Online Appendixes

for

Decomposing aggregate CO_2 emission changes with heterogeneity: An extended production-theoretical approach

H. Wang[*], *B.W. Ang*[*], *and P. Zhou*[†]

A. Calculation of multiplicative effects in Eq. (9)

As discussed in Section 2.2, calculation of the effects in Eq. (9) is not straightforward. Relevant technique in index number theory is required. When using LMDI-I, the seven multiplicative effects in Eq. (9) can be calculated as follows:

$$D_{PCF} = \exp\left(\sum_{ij} w_{ij} \ln \frac{PCF_{ij}^{T}}{PCF_{ij}^{0}} \right) \tag{A.1}$$

$$D_{PEI} = \exp\left(\sum_{ij} w_{ij} \ln \frac{PEI_{ij}^{T}}{PEI_{ij}^{0}} \right) \tag{A.2}$$

$$D_{CP} = \exp\left(\sum_{ij} w_{ij} \ln \frac{\left(D_{C,ij}^{0}(T) D_{C,ij}^{T}(T)\right)^{1/2}}{\left(D_{C,ij}^{0}(0) D_{C,ij}^{T}(0)\right)^{1/2}} \right) \tag{A.3}$$

$$D_{EP} = \exp\left(\sum_{ij} w_{ij} \ln \frac{\left(D_{E,ij}^{0}(T) D_{E,ij}^{T}(T)\right)^{1/2}}{\left(D_{E,ij}^{0}(0) D_{E,ij}^{T}(0)\right)^{1/2}} \right) \tag{A.4}$$

[*] Department of Industrial and Systems Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260.

[†] Corresponding author. (Email: cemzp@nuaa.edu.cn. College of Economics and Management & Research Center for Soft Energy Science, Nanjing University of Aeronautics and Astronautics, No. 29 Jiangjun Avenue, Nanjing, China 211106.

$$D_S = \exp\left(\sum_{ij} w_{ij} \ln \frac{S_{ij}^T}{S_{ij}^0}\right) \tag{A.5}$$

$$D_U = \exp\left(\sum_{ij} w_{ij} \ln \frac{U_j^T}{U_j^0}\right) \tag{A.6}$$

$$D_Y = \exp\left(\sum_{ij} w_{ij} \ln \frac{Y^T}{Y^0}\right) \tag{A.7}$$

where w_{ij} is the weight function that is defined as $w_{ij} = L\left(C_{ij}^T, C_{ij}^0\right) \big/ L\left(C^T, C^0\right)$. The item $L(\cdot,\cdot)$ is the logarithmic function

$$L(a,b) = \begin{cases} \dfrac{a-b}{\ln a - \ln b}, \text{ if } a \neq b \\ a, \text{ if } a = b \end{cases}$$

B. Calculation of additive effects in Eq. (13)

Similar to Eq. (9), the calculation of the effects in Eq. (13) also requires techniques in index number theory. When using the additive LMDI-I, the nine additive effects in Eq. (13) can be calculated as follows:

$$\Delta C_{PCF} = \sum_{ij} w_{ij}^{'} \ln \frac{PCF_{ij}^T}{PCF_{ij}^0} \tag{B.1}$$

$$\Delta C_{PEI} = \sum_{ij} w_{ij}^{'} \ln \frac{PEI_{ij}^T}{PEI_{ij}^0} \tag{B.2}$$

$$\Delta C_{CE} = \sum_{ij} w_{ij}^{'} \ln \frac{CE_{ij}^0}{CE_{ij}^T} \tag{B.3}$$

$$\Delta C_{CTECH} = \sum_{ij} w_{ij}^{'} \ln \frac{\left(D_{C,ij}^0(0) D_{C,ij}^0(T)\right)^{1/2}}{\left(D_{C,ij}^T(0) D_{C,ij}^T(T)\right)^{1/2}} \tag{B.4}$$

$$\Delta C_{EE} = \sum_{ij} w_{ij}^{'} \ln \frac{EE_{ij}^0}{EE_{ij}^T} \tag{B.5}$$

$$\Delta C_{ETECH} = \sum_{ij} w_{ij}^{'} \ln \frac{\left(D_{E,ij}^{0}(0) D_{E,ij}^{0}(T)\right)^{1/2}}{\left(D_{E,ij}^{T}(0) D_{E,ij}^{T}(T)\right)^{1/2}} \tag{B.6}$$

$$\Delta C_{S} = \sum_{ij} w_{ij}^{'} \ln \frac{S_{ij}^{T}}{S_{ij}^{0}} \tag{B.7}$$

$$\Delta C_{U} = \sum_{ij} w_{ij}^{'} \ln \frac{U_{j}^{T}}{U_{j}^{0}} \tag{B.8}$$

$$\Delta C_{Y} = \sum_{ij} w_{ij}^{'} \ln \frac{Y^{T}}{Y^{0}} \tag{B.9}$$

where $w_{ij}^{'} = L\left(C_{ij}^{T}, C_{ij}^{0}\right)$.

According to Ang (2004), there exists a simple relationship between additive effects and corresponding multiplicative effects when using LMDI-I to conduct decomposition. For example, $\Delta C_{PCF} / \ln D_{PCF} = L(C^{T}, C^{0})$. It can be found that this relationship holds for all other effects.

C. Data processing details

As stated in Section 3.1, our dataset covers five economic sectors. To be consistent with China's statistical data, the transport sector in our study covers the transport, storage and post sectors, while the service sector includes the wholesale, retail trade, hotels and catering services. CO_2 emissions is calculated following the IPCC guidelines, and the conversion factor data is collected from the China Statistics Yearbook. The labor data for the agriculture sector is directly available in the yearbooks. For the other four sectors, however, this is not the case. We use the average employees in the above-designated-size industrial enterprises as a proxy for the industry sector's labor, use the number of staff and workers in construction enterprises as a proxy for the construction sector's labor, use the number of employed persons in transport, postal and telecommunication services as a proxy for the transport sector's labor, and use the number of employees in above-designated-size service enterprises as a proxy for the service sector's labor.

D. Brief description of IDA and SDA

In the literature, IDA and SDA have widely been applied to study changes in energy and emissions (Wang et al., 2017a). Taking aggregate CO_2 emissions in a country as an example, the conventional four-factor IDA model is defined as follows:

$$C = \sum_{ij} \frac{C_{ij}}{Y_{ij}} \frac{Y_{ij}}{Y_j} \frac{Y_j}{Y} Y = \sum_{j} I_{ij} S_{ij} U_j Y \quad \text{(D.1)}$$

where I denotes carbon intensity. All other notations are similarly defined as those in Section 2. A change in aggregate emissions can then be explained by the four factors, i.e. activity intensity, economy structure within region j, the economy's spatial structure, and the overall activity level. Following Eq. (D.1), the change in the aggregate emissions during time period 0 and T can be decomposed as

$$C^T - C^0 = \Delta C_{int} + \Delta C_S + \Delta C_U + \Delta C_Y \quad \text{(D.2)}$$

$$\frac{C^T}{C^0} = D_{int} D_S D_U D_{act} \quad \text{(D.3)}$$

where the subscript *int* denotes the intensity effect.

SDA is formulated on the basis of the I-O model. The conventional Leontief I-O model is given as:

$$x = \left(I - A_d\right)^{-1} q = L_d q \quad \text{(D.4)}$$

where x is the total output vector, q is the final demand vector and A_d is the domestic intermediate coefficients. $L_d = \left(I - A_d\right)^{-1}$ is the Leontief inverse matrix. Combined with energy/environmental multipliers, energy and emissions can be further modelled on the basis of Eq. (D.4). As an example, aggregate emissions is usually formulated as follows:

$$C = f L_d S_d Q \quad \text{(D.5)}$$

where f is the row vector of emission intensity that is defined as emissions per unit of total output, S_d is the final demand structure vector and Q is the total final demand. Equation (D.5) can be rewritten as:

$$C = \sum_{ij} C_{ij} = \sum_{ij} f_i L_{d,ij} S_{d,j} Y \quad \text{(D.6)}$$

where i and j denote sectors in the I-O table. Equation (D.6) shows that four factors, i.e. emission intensity, Leontief structure, final demand structure and total final demand, are responsible for the change in aggregate emissions. Similar to Eqs. (D.2)-(D.3), the arithmetic and ratio change in the aggregate energy consumption between time period 0 and T can be decomposed as:

$$C^T - C^0 = \Delta C_{int} + \Delta C_{lstr} + \Delta C_{dstr} + \Delta C_{tfd} \quad \text{(D.7)}$$

$$\frac{C^T}{C^0} = D_{int} D_{lstr} D_{dstr} D_{tfd} \quad \text{(D.8)}$$

where the subscript *lstr* denotes the Leonteif structure effect, *dstr* the final demand structure effect and *tfd* the total final demand effect. The Leontief structure effect captures the impact of an economy's production technology on energy use, which depicts the detailed relationship between the supply and demand of an economy. The final demand structure effect quantifies the impact of demand composition variation, and the total final demand effect reflects the impact of final demand volume change.

E. The traditional PDA model by Zhou and Ang (2008) and relevant decomposition results

Following Zhou and Ang (2008), an economy's aggregate emission is divided by regions (indexed by j and $j = 1, ..., N$). The emission of entity j is formulated as:

$$C_j = \frac{C_j}{E_j} \frac{E_j}{Y_j} Y_j \quad \text{(E.1)}$$

By incorporating relevant distance functions, Eq. (E.1) is rewritten as:

$$C_j = \frac{C_j / D_{C,j}}{E_j} \frac{E_j / D_{E,j}}{Y_j} D_{C,j} D_{E,j} Y_j \quad \text{(E.2)}$$

With the data in year 0 and T, the ratio change in entity j's emission is modelled as follows:

$$
\begin{aligned}
\frac{C_j^T}{C_j^0} &= \frac{\left(C_j^T \Big/ \left(D_{C,j}^T(T) D_{C,j}^0(T)\right)^{1/2}\right) \Big/ E_j^T}{\left(C_j^0 \Big/ \left(D_{C,j}^T(0) D_{C,j}^0(0)\right)^{1/2}\right) \Big/ E_j^0} \frac{\left(E_j^T \Big/ \left(D_{E,j}^T(T) D_{E,j}^0(T)\right)^{1/2}\right) \Big/ Y_j^T}{\left(E_j^0 \Big/ \left(D_{E,j}^T(0) D_{E,j}^0(0)\right)^{1/2}\right) \Big/ Y_j^0} \\
&\quad \left(\frac{D_{C,j}^T(T) D_{C,j}^0(T)}{D_{C,j}^T(0) D_{C,j}^0(0)}\right)^{1/2} \left(\frac{D_{E,j}^T(T) D_{E,j}^0(T)}{D_{E,j}^T(0) D_{E,j}^0(0)}\right)^{1/2} \frac{Y_j^T}{Y_j^0} \\
&= D_{PCI,j} D_{PEI,j} D_{CE,j} D_{CTECH,j} D_{EE,j} D_{ETECH,j} D_{act,j}
\end{aligned}
\tag{E.3}
$$

Equation (E.3) is referred to as the Z&A model. These seven effects in Eq. (E.3) can be calculated directly without use of any index number techniques. Using the dataset as described in Section 3.1, we conduct the decomposition analysis following the Z&A model. It should be noted that the five sectors in our dataset are aggregated together to fit Eq. (E.3). The decomposition results are summarized in Table E.1.

Table E.1 Decomposition results using Z&A model

Region	*Dpcf*	*Dpei*	*Dce*	*Dctech*	*Dee*	*Detech*	*Dgdp*	Total
Beijing	1.1024	0.8166	0.9255	0.8949	1.0000	0.8600	1.6392	1.0510
Tianjin	1.3318	0.8584	0.8752	0.8928	0.9099	0.8584	2.1575	1.5052
Hebei	0.7332	0.6165	1.0958	1.2930	1.1412	1.1951	1.7102	1.4939
Shanxi	0.6943	0.5773	0.8464	1.5584	1.0000	1.4404	1.6752	1.2755
Inner Mongolia	0.7780	0.5986	0.9338	1.3317	1.0443	1.2308	2.2705	1.6901
Liaoning	1.1480	1.0000	1.1370	0.7971	1.1823	0.7368	1.9622	1.7784
Jilin	1.3959	1.0000	0.9198	0.7971	0.9723	0.7368	2.0031	1.4687
Heilongjiang	1.5679	1.0729	0.6411	0.9819	0.7669	0.9175	1.7564	1.3088
Shanghai	1.0854	0.9050	1.0000	0.8928	1.0000	0.8584	1.6531	1.2445
Jiangsu	1.2243	0.9446	0.9191	0.9121	1.0012	0.8998	1.8601	1.6246
Zhejiang	1.2360	0.9688	0.7679	1.0027	0.8554	0.9364	1.7112	1.2638
Anhui	1.2798	1.0000	0.9111	0.8469	0.9358	0.8350	1.9281	1.4879
Fujian	1.4430	1.0458	0.6816	0.9892	0.8272	0.9412	1.9289	1.5282
Jiangxi	1.2095	1.0580	0.8339	0.9228	0.9638	0.8834	1.8861	1.5812
Shandong	1.2561	0.9833	0.9680	0.8142	1.0578	0.7493	1.8460	1.4245
Henan	1.3033	1.0580	0.8525	0.9228	0.8944	0.8834	1.8433	1.5799
Hubei	1.2708	1.0262	1.1142	0.7414	1.1484	0.7180	1.9217	1.7069
Hunan	0.9952	0.6395	0.6332	1.5267	0.7080	1.4615	1.9045	1.2124
Guangdong	1.1022	0.9138	1.0000	0.9203	1.0000	0.9138	1.8062	1.5298
Guangxi	1.1539	1.0000	0.9828	0.8469	1.0379	0.8350	1.9453	1.6192
Hainan	1.0943	1.0580	1.0091	0.9228	1.0653	0.8834	1.8012	1.8273
Chongqing	1.6444	1.2550	0.7302	0.8217	0.8739	0.7843	2.0292	1.7221
Sichuan	1.1193	1.0580	1.0705	0.9228	1.0415	0.8834	1.9223	2.0689
Guizhou	1.0000	0.6850	0.9873	1.0144	1.0000	1.0000	1.7131	1.1752
Yunnan	0.6864	0.5440	0.9647	1.4778	1.0000	1.4569	1.7633	1.3677
Shaanxi	1.7522	1.2550	0.6866	0.8217	0.8201	0.7843	1.9614	1.5653
Gansu	0.6811	0.5310	0.9816	1.5793	1.0000	1.5119	1.7018	1.4426
Qinghai	0.7517	0.7704	1.0227	1.3385	1.1735	1.2777	1.8550	2.2050
Ningxia	0.8818	0.6869	1.0000	1.0970	1.1185	1.0614	1.8723	1.4768
Xinjiang	0.9563	1.0000	1.2769	0.7971	1.4193	0.7368	1.6320	1.6611
National geometric mean	**1.0939**	**0.8728**	**0.9129**	**0.9962**	**0.9892**	**0.9506**	**1.8497**	**1.5104**