological points of view. In the context of change in energy use, the MCDA shows that technological change is the primary constituent, whereas the CRSDA describes substitution effects as essential. As has been shown, the distinction can be clearly explained by their theoretical characteristics.

Here, to shed light on the differences between the methodologies, this paper attempts a more in-depth analysis of the price substitution effect in the MCDA and the substitution effect in the CRSDA. For further investigation, Table 3 decomposes SUBs into KLEMSUBs and IFSUBs. IFSUB explains the substitution between energy inputs, as Casler and Rose (1998, p. 357) considers it to be the effect to ‘primarily capture the changes in relative prices’. Table 3 indicates the complementary relationship of IFSUBs; that is, IFSUBs have contrasting signs in a sector, which reflects the substitution between the types of energy.

However, the results of IFSUBs differ considerably from those of PSs in Table 1, which mean the price substitution effects in the MCDA. Table 4 shows the correspondence between the relative energy price changes and the substitution effects estimated by the respective methodologies. In other words, Table 4 illustrates the relationship between the relative energy price changes and the changes in energy use. The shaded regions indicate the case where the direction of the substitution effects is the same as the one of the relative price changes, which runs counter to predictions of production theory. As shown in Table 4, the price substitution effects in the MCDA respond accurately to the relative price changes (no shaded areas); the PS increases when the relative price decreases, and vice versa. It is an advantage of the MCDA that it captures the price substitution effect in a manner consistent with production theory. Theoretically, it is clear from Equations (11)-(13) that the PSs in the MCDA have the opposite signs to the relative price changes.

It is difficult to say whether the substitution effect in the CRSDA (IFSUB) exactly represents the price substitution effect. Table 4 indicates many anomalies in the directions of the IFSUBs (the shaded regions) which do not reflect the price substitution effect. Although the substitution effects in the CRSDA are supposed to capture the changes in relative prices, it is found that they do not exactly capture the price substitution effect. This result empirically shows that the substitution effect in the CRSDA may be less than obvious from a commonly accepted explanation.

Of course, it is a strong presumption for the above examination to regard the substitution effect in the CRSDA as a pure price substitution effect. It certainly represents some kind of substitution effects. Nevertheless, it should be pointed out that it is difficult to interpret correctly the causality of the decomposed components in the CRSDA. By contrast, the MCDA has robust micro-theoretical foundations. It explicitly incorporates the price substitution effect owing to the change in relative prices into the model structure, which is based on the explicit assumptions of the two-tier CES functions and the elasticities. As a *quid pro quo* for more data requirements, the causal components in the MCDA are easy to understand and interpret. In this aspect, the MCDA has the advantage and could be a supplement to the conventional SDA methodology.

Table 1 Decomposition of the changes in energy inputs by MCDA

Input		Sector														
		AGM			EII			MAC			OMF			SER		
		CFI	TC^{MC}	PS	CFI	TC^{MC}	PS	CFI	TC^{MC}	PS	CFI	TC^{MC}	PS	CFI	TC^{MC}	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%
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%
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%
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%

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.

(3) Shaded regions represent negative values.

Table 2 Decomposition of the changes in energy inputs by CRSDA

Input		Sector														
		AGM			EII			MAC			OMF			SER		
		CFI	TC^{SD}	SUB	CFI	TC^{SD}	SUB	CFI	TC^{SD}	SUB	CFI	TC^{SD}	SUB	CFI	TC^{SD}	SUB
COAL	1970-75	-59.5%	6.4%	-66.0%	29.6%	-6.9%	36.5%	-70.1%	-6.2%	-63.9%	-43.6%	0.9%	-44.5%	-5.2%	2.1%	-7.3%
	1975-80	-23.6%	0.1%	-23.6%	-31.7%	-0.2%	-31.5%	-19.2%	-15.1%	-4.1%	-14.1%	7.4%	-21.5%	-0.3%	0.9%	-1.3%
	1980-85	-68.5%	-0.3%	-68.1%	-36.1%	-4.9%	-31.2%	-60.1%	-2.4%	-57.7%	-36.8%	-0.7%	-36.2%	-32.7%	0.8%	-33.5%
	1985-90	32.2%	5.9%	26.3%	-25.4%	-0.9%	-24.5%	-3.6%	-7.4%	3.7%	-22.5%	-2.5%	-20.0%	-19.3%	2.9%	-22.2%
OIL	1970-75	-9.2%	14.5%	-23.7%	0.6%	-5.3%	5.9%	-51.0%	-10.2%	-40.9%	-6.6%	1.5%	-8.1%	-22.0%	1.7%	-23.7%
	1975-80	-1.5%	0.1%	-1.6%	-8.2%	-0.3%	-7.9%	-36.8%	-11.8%	-25.0%	7.6%	9.3%	-1.6%	-23.2%	0.7%	-23.9%
	1980-85	-43.2%	-0.6%	-42.7%	-23.9%	-5.8%	-18.1%	-28.0%	-4.3%	-23.7%	-38.8%	-0.7%	-38.2%	-15.2%	1.0%	-16.2%
	1985-90	-4.1%	4.3%	-8.3%	-32.0%	-0.8%	-31.1%	-41.8%	-4.4%	-37.4%	-31.1%	-2.2%	-28.9%	-22.9%	2.8%	-25.6%
GAS	1970-75	14.3%	18.2%	-3.9%	2.8%	-5.5%	8.3%	-36.3%	-13.2%	-23.1%	-13.2%	1.4%	-14.6%	49.1%	3.3%	45.8%
	1975-80	30.6%	0.1%	30.4%	34.0%	-0.5%	34.5%	-13.4%	-16.2%	2.8%	62.0%	13.9%	48.0%	15.4%	1.1%	14.3%
	1980-85	-24.7%	-0.7%	-24.0%	-51.0%	-3.7%	-47.3%	-42.8%	-3.4%	-39.4%	84.7%	-2.0%	86.7%	-17.8%	1.0%	-18.8%
	1985-90	-40.2%	2.7%	-42.9%	88.3%	-2.3%	90.6%	-41.9%	-4.4%	-37.4%	19.0%	-3.9%	22.9%	-15.5%	3.0%	-18.5%
ELC	1970-75	7.5%	17.1%	-9.6%	12.9%	-6.0%	18.9%	-17.9%	-17.1%	-0.8%	20.9%	1.9%	19.0%	21.0%	2.7%	18.4%
	1975-80	23.3%	0.1%	23.2%	-9.1%	-0.3%	-8.7%	-16.4%	-15.6%	-0.8%	19.2%	10.2%	8.9%	1.3%	1.0%	0.3%
	1980-85	-24.5%	-0.7%	-23.7%	-7.7%	-7.0%	-0.6%	37.0%	-8.2%	45.2%	-6.3%	-1.0%	-5.3%	-2.9%	1.2%	-4.1%
	1985-90	25.8%	5.6%	20.2%	0.5%	-1.2%	1.8%	-24.0%	-5.8%	-18.2%	-6.1%	-3.1%	-3.0%	8.3%	3.9%	4.4%

Note: (1) Classifications are the same as in Table 1.

(2) Shaded regions represent negative values.

Table 3 Decomposition of the SUBs in CRSDA

Input		Sector														
		AGM			EII			MAC			OMF			SER		
			KLEM			KLEM			KLEM			KLEM			KLEM	
		SUB	SUB	IFSUB	SUB	SUB	IFSUB	SUB	SUB	IFSUB	SUB	SUB	IFSUB	SUB	SUB	IFSUB
COAL	1970-75	-66.0%	-9.9%	-56.0%	36.5%	23.5%	13.0%	-63.9%	-9.3%	-54.6%	-44.5%	3.0%	-47.5%	-7.3%	-8.0%	0.7%
	1975-80	-23.6%	0.3%	-23.9%	-31.5%	-13.2%	-18.3%	-4.1%	-10.3%	6.3%	-21.5%	3.5%	-24.9%	-1.3%	-15.6%	14.3%
	1980-85	-68.1%	-22.1%	-46.1%	-31.2%	-13.0%	-18.3%	-57.7%	4.9%	-62.5%	-36.2%	-13.8%	-22.4%	-33.5%	-10.0%	-23.5%
	1985-90	26.3%	-6.4%	32.7%	-24.5%	-14.3%	-10.2%	3.7%	-31.8%	35.5%	-20.0%	-9.0%	-11.0%	-22.2%	-12.5%	-9.7%
OIL	1970-75	-23.7%	-22.3%	-1.4%	5.9%	18.2%	-12.3%	-40.9%	-15.3%	-25.6%	-8.1%	5.0%	-13.0%	-23.7%	-6.6%	-17.1%
	1975-80	-1.6%	0.4%	-2.0%	-7.9%	-17.7%	9.8%	-25.0%	-8.1%	-16.9%	-1.6%	4.3%	-5.9%	-23.9%	-12.1%	-11.9%
	1980-85	-42.7%	-39.7%	-2.9%	-18.1%	-15.4%	-2.7%	-23.7%	8.7%	-32.5%	-38.2%	-13.3%	-24.8%	-16.2%	-12.6%	-3.6%
	1985-90	-8.3%	-4.6%	-3.7%	-31.1%	-13.0%	-18.1%	-37.4%	-19.2%	-18.2%	-28.9%	-8.0%	-20.9%	-25.6%	-12.0%	-13.7%
GAS	1970-75	-3.9%	-28.0%	24.1%	8.3%	18.6%	-10.3%	-23.1%	-19.9%	-3.2%	-14.6%	4.6%	-19.2%	45.8%	-12.5%	58.3%
	1975-80	30.4%	0.5%	29.9%	34.5%	-25.9%	60.4%	2.8%	-11.1%	13.9%	48.0%	6.5%	41.5%	14.3%	-18.1%	32.5%
	1980-85	-24.0%	-52.7%	28.7%	-47.3%	-9.9%	-37.4%	-39.4%	7.0%	-46.3%	86.7%	-40.2%	126.9%	-18.8%	-12.2%	-6.6%
	1985-90	-42.9%	-2.9%	-40.0%	90.6%	-36.0%	126.6%	-37.4%	-19.2%	-18.2%	22.9%	-13.8%	36.6%	-18.5%	-13.1%	-5.4%
ELC	1970-75	-9.6%	-26.4%	16.7%	18.9%	20.4%	-1.6%	-0.8%	-25.6%	24.8%	19.0%	6.4%	12.6%	18.4%	-10.2%	28.5%
	1975-80	23.2%	0.5%	22.7%	-8.7%	-17.6%	8.8%	-0.8%	-10.7%	9.9%	8.9%	4.8%	4.1%	0.3%	-15.9%	16.2%
	1980-85	-23.7%	-52.8%	29.1%	-0.6%	-18.7%	18.1%	45.2%	16.6%	28.5%	-5.3%	-20.4%	15.1%	-4.1%	-14.4%	10.3%
	1985-90	20.2%	-6.0%	26.3%	1.8%	-19.2%	21.0%	-18.2%	-25.1%	6.8%	-3.0%	-10.8%	7.8%	4.4%	-16.8%	21.2%

Note: (1) Classifications are the same as in Table 1.

(2) Shaded regions represent negative values.

Table 4 Direction of substitution effects

Input		Sector														
		AGM			EII			MAC			OMF			SER		
		$p_e/p_{E(j)}$	PS	IFSUB	$p_e/p_{E(j)}$	PS	IFSUB	$p_e/p_{E(j)}$	PS	IFSUB	$p_e/p_{E(j)}$	PS	IFSUB	$p_e/p_{E(j)}$	PS	IFSUB
COAL	1970-75	-	+	-	-	+	+	-	+	-	-	+	-	-	+	+
	1975-80	-	+	-	-	+	-	-	+	+	-	+	-	-	+	+
	1980-85	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
	1985-90	+	-	+	+	-	-	+	-	+	+	-	-	+	-	-
OIL	1970-75	+	-	-	+	-	-	+	-	-	+	-	-	+	-	-
	1975-80	+	-	-	+	-	+	+	-	-	+	-	-	+	-	-
	1980-85	-	+	-	-	+	-	-	+	-	-	+	-	-	+	-
	1985-90	-	+	-	-	+	-	-	+	-	-	+	-	-	+	-
GAS	1970-75	-	+	+	-	+	-	-	+	-	-	+	-	-	+	+
	1975-80	-	+	+	-	+	+	-	+	+	-	+	+	-	+	+
	1980-85	+	-	+	-	+	-	-	+	-	-	+	+	-	+	-
	1985-90	-	+	-	-	+	+	-	+	-	-	+	+	-	+	-
ELC	1970-75	-	+	+	-	+	-	-	+	+	-	+	+	-	+	+
	1975-80	-	+	+	+	-	+	-	+	+	-	+	+	-	+	+
	1980-85	+	-	+	+	-	+	+	-	+	+	-	+	+	-	+
	1985-90	+	-	+	-	+	+	+	-	+	+	-	+	+	-	+

Note: (1) Classifications are the same as in Table 1.

(2) The signs represent positive change in the period as ‘+’ and negative change as ‘-’.

(3) For actual values of PS and IFSUB, see Tables 1 and 3.

(4) Shaded regions represent the case where the direction of the substitution effects is the same as that of the relative price changes, which is theoretically anomalous with the price substitution effect.

4. Comparison of the Methodologies: CO_2 Emissions in Japan

This section compares the two methodologies through an analysis of the change in CO_2 emissions in the Japanese economy from 1970 to 1990. This section undertakes the decomposition of a factor input matrix by utilizing the above results from Section 3, which were obtained from the MCDA and CRSDA methodologies. In other words, the earlier results in Table 1 and Table 2 now form the basis of the decomposition of the change in CO_2 emissions.

As well as the conventional SDA methodology, the change in CO_2 emissions is decomposed into three major components: KLEM effects due to the change in a factor input matrix, a final demand effect attributable to the change in a final demand vector, and an interaction effect. The KLEM effects are further subdivided into the components representing price substitution or substitution effect and technological change as respectively defined.

The formulation and notations below are based on Casler and Rose (1998) and Okushima and Tamura (2007). In the formulation, the MCDA subdivides the KLEM effects into:

$$\begin{aligned}\Delta\boldsymbol{\Pi}_{TOT} \cong\ & \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_K^{\mathrm{TC^{MC}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_K^{\mathrm{PS}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_L^{\mathrm{TC^{MC}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_L^{\mathrm{PS}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} \\ & + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_E^{\mathrm{TC^{MC}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_E^{\mathrm{PS}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_M^{\mathrm{TC^{MC}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_M^{\mathrm{PS}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y},\end{aligned} \tag{24}$$

where $\Delta\boldsymbol{\Pi}_{TOT}$ is the change in the CO_2 emission vector owing to the KLEM effects, $\boldsymbol{\Pi}$ is the emission intensity matrix, $\overline{\boldsymbol{\Pi}}$ is the Leontief inverse, and $\mathbf{Y}$ is the final demand vector. With regard to the change in the factor input matrix, $\Delta\mathbf{A}_I^{\mathrm{TC^{MC}}}$ (I = K, L, E, M) represents the MCDA technological change ($\mathrm{TC^{MC}}$), and $\Delta\mathbf{A}_I^{\mathrm{PS}}$ (I = K, L, E, M) does the price substitution (PS). Here, $\Delta\mathbf{A}_K^{\mathrm{PS}}$ and $\Delta\mathbf{A}_L^{\mathrm{PS}}$ do not exist because the elasticity of substitution in the top tier is zero, as Fig. 1 shows.

In the same way, the CRSDA decomposes the KLEM effects into the following components:

$$\begin{aligned}\Delta\boldsymbol{\Pi}_{TOT} \cong\ & \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_E^{\mathrm{S}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_M^{\mathrm{S}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} \\ & + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{KKLEM}^{\mathrm{S}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{LKLEM}^{\mathrm{S}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{EKLEM}^{\mathrm{S}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{MKLEM}^{\mathrm{S}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} \\ & + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{KKLEM}^{\mathrm{TC^{SD}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{LKLEM}^{\mathrm{TC^{SD}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{EKLEM}^{\mathrm{TC^{SD}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y} + \boldsymbol{\Pi}^{t-1}\Delta\mathbf{A}_{MKLEM}^{\mathrm{TC^{SD}}}\overline{\boldsymbol{\Pi}}^{t-1}\mathbf{Y},\end{aligned} \tag{25}$$

where $\Delta\mathbf{A}_I^{\mathrm{S}}$ (I = E, M) represents the substitution within the energy aggregate (IFSUB) or the material aggregate (IMSUB), $\Delta\mathbf{A}_{IKLEM}^{\mathrm{S}}$ (I = K, L, E, M) does the substitution between KLEM aggregates (KLEMSUB), and $\Delta\mathbf{A}_{IKLEM}^{\mathrm{TC^{SD}}}$ (I = K, L, E, M) does the CRSDA technological change ($\mathrm{TC^{SD}}$). The substitution effects for energy and material inputs in both the top and bottom tiers are aggregated in the following, as well as in Section 3.

The data sources and classifications are the same as earlier. The CO_2 emissions in Japan are obtained by multiplying the energy consumption by their corresponding emission coefficients (IEA 1999). Between 1970 and 1990, they rose by 91 million carbon metric tons (Mt-C), from 204 to 295 Mt-C, representing a 45% increase. The energy inputs in the analysis that lead to CO_2

emissions are coal, oil, and gas; in contrast, the use of electricity does not directly generate CO_2. The change in CO_2 emissions from individual fuels during the period are as follows: coal: 58 to 73 Mt-C, oil: 144 to 198 Mt-C, and gas: 1.7 to 24.4 Mt-C.

Table 5 and Table 6 illustrate the respective decomposition results of the changes in CO_2 emissions for the MCDA and the CRSDA. In each column, the sum of the entries is equal to the total, excluding minor rounding errors. Clearly, from the definitions, a final demand effect and an interaction effect are equivalent in both methodologies. The results show that the final demand effect is the major contributor to the CO_2 emission increase. This represents the expansion of the economy. Usually, such a result is observed in a continuously growing economy, and is consistent with the results of empirical studies on energy use in the Japanese economy (see, e.g., Kagawa and Inamura 2001).

With regard to the KLEM effects, the decomposed components differ between the MCDA and CRSDA, reflecting the previous results. However, recall that both methodologies decompose the same object, the change in factor inputs (CFI). Hence, the sum of the decomposed components for each aggregate (K, L, E, and M) is equivalent between the MCDA and CRSDA, such that $TC^{MC} + PS = TC^{SD} + SUB = CFI$.

From the viewpoint of the CFIs, the capital CFI contributes substantially to the increase in CO_2 emissions. This is because of the continuously increasing trend in capital intensity in the Japanese economy. In contrast, the negative contribution of the labor CFI is highlighted, reflecting the increase in labor productivity. These results can be inferred from other empirical results on structural change in the Japanese economy (see, e.g., Tokutsu 1998). The energy CFI has a downward effect on the emission increases and the material CFI has the opposite effect.

The two methodologies differ on the point of how to separate the CFIs into the individual components (see Table 5 and Table 6). As for technological change, the MCDA result in Table 5 illustrates that the negative contribution of the LTC^{MC} stands out; in contrast, the KTC^{MC} and MTC^{MC} substantially contribute to the increase in CO_2 emissions. When examining technological change regarding energy, the ETC^{MC}s for coal and oil are negative, and the former has a large negative impact on emissions. This is implied by the result in Table 1, which shows that the TC^{MC}s for coal are mainly negative regardless of the period or industry, in addition to the fact that coal is the most carbon intensive. Hence, the total ETC^{MC} is negative despite the positive contribution of gas. The results show that technological change for labor and energy played a key part in cutting off CO_2 emissions.

Next, let us turn to price substitution. MPSs for all types of energy have positive effects on the emissions, as shown in Table 5. The EPS for oil is negative, whereas those for coal and gas are positive. This reflects the price substitution from oil to other types of energy after the oil crises. It is noteworthy that the price substitution effects mutually cancel out in terms of their influence on CO_2 emissions. This exactly reflects the MCDA result in Section 3, which showed the complementary relationship caused by the price substitution effect. Accordingly, the MCDA indicates that price substitution for energy has a virtually neutral effect on emissions.

However, the result of the CRSDA, shown in Table 6, indicates that all kinds of technological change (TC^{SD}) have increased the CO_2 emissions. In other words, all TC^{SD}s are positive without regard to KLEM effects or the types of energy. Table 6 shows that the MTC^{SD} is the most significant cause of the increase in emissions. It also illustrates that even LTC^{SD} and ETC^{SD} tend to increase the CO_2 emissions, contrary to the MCDA's result.

On the other hand, the substitution effects (SUBs) are negative, except for KSUB. As in the previous result, SUBs generally have large absolute values and explain the greatest part of CFIs. As TC^{SD}s are entirely positive, all diminishing contributors among the KLEM effects are ascribed to SUBs. The result shows that LSUB, ESUB, and MSUB are the negative causes of the emission increase, which reflects the fact that there is a substitution effect from these inputs to capital in the CRSDA. ESUB is the leading cause of the decline in CO_2 emissions. It is notable that the result in Table 6 has much in common with Casler and Rose's (1998) result.

This section compares the two decomposition results of the change in CO_2 emissions in Japan. The two decomposition methodologies, the MCDA and CRSDA, provide insights into the determinants of emission changes. Both methodologies determine that the final demand effect is the major contributor to the emission increase. On the other hand, the results regarding KLEM effects are distinct for each methodology. The MCDA concludes that technological change, especially for labor and energy, is the primary negative impact on emissions. However, the CRSDA evaluates technological change as having a positive effect on emissions, but finds that substitution effects, especially for labor and energy, are significant negative influences on emissions.

The reason for the differences can be inferred from the characteristics of both decomposition methodologies, as has been discussed in the previous sections. In the MCDA, price substitution effects (PSs) are derived from the relative price changes over the periods and most of the effects are cancelled out within the aggregates. Thus, technological changes (TC^{MC}s), which embody those parts of the CFI that cannot be explained by PSs, represent negative contributors to the emissions. However, in the CRSDA, the analysis shows that technological changes (TC^{SD}s) are all positive. As a result, substitution effects (SUBs) represent negative contributors entirely. Therefore, the MCDA depicts that technological change is of great importance in the context of reducing CO_2 emissions, whereas the CRSDA finds that substitution effect is the most significant cause. The comparison of the results proves that understanding the theoretical properties of the methodologies is indispensable in interpreting empirical results.

Table 5 Decomposition of the changes in CO_2 emissions by MCDA, 1970-1990 [Mt-C]

	COAL	OIL	GAS	TOTAL
KLEM effects				
Capital CFI	15.5	65.1	9.8	90.4
Capital TC (KTC^{MC})	15.5	65.1	9.8	90.4
Labor CFI	-5.6	-25.7	-4.7	-36.1
Labor TC (LTC^{MC})	-5.6	-25.7	-4.7	-36.1
Energy CFI	-8.2	-12.6	10.9	-9.9
Energy TC (ETC^{MC})	-9.7	-5.8	5.6	-9.9
Energy PS (EPS)	1.4	-6.8	5.3	-0.1
Material CFI	9.9	46.6	7.4	63.8
Material TC (MTC^{MC})	6.1	37.4	5.6	49.1
Material PS (MPS)	3.8	9.2	1.8	14.7
Final demand effects	24.6	91.5	23.1	139.3
Interaction effects	-20.9	-111.4	-23.8	-156.1
Total	15.2	53.5	22.7	91.4

Table 6 Decomposition of the changes in CO_2 emissions by CRSDA, 1970-1990 [Mt-C]

	COAL	OIL	GAS	TOTAL
KLEM effects				
Capital CFI	15.5	65.1	9.8	90.4
Capital TC (KTC^{SD})	4.7	19.7	3.0	27.3
Capital SUB (KSUB)	10.8	45.4	6.8	63.0
Labor CFI	-5.6	-25.7	-4.7	-36.1
Labor TC (LTC^{SD})	1.0	4.7	0.9	6.6
Labor SUB (LSUB)	-6.7	-30.5	-5.6	-42.7
Energy CFI	-8.2	-12.6	10.9	-9.9
Energy TC (ETC^{SD})	2.8	23.3	8.8	34.9
Energy SUB (ESUB)	-11.1	-35.9	2.1	-44.9
Material CFI	9.9	46.6	7.4	63.8
Material TC (MTC^{SD})	15.1	65.2	9.1	89.4
Material SUB (MSUB)	-5.2	-18.6	-1.7	-25.6
Final demand effects	24.6	91.5	23.1	139.3
Interaction effects	-20.9	-111.4	-23.8	-156.1
Total	15.2	53.5	22.7	91.4

5. Conclusion

This paper compares the two practical decomposition methodologies equivalent to the full-fledged KLEM model, the Multiple Calibration Decomposition Analysis (MCDA) and Casler and Rose's (1998) Structural Decomposition Analysis (CRSDA). Both MCDA and CRSDA can distinguish causal components from their respective points of view. The MCDA is able to make a distinction between price substitution and technological change to be made for each sector, consistent with microeconomic theory. The CRSDA is excellent and one of the most sophisticated SDA methodologies, which can examine various substitution and technological change effects between and within KLEM aggregates.

The purpose of this paper is to expound the theoretical properties of the decomposition methodologies. "Thoughts without content are empty, intuitions without concepts are blind" (Immanuel Kant, *Critique of Pure Reason*). In order to appropriately interpret the empirical results, there is a real need to understand the theoretical groundings of the methodologies. The MCDA is usable, and can provide hints to assist in understanding the theoretical foundations of the conventional decomposition methodologies. This paper attempts to reexamine the properties of CRSDA, and compares the empirical results between the two methodologies. This paper applies the two decomposition methods to the changes in energy use and carbon dioxide (CO_2) emissions in the Japanese economy during 1970-1990.

In the CRSDA, technological change (TC^{SD}) is represented as the change in the total of input coefficients for overall KLEM aggregates, and is identical with regard to the signs in each sector. Meanwhile substitution effect in the CRSDA (SUB) is represented as the change in input coefficients which are rescaled by the unit cost ratio. SUB generally tends to account for a greater part of the change in factor inputs (CFI) than does TC^{SD}. Hence, it is important to recognize what SUB stands for. This paper empirically illustrates that the substitution effect in the CRSDA does not always correspond to the relative price change. In other words, it may not be clear for it to capture the price substitution effect. As the result, the CRSDA assesses technological changes as contributing positively overall to energy use or CO_2 emissions, whereas substitution effects are the leading negative causes. The result is quite similar to that of Casler and Rose (1998).

In contrast, the MCDA explicitly depicts substitution effect (PS) in consistent with the relative price change as it represents the change in factor inputs along the production function. For instance, it shows that PS for oil is a negative contributor to the energy use and emission increases, reflecting the fact that other types of energy that have lower relative prices are being substituted for oil. Technological change in the MCDA (TC^{MC}) is defined as CFI minus PS, which embodies the shift in the production function. The MCDA evaluates that technological changes, rather than price substitution effects, mitigated the overall increase in energy use and CO_2 emissions.

Both CRSDA and MCDA are important methodologies for empirical decomposition analysis, and are rewarding frameworks that provide detailed information about the sources of structural change of the economy. Nevertheless, this paper shows that precise interpretation of the decomposition result requires a better understanding of the theoretical base.

There are many shared features in the MCDA and SDA methodologies. Both methodologies employ a deterministic procedure, which has the advantage of necessitating less data, at least a two-period dataset, compared with econometric methods. In addition, both methodologies can distinguish between direct and indirect effects, and provide detailed information, compared with Index Decomposition (ID).[9]

On the other hand, there are discrepancies between these two methodologies. The MCDA is more data intensive than the SDA, as price data and elasticities of substitution are requisites. The latter involves a similar problem that occurs with an applied general equilibrium analysis, in that there are still few estimates of elasticities in the literature, despite the importance of elasticity parameters (see, e.g., Shoven and Whalley 1984, 1992). With regard to the data requirement, the SDA is better than the MCDA. However, the additional data required by the MCDA enables the MCDA methodology to have micro-theoretical foundations, which makes the decomposition more theoretically robust and the decomposed factors more easily interpretable, compared with the SDA. In summary, in terms of requiring less data, the ID methodology is preferable, followed by the SDA, the MCDA, and the econometric one, respectively, whereas in terms of the provision of more detailed information, the order of the preferable methodologies is reversed.

It should be emphasized that the selection of decomposition methodologies depends on the goal of the analysis and the availability of data. It is indubitable that the MCDA methodology could be more fruitful when used complementarily with the SDA -and vice versa- or with other methods such as an econometric one. It is hoped that this paper will provide a better understanding of the theoretical properties of decomposition methodologies to aid a precise interpretation of empirical results.

Acknowledgements

This research was supported by the Grant-in-Aid for Scientific Research and the Asahi Glass Foundation. The name order is alphabetical.

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[9] Index Decomposition (ID) or Index Number Analysis (INA) requires less data but it cannot distinguish direct effects from indirect effects. See Ang and Zhang (2000), Hoekstra and van den Bergh (2003), and Hoekstra (2005).

Appendix:

Comparison of the Methodologies: Counterfactual Point and 'Substitution Parameter'

Decomposition analysis makes counterfactual points to separate some interesting causal factors from the observed outcomes. Each decomposition methodology can be characterized by how it creates the counterfactual points and their meanings. The MCDA constructs the counterfactual point in a manner directly grounded in microeconomic production theory. Namely, the MCDA builds the counterfactual point in order to extract the price substitution effect which exactly reflects the relative price change between the initial and terminal periods on the two-tier CES production function, as shown in Equations (11)-(13). On the other hand, the CRSDA sets the counterfactual points based on the unit cost ratios, as in Equations (18)-(20). The unit cost refers to the total of input coefficients for the overall KLEM aggregates, the energy aggregate, or the material aggregate. It is important to know what these counterfactual points really indicate in order to understand the theoretical properties of the decomposition methodologies.

This appendix reexamines the counterfactual points in the CRSDA by estimating types of 'substitution parameters' in the MCDA methodology. In a practical manner, the SDA methodology has 'an implicit production function' and the implicitly defined underlying model could be interpreted as 'a flexible functional form production function' (Casler and Rose 1998, pp. 360-361). However, the production function needs to be clearly specified in order to interpret the derived components. As mentioned by Casler and Rose (1998, p. 361), elasticities of substitution are implicit in the SDA methodology but can be inferred. Hence, this analysis attempts to identify 'an implicit production function' approximately by estimating the fictitious 'substitution parameters' in the CRSDA. Notwithstanding the limitations -that the analysis imposes the two-tier CES production functions on the CRSDA and regards the substitution effect in the CRSDA as the price substitution effect in the MCDA- this experiment may facilitate theoretical comparison between the two methodologies.

From Equations (13), (18), and (19), the fictitious 'substitution parameters' ($\sigma^{*}_{E(ej)}$ and $\sigma^{**}_{E(ej)}$) for energy which equalize the counterfactual point a^{c} in the MCDA with a^{c1} and a^{c2} in the CRSDA are given by:

$$\sigma^{*}_{E(ej)} = \ln\left(\frac{\beta_{E(j)} \cdot a^{c1}_{ej}}{A^{t-1}_{Ej}}\right) \Bigg/ \ln\left(\beta_{E(j)} \cdot \alpha_{E(ej)} \frac{p^{t}_{E(j)}}{p^{t}_{e}}\right), \tag{A.1}$$

$$\sigma^{**}_{E(ej)} = \ln\left(\frac{\beta_{E(j)} \cdot a^{c2}_{ej}}{\beta_{j}^{\sigma-1}\left(\alpha_{Ej} \dfrac{p^{t}_{j}}{p^{t}_{E(j)}}\right)^{\sigma}}\right) \Bigg/ \ln\left(\beta_{E(j)} \cdot \alpha_{E(ej)} \frac{p^{t}_{E(j)}}{p^{t}_{e}}\right). \tag{A.2}$$

In the calculation, the parameters or variables -a, α, β, σ, and p- have the same values as the aforesaid result. The counterfactual point a^{c} determines the price substitution effect (PS) in the MCDA, whereas the counterfactual points a^{c1} and a^{c2} do the substitution effects in the CRSDA.

$\sigma^{*}_{E(ej)}$ is the fictitious 'substitution parameter' which is calculated by the comparison between a^{c1}, including the interfuel substitution (IFSUB), and the corresponding counterfactual point in the MCDA, including the price substitution effect (PS) in the bottom tier. Meanwhile, $\sigma^{**}_{E(ej)}$ is the fictitious 'substitution parameter' that is calculated between a^{c2}, including the overall substitution effect (SUB), and the corresponding counterfactual point in the MCDA, including the price substitution effect (PS) in both the top and bottom tiers. Therefore, Equation (A.1) determines how much $\sigma^{*}_{E(ej)}$ needs to reach a consensus between PS and IFSUB, and Equation (A.2) does how much $\sigma^{**}_{E(ej)}$ does between PS and SUB, holding the other variables constant with the aforesaid result. This analysis provides rough 'guesstimates' of the 'substitution parameters' for energy in the CRSDA.

Table A.1 and Table A.2 show the possible values of $\sigma^{*}_{E(ej)}$ and $\sigma^{**}_{E(ej)}$. It is notable that they can be calculated by energy type and by sector in Equations (A.1) and (A.2). Even though the parameters in Table A.1 and Table A.2 are expediently computed by the application of the MCDA framework to the CRSDA, they nevertheless vary widely, and differ in size from those in the existing literature that econometrically estimates these elasticities for the Japanese economy (see, e.g., Okushima and Goto 2001).

The results in Table A.1 and Table A.2 are nothing more than a kind of tentative interpretation of the underlying model in the CRSDA. It is a strong assumption in the above experiment that the CRSDA is restricted by the two-tier CES production function, and to change only the 'substitution parameters' for energy, while keeping the others constant. Nonetheless, the result implies that the underlying production function in the CRSDA could not be clearly predictable.

Table A.1 'Substitution parameter' for energy ($\sigma^{*}_{E(ej)}$) in CRSDA

		AGM	EII	MAC	OMF	SER
1970-75	COAL	1.26	1.41	1.31	1.31	1.09
	OIL	1.12	0.61	1.59	0.70	0.86
	GAS	1.02	1.10	1.24	1.15	0.91
	ELC	1.12	0.32	1.17	0.95	0.70
	Range	1.02---1.26	0.32--- 1.41	1.17---1.59	0.70---1.31	0.70---1.09
1975-80	COAL	1.12	*n.a.*	1.06	1.21	1.11
	OIL	0.95	*n.a.*	2.27	0.90	0.84
	GAS	1.00	0.88	1.03	0.95	0.95
	ELC	0.95	*n.a.*	1.20	1.00	0.46
	Range	0.95---1.12	*n.a.*---0.88	1.03---2.27	0.90---1.21	0.46---1.11
1980-85	COAL	1.08	1.35	1.22	1.05	1.09
	OIL	0.85	0.80	5.67	9.32	0.87
	GAS	0.97	1.16	1.43	0.75	1.04
	ELC	0.86	12.88	1.78	1.76	0.12
	Range	0.85---1.08	0.80---12.88	1.22---5.67	0.75---9.32	0.12---1.09
1985-90	COAL	0.92	0.85	0.90	0.97	0.94
	OIL	0.81	*n.a.*	1.39	1.95	0.52
	GAS	1.07	0.80	1.13	0.90	1.06
	ELC	0.83	2.11	1.24	1.30	*n.a.*
	Range	0.81---1.07	*n.a.*---2.11	0.90---1.39	0.90---1.95	*n.a.*---1.06

Note: "*n.a.*" (not available) indicates a negative value.

Table A.2 'Substitution parameter' for energy ($\sigma^{**}_{E(ej)}$) in CRSDA

		AGM	EII	MAC	OMF	SER
1970-75	COAL	1.32	2.76	1.39	1.29	1.14
	OIL	*n.a.*	*n.a.*	3.74	0.52	0.61
	GAS	1.06	1.04	1.48	1.13	0.95
	ELC	1.28	1.15	0.64	1.06	2.26
	Range	*n.a.*---1.32	*n.a.*--- 2.76	0.64---3.74	0.52---1.29	0.61---2.26
1975-80	COAL	1.12	*n.a.*	1.09	1.19	1.19
	OIL	0.97	0.24	3.58	0.54	0.47
	GAS	1.00	0.94	1.11	0.93	1.03
	ELC	0.95	1.26	0.89	1.16	1.24
	Range	0.95---1.12	*n.a.*---1.26	0.89---3.58	0.54---1.19	0.47---1.24
1980-85	COAL	1.16	1.79	1.19	1.10	1.15
	OIL	*n.a.*	0.25	4.29	14.62	0.55
	GAS	1.03	1.22	1.35	0.81	1.11
	ELC	1.11	0.65	2.13	0.80	1.17
	Range	*n.a.*---1.16	0.25---1.79	1.19---4.29	0.80---14.62	0.55---1.17
1985-90	COAL	0.92	1.10	0.95	0.99	1.00
	OIL	0.63	*n.a.*	1.78	2.30	0.14
	GAS	1.08	0.85	1.25	0.94	1.13
	ELC	0.85	1.05	0.54	0.99	*n.a.*
	Range	0.63---1.08	*n.a.*---1.10	0.54---1.78	0.94---2.30	*n.a.*---1.13

Note: "*n.a.*" (not available) indicates a negative value.

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