CO₂ Mitigation in Fujian Province: an Input-output based Network Utility Analysis Method

G. Y. Wang¹, J. Liu¹,a, Y. K. Ding², L. R. Chen¹ and Y. P. Li¹,b

¹School of Environmental Science and Engineering, Xiamen University of Technology, Xiamen 361024, China
²State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, China

Corresponding Author E-mail: a zyljing@126.com; b yongpingli33@163.com

Abstract. This paper proposes an input-output based network utility analysis model to diagnose urban CO₂ emissions metabolism. It is applied to Fujian Province to demonstrate its feasibility. The direct and indirect CO₂ emissions of six major sectors are calculated using the input-output table. It is revealed that the total carbon emissions of the industrial sector were higher than other sectors, accounting for 74% of Fujian Province total carbon emissions. And the indirect emissions generated during the consumption process in the industrial sector were also the largest, with 0.43×10⁹ tons of emissions. The wholesale and retail catering sector had the smallest carbon emissions, with only 14.9×10⁶ tons of emissions. In addition, carbon emissions in all industries were on the rise. Then, network utility analysis is employed to define the various relationships between different sectors. It is found that the mutual relationship between various sectors in Fujian Province has developed from 1 pair of competition relationships to 3 pairs of competition relationships, which has reduced from 13 pairs of exploitation relationships to 12 pairs of exploitation relationships. The results can help to provide integral reference for policy makers to propose the effective mitigation strategies.

1. Introduction

As the world's largest developing country, China is in a period of rapid industrialization. However, the continuous improvement of economic level inevitably leads to the continuous increase of carbon emissions [1]. As China’s first ecological civilization demonstration zone and one of the earliest areas to open to the outside world, the carbon emissions of Fujian increased from 4480 million tons in 1996 to 22245 million tons in 2016, nearly 5 times [2]. Consequently, it is vital to study carbon emissions between various industries in Fujian Province and the interrelationship between various industries.

Previously, Leontief put forward the concept of input-output table (IOT) which systematically analysed the interdependence (e.g., intricate monetary transactions) between various social-economic sectors [3]. Then, researchers converted monetary IOT into physical IOT (e.g., energy, carbon, water, etc) through introducing the specific calculation formulas [4]. Zhang et al. analysed urban metabolic processes of Beijing based on input-output method [5]. Jain used input-output analysis (IOA) to
measure the intrinsic energy present in commodities [6]. Singh et al. have combined the carbon cycle with economic input-output models to account for emissions and convergence of the carbon biogeochemical cycle in the America [7]. The IOT can reflect the source of production inputs and the distribution of various products, and can clearly reveal the intrinsic link of the industrial structure of each sector. It can also reflect the direct and indirect relationship between different sectors of the production process, the balance between production and distribution and use, and the balance between production and consumption. However, IOT cannot directly analyze the interrelationships between sectors, such as competition relationships, exploitation relationships, and mutualism relationships, and thus cannot provide advice for improving the relationship between sectors. Network control analysis (NUA) is a mathematical method used to measure the control or dominance of a department to another department in its natural environment [8]. Fath et al. used NUA to uncover the mutual relationships between different sub-departments of the urban metabolic system [9]. Fath analysed positive utility in ecosystems based on NUA [10]. IOT coupled with NUA can be effectively revealing the integral mutual relationships and the structure of the network.

However, the research about carbon emission in Fujian province is still limited, most of which are concentrated on direct emission. Moreover, previous studies have mostly concentrated on the impact of a single department on carbon emissions, ignoring the integral impact of other departments. And most of which are concentrated on direct emissions, and there is currently no research on carbon emissions in Fujian Province based on input-output table use with network utility analysis. Therefore, the use of network utility analysis based on input-output tables is essential for the study of carbon emissions across sectors.

2. Methodology
For the value input-output tables, the horizontal of a table means the circulation of the output of each sector in the entire economic system and the columns represents the intermediate input of all other sectors required for the output of the sector [11]. We define department i to department j as \( f_{ij} \), and the value input-output table can be transformed into the physical input-output table according to the formula (1) and (2)[12].

\[
E + \varepsilon H = \varepsilon M
\]  
\[
\varepsilon = E[M - H]^{-1}
\]

Where \( E \) represents the initial resources of the department, \( H \) is the value flow of each sector in the value input-output table, and \( M \) represents a diagonal matrix of the total output of each department. Here, carbon emissions as the negative resource for the input. Then:

Network utility analysis was first developed by Patten and was used to analyse interrelationships between sectors [13]. The direct utility matrix \( D \) identifies the direct relationships between different sectors, which could be calculated as in equation (3).

\[
d_{ij} = \frac{f_{ij} - f_{ji}}{T_i}
\]

Where matrix element \( d_{ij} \) represents the utility of the flow from sector j to sector i. The role of the matrix \( U \) is to identify whether the indirect flow path between departments is from sector i to sector j or from department j to department i, as shown in equation (4).

\[
U = (I - D)^{-1}
\]

Where \( u_{ij} \) indicates the integral value of \( d_{ij} \), which is calculated using a Leontief inverse matrix. The data of matrix \( D \) and matrix \( U \) are used for analysis. For each pair of sectors whose flow sector i to sector j or sector j to sector i. Two signs can be obtained: ‘+’, ‘−’, where ( +, + ) means
mutualistic relationship, (−,−) for competition, (−,+), or (+,−) represents exploitation relationship [14]. For example, \((u_{21}, u_{12}) = (+,−)\) indicates that sector 2’s output to sector 1 is less than sector 1’s output to sector 2. \((u_{21}, u_{12}) = (0,0)\) indicates that the outputs of the two sectors are equal, and \((u_{21}, u_{12}) = (−,−)\) indicates that sector 1 competes with sector 2 [15]. The carbon emission data and energy use data of various departments are taken from the China Energy Statistical Yearbook 2007 compiled by the Central Government and Fujian Province, China Energy Statistical Yearbook 2012, Fujian Statistical Yearbook 2007 and Fujian Statistical Yearbook 2012.

3. Results and discussion

Since indirect emissions flows are much higher than direct emissions, it is vital to analyse the indirect emissions flows for each sector. Indirect carbon emissions \((\sum_{i=1}^{n} f_{ji})\) for different sectors were obtained from the input-output table of Fujian Province.

![Figure 1. Indirect and direct carbon emissions a. 2007 b. 2012.](image)

As shown in Figure 1a, obviously, the direct and indirect carbon emissions of the Ind department are much higher than other departments. And all industries emit more indirect emissions than direct emissions except Tra sector. The direct emission of Ind sector is caused by the direct consumption of a large amount of fossil energy in the production process, while the indirect emission is twice as much as the direct emission, which indicates that the Ind sector also produces a large number of indirect emissions in the consumption process. For example, the emission generated when transferring various mechanical equipment and maintaining machines. The same phenomenon can be founded in Agr sector, Wrc sector and Ser sector. It is worth mentioning that indirect emissions from the Con sector are nearly ten times greater than direct emissions because the Con sector produced lots of emissions during the consumption process. For example, build housing and the construction of infrastructure would generate little direct emissions, and most of those emissions are generated almost entirely from the use of gasoline and electricity.

As shown in Figure 1b, the overall trend is similar to Figure 1a, with a partial increase in total emissions for each sector. Likewise, Ind sector remains the biggest emitter, either directly or indirectly. Therefore, in order to reduce carbon emissions in the industrial sector, we need to reduce fossil energy use in the Ind sector. In addition, reducing carbon emissions in the consumption process of the construction industry, that is, improving technology to reduce the use of fossil energy in the construction process, is also one of the effective ways to reduce emissions.
Figure 2. Intersectoral carbon dioxide flows in Fujian Province. a. 2007. b. 2012.

We analysed the carbon dioxide flows between sectors in Fujian Province in 2007, as demonstrated in Figure 2a. To investigate the sources of CO₂ in various sectors, we analysed the carbon flows between each sector and the inflows and outflows for each sector according to the width of the flows. According to carbon dioxide flows in the sectors as shown in Figure 2a and Figure 2b, it can be seen that major carbon dioxide outflow sector was Ind sector, while the main carbon dioxide inflow was also Ind sector. Ind as an outflow sector, transferred a large amount of carbon dioxide to Ind sector, Con sector and Ser sector, among which Ind sector transferred the most carbon dioxide to Ind sector, accounting for more than 40% of the total carbon dioxide flow. In addition, Tra sector is the second largest carbon dioxide outflow sector, accounting for 28 percent of the total carbon dioxide flow.

Figure 2b is the carbon dioxide flow chart of each sectors in Fujian Province in 2012. By comparing Figure 2a. and Figure 2b, we find that the flow trend of carbon dioxide in various sectors has hardly changed. But the total flow of carbon dioxide in each sector has almost doubled. The reason for this phenomenon is that from 2007 to 2012, the use of fossil energy in Fujian Province has gradually increased with the development of the economy, so the carbon emissions of various sectors have almost increased.
Figure 3. The relationship between sectors in the direct utility matrix (D). a. 2007 c.2012
The relationship between sectors in the integral utility matrix (U). b. 2007 d.2012

Figures 3a and 3b present the direct utility matrix (D) and integral utility matrix (U) in 2007, respectively. As shown in Figure 3a, it is revealed that the direct relationship of all 15 pairs would be exploitation. For example, \((D_{3,4}, D_{4,3}) = (0.066, -0.056)\) means that Tra department has a positive impact on Con department. And the output of Con department to Tra department less than the output from Tra department to Con department. As shown in Figure 3b, it is discovered that the integral relationship of various sectors would be exploitation and competition (accounting for 86.67% and 13.33%, respectively).

For exploitation relationship, \((U_{1,6}, U_{6,1}) = (0.019, -0.022)\) represents that the positive utility of Ser department to Agr department is 0.019. \((U_{3,6}, U_{6,3}) = (-, -)\) indicates that the Con sector and Ser sector are in a competitive relationship, which is beneficial to the devaluation of carbon emissions as a negative resource. In addition, all the values in row Tra are positive which indicates that Tra has been used by most sectors. The Tra department have positive impacts on other departments, that is, the positive impact of the Tra sector on other sectors is that reduced inter-sectoral mobility between the Tra department and other departments will contribute to the reducing carbon emissions from the Agr, Ind and other sectors.

The same or similar symmetric color blocks represents the mutual or competitive relationship between two sectors. For Con and Ser sectors, the colors of the two squares are light blue stand for the competitive relationship between the two sectors. For negative resources, the competitive relationship is conducive to achieving the goal of carbon emission reduction.

Similarly, we analysed the direct relationship between various departments in Fujian in 2012, as shown in Figure 3c. There is also only one relationship: exploitation (i.e. 15 pairs). It's worth noting that there are 3 pairs of competitive relationships in Figure 3d. The three competitive sectors are Agr and Con, Ind and Wrc, Ser and Con, respectively. In general, comparing Figure 3a. with Figure 3c, we can see the direct interrelationship between various departments in Fujian Province has hardly changed between 2007 and 2012. Comparing Figure 3b with Figure 3d, the exploitation has reduced by 1 and the competition has increased by 1. It can be seen that the carbon emission structure of Fujian Province is developing in a favorable direction. While maintaining the status quo, in order to transform the department into competitive relationship to achieve the goal of reducing emissions faster, it is vital to reduce mutual carbon emissions by improving production technology.

4. Conclusions
The study uses input-output economic analysis formulas to calculate direct and indirect carbon emissions between each department, emphasizes the importance of direct and indirect flows between departments and analyses the interrelationships between departments. From the direct and indirect carbon emissions of various sectors, carbon emissions from the Ind sector remain the main source of carbon emissions today. Therefore, in order to achieve the goal of carbon emission reduction, the Ind sector should reduce the consumption of fossil energy, or improve production technology to replace fossil energy with clean energy.

From the perspective of carbon flows between sectors, the competitive relationship between
sectors will be a means of reducing carbon emissions, so technical updates are needed to change the relationship between sectors. NUA discovers the mutual relationships between different sectors. From a carbon emissions perspective, the competitive relationship between sectors is favorable in terms of carbon emission reduction.

In terms of intersectoral relationships, 12 pairs of sectors were exploitative, accounting for 80 percent of the total, while competition and reciprocity accounted for less than 20 percent. It is necessary to increase the number of competition relationships between sectors in order to achieve carbon reduction targets.

The study concludes that the competition relationship shows a good interaction with regard to emission reductions, while the mutualism relationship affords an effective way to mitigate emissions between the pair of sectors. And network utility analysis can help to discern whether sectors should adjust production structure. We hope that this paper can provide suggestions for policy makers to promote the development of low-carbon industry.

Acknowledgement
This research was supported by the High Level Talents Programming of Xiamen University of Technology (Grant No. YKJ17018R) and Scientific Research Climbing Plan of Fujian Province (Grant No. JT180453).

References
[1] Shan Y, Guan D, Zheng H, et al. 2018 China CO2 emission accounts 1997-2015 Sci. Data 5 170–201.
[2] Liu ZY, Tan HQ, et al. 2018 Analysis of the impact factors on carbon emission in Fujian province IOP Conference Series: Earth and Environmental Science. 170 11–12.
[3] Leontief W W Q 1936 uantitative input and output relations in the economic systems of the United States Rev. Econ. Stat. 18 (3) 105–125.
[4] Duchin F 2004 Input-output economics and material flows Input-output economics and material flows. Rensselaer Working Paper Economics. 0424 23–41.
[5] Zhang Y, Liu H, et al. 2014 Analysis of urban metabolic processes based on input-output method: model development and a case study for Beijing Front. Earth Sci. 8 (2) 190–201.
[6] Jain S. 2012An input-output analysis to estimate embodied energy of goods Int. J. Sci. Res. Publ. 2 1-12.
[7] Singh S, Bakshi, B R. 2015 Accounting for emissions and sinks from the biogeochemical cycle of carbon in the U.S Ind. Ecol. 18 (6) 818–828.
[8] Sun X, An H. 2018 Emergy network analysis of Chinese sectoral ecological sustainability. Clean. Prod. 174 548–559.
[9] Fath B D, Borrett S R. 2006 A MATLAB® function for network environ analysis Environ. Modell. Softw. 21 375–405.
[10] Fath B D. 2007 Network mutualism: positive community-level relations in ecosystems Ecol. Model. 208 56–67.
[11] Simpson D, Tsukui J. 1965 The fundamental structure of input-output tables, an international comparison Rev. Econ. Stat. 47 (4) 434–446.
[12] Zhang Y, Zheng H, et al. 2014 Ecological network analysis of an urban metabolic system based on input-output tables: model development and case study for Beijing Sci. Total Environ. 468–469 642–653.
[13] Patten B C. 1992 Energy, emergy and environs Ecol. Model. 62 (1-3) 29–69.
[14] Li S, Zhang Y, Yang Z, et al. 2012 Ecological relationship analysis of the urban metabolic system of Beijing, China Environ. Pollut. 170 (8) 169.
[15] Li J Z, Huang G H, Liu L R. 2018 Ecological network analysis for urban metabolism and carbon emissions based on input-output tables: A case study of Guangdong province Ecol Model. 383 118–126.