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# Multi-region comparisons of emission performance: The structural decomposition analysis approach

Bin Su[a,*], B.W. Ang[b]

[a] Energy Studies Institute, National University of Singapore, Singapore
[b] Department of Industrial and Systems Engineering, National University of Singapore, Singapore

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ABSTRACT

Structural decomposition analysis (SDA) has been widely used by researchers to study changes in carbon emissions or aggregate emission intensity over time in a country. These studies may be called temporal-SDA analysis. Similarly, SDA analysis can be conducted by studying variations in carbon emissions or aggregate emission intensity between countries or between regions in a country, i.e. a decomposition analysis conducted spatially. In spatial-SDA analysis, the objective is often to understand the contributions of factors such as emission intensity, Leontief structure, and final demand in explaining the difference in total carbon emissions or aggregate emission intensities between two countries or regions. We review the literature of spatial-SDA analysis and propose a spatial-SDA framework for multi-region comparisons. Both the additive and multiplicative SDA forms are presented in the framework. Using the framework, 30 geographical regions in China are compared and ranked based on their emission performance. This proposed framework can also be used to evaluate other performance indicators in multi-region comparisons.



## 1. Introduction

Decomposition analysis has been widely used by researchers to quantify the driving forces of changes of an aggregate indicator in economics, energy, emissions, and other social-economic areas over time. We shall refer to such studies as temporal decomposition analysis. Two popular decomposition analysis techniques in the literature are index decomposition analysis (IDA) and structural decomposition analysis (SDA).[1] Comparisons between IDA and SDA pertaining to methodological developments can be found in Su and Ang (2012a).

Besides temporal decomposition analysis, there is another type of decomposition analysis which looks into variations of an aggregate indicator (such as total energy or emissions, or energy or emission intensity) between regions and may be called spatial decomposition analysis. If the aggregate indicator is a performance indicator, spatial decomposition analysis can reveal the effects that contribute to differences in performance between countries or regions. Temporal decomposition analysis is useful for understanding the historical trend of a region's performance over time, while spatial decomposition analysis can provide insights into the relative performance of regions in a specific year. The concept of spatial decomposition analysis is similar to benchmarking analysis. It is particularly useful when the energy and emission performances of different regions within a country or countries within a world region are to be compared. As a result, these regions/countries can be ranked in terms of their energy or emission performances.

In the SDA literature, five studies dealing with spatial decomposition analysis on energy or emissions have been reported. The earliest work, Proops et al. (1993), study the difference in $CO_2$ emission between Germany and the UK. More recent studies look into differences of an absolute indicator (such as total $CO_2$ emissions or energy consumption) or an intensity indicator (such as emission intensity or energy intensity) among countries. For example, Chung (1998) analyzes differences in the $CO_2$ emissions among China, Japan, and South Korea, de Nooij et al. (2003) study the energy consumption differences among eight OECD countries, Alcántara and Duarte (2004) investigate the emission intensity performance differences among 14 EU countries, and Hasegawa (2006) compares the emission intensity performance among regions in Japan.

Recently, Ang et al. (2015) study the methodological issues in spatial-IDA analysis applied to multi-region comparisons of energy

* Corresponding author. Tel.: +65 6601 2075; fax: +65 6775 1831.
*E-mail addresses:* subin@nus.edu.sg, subin.nus@gmail.com (B. Su).

[1] The review of IDA studies applied to energy and emissions can be found in Ang and Zhang (2000) and Xu and Ang (2013), while the review of SDA studies applied to energy and emissions can be found in Hoekstra and van den Bergh (2002) and Su and Ang (2012a).

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performance. They review different approaches to spatial-IDA and propose a spatial-IDA framework for multi-region comparisons. Their proposed framework for energy efficiency comparisons is based on the multiplicative IDA. It cannot be simply extended to spatial-SDA because there are several features associated with the I–O framework which are unique to SDA, such as imports assumption (Su and Ang, 2013), decomposition forms (Su and Ang, 2012a; Su and Ang, 2015), I–O model selection (Su et al., 2013; Su and Ang, 2015), and approaches to calculating GDP (United Nations, 1999).

This paper proposes a spatial-SDA framework for multi-region comparisons of emission performance based on the I–O analysis. Both the additive and multiplicative decomposition forms are covered so that inter-region comparisons of absolute and intensity indicators can be conveniently studied. The additive SDA has been commonly used in energy and emission studies (Su and Ang, 2012a), whereas the multiplicative form has only been adopted in more recent studies, such as Fan and Xia (2012), Su and Ang (2014, 2015), and Zhang and Lahr (2014). The attribution analysis for SDA proposed in Su and Ang (2014) allows the contributions by sector to the aggregate indicator change in multiplicative SDA be quantified. Through combining the multiplicative spatial-SDA and attribution analysis, the emission performance index at both the aggregate and sectoral levels for cross-region comparisons can be constructed.

The sections that follow are organized as follows: Section 2 discusses the general spatial decomposition analysis framework and different approaches to spatial-SDA. In Section 3, four different I–O models for spatial-SDA analysis using the Leontief I–O framework are formulated. Numerical results of an empirical study using China's regional dataset (30 regions and 42 sectors for each region) are presented in Section 4. Discussion and conclusions are presented in Section 5.

## 2. Spatial decomposition analysis framework

In decomposition analysis, the aggregate measure of interest is presented as the summation of sub-category values. Assuming the aggregate refers to a region and the sub-categories are industry sectors which is often the case in SDA studies. For any region $n$, further assume that the sub-category $y_n(x_1, x_2, \ldots, x_m)$ is a function of $m$ factors and $y_n(x_1, x_2, \ldots, x_m) = x_{n,1} \cdot x_{n,2} \ldots x_{n,m}$. The identity for any region $n$ can then be written as

$$V_n = \sum_{k=1}^{K} V_{n,k} = \sum_{k=1}^{K} y_{n,k}(x_1, x_2, \ldots, x_m) = \sum_{k=1}^{K} x_{n,1k} \cdot x_{n,2k} \cdot \cdot x_{n,mk} \quad (1)$$

where $V_n$ is the aggregate measure, $V_{n,k} = y_{n,k}(x_1, x_2, \ldots, x_m)$ is the sub-category of the aggregate for the $k$th sector, $x_{n,ik}$ is the value of $i$th factor at the $k$th sector, and $K$ is the number of sub-categories.

For a group of regions $\Phi = \{1, 2, \ldots, N\}$, spatial-SDA focuses on understanding the differences between any two regions' aggregate measures. Taking region $R1$ and $R2$ as an example, the aggregate measure difference between $V_{R1}$ and $V_{R2}$ can be measured as the absolute difference $\Delta V^{(R1-R2)} = V^{R1} - V^{R2}$ or the ratio $D^{(R1-R2)} = V^{R1}/V^{R2}$. We can decompose $\Delta V^{(R1-R2)}$ or $D^{(R1-R2)}$ to give the contributions to this difference as

$$\Delta V^{(R1-R2)} = \sum_{i=1}^{m} \Delta V_{x_i}^{(R1-R2)} \quad \text{or} \quad D^{(R1-R2)} = \prod_{i=1}^{m} D_{x_i}^{(R1-R2)} \quad (2)$$

where $\Delta V_{x_i}^{(R1-R2)}$ and $D_{x_i}^{(R1-R2)}$ give the effects associated with factor $x_i$ in additive and multiplicative decomposition analyses respectively. When perfect decomposition techniques are used, there is no residual term on the right-hand side of Eq. (2).

With only two regions in the group $\Phi$, i.e. $N = 2$, it is easy to use Eq. (2) in spatial decomposition analysis, such as in Proops et al. (1993). If the number of regions in the group $\Phi$ is three or more, i.e. $N \geq 3$, there are a few approaches to conducting spatial decomposition. The review by Ang et al. (2015) presents three of them, namely the bilateral-regional (B-R), radial-regional (R-R), and multi-regional (M-R) approaches.

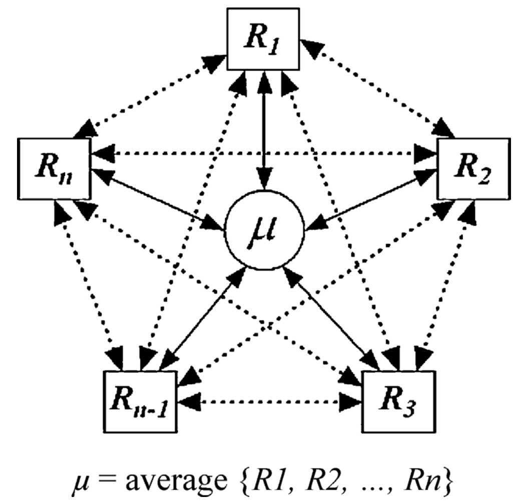


**Fig. 1.** The multi-regional (M-R) approach to spatial decomposition analysis.

In the B-R approach, every two regions in the comparison group are compared. The advantage is simplicity. The disadvantages are that the number of decomposition pairs increases exponentially with the number of regions. For example, there are 15 decomposition pairs for six regions and 45 pairs for 10 regions. Furthermore, the linkages between the results of different decomposition pairs are not obvious or unknown. Chung (1998) analyzes the $CO_2$ emission differences among China, Japan, and South Korea using the B-R approach.

In the R-R approach, a benchmark region is first chosen. Decomposition analysis is conducted between each target region and the benchmark region. The number of decomposition pairs is greatly reduced as compared to the B-R approach. However, the decomposition results depend heavily on the benchmark region and comparisons between target regions are difficult to make. Unless a benchmark region is prescribed or strongly preferred, the decomposition results obtained could be fairly arbitrary. de Nooij et al. (2003) apply the R-R approach to comparing the energy consumption of seven OECD countries with that of the US.

To avoid the drawbacks found in the B-R and R-R approaches, Ang et al. (2015) propose the use of the M-R approach. In this approach, comparison is made between each target region and the group average. A very desirable property of this approach is that the results obtained pass the circularity test.[2] This ensures consistency in the decomposition results irrespective of the order in which the regions in the comparison group are arranged in the decomposition analysis. The numerical results that are directly obtained through decomposition analysis can be easily used to generate "indirect" decomposition results which are both valid and meaningful. Fig. 1 shows the concept of the M-R approach. The solid lines indicate the direct decomposition analysis between each region and the group average, while the dash lines indicate the indirect calculations that can be performed based on their direct decomposition results. For

[2] In index number theory, the circularity test requires that given three ordered periods T1, T2 and T3, the price index for periods T1 and T2 times the price index for periods T2 and T3 should equal to the price index for period T1 and T3 (Balk, 2008).