

## **Input-Output Analysis for Sustainability**

Ming Xu, Braden Allenby, and Junbeum Kim

Arizona State University, Department of Civil and Environmental Engineering  
P.O. Box 875306, Tempe, AZ 85287, USA



**Center for Sustainable Engineering**

A Center for Sustainable Engineering Education Module

## SUMMARY

Almost all the environmental and sustainability problems we are confronted with today are related to human economic activities, which are spreading to every corner of the world in this era of globalization. For this reason, it is important to develop methods to understand the structural characteristics of economic systems and their relationships to environmental systems, especially at national and regional scales. Improved data and analytical techniques are also needed to guide business leaders and policy makers, as well as educators and the next generation of students.

The main purpose of this course module is to introduce concepts and methods of input-output analysis, and to show how they can be used to develop a better understanding of the world humans are creating, and advance the study of economic and environmental systems, and thus sustainability. There are three components to this module. The first part introduces the history and general terms of input-output analysis, and an overview of how to construct input-output tables and the computational structure of the input-output analysis. Methods of applying input-output analysis to the study of sustainability are then discussed. Finally, a case study of input-output analysis for sustainability study, the physical input monetary output (PIMO) model, is presented.

The target audiences of this module are advanced undergraduate engineering classes and graduate classes in sustainable engineering and industrial ecology.

This module is part of a series designed for the Center for Sustainable Engineering (CSE). Instructors' guides and further information are available at the Center's website ([www.csengin.org](http://www.csengin.org)).

**Keywords:** Input-output analysis (IOA); monetary input-output table (MIOT), physical input-output table (PIOT); industrial ecology; sustainability

# Input-Output Analysis for Sustainability

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*“[The Pioneer of input-output analysis, Wassily] Leontief has argued that if you want to explain an economy to high school students, it is extremely confusing if you begin to talk about supply and demand curves. Nobody ever saw a supply or a demand curve, while the movement of commodities and services between different sectors, which provides the logic of input-output analysis, can be observed and described.” (Amsden, 1995).*

## 1. Introduction

Since the Industrial Revolution, human economic activity has been among the strongest and most dominating forces on the Earth. In this era of globalization, economic activities are spreading to almost every corner of the world. As a result, there are a great number of demands for analysis of changing patterns of economic structure, as well as pressures to understand the environmental impact of human activities such as carbon dioxide (CO<sub>2</sub>) emissions. Improved data and analytical techniques are also needed to guide business leaders and policy makers, and so that educators and the next generation.

The main purpose of our work is to show how input-output analysis can better understand the world human are creating, benefit the study of economic and environmental systems, and thus sustainability. The paper contains three components. The first part introduces the history and general terms of input-output analysis, and how to construct input-output tables and the computational structure of the input-output analysis. The second part discusses the main topic and methods of applying input-output analysis to the study of sustainability. Finally, a case study of input-output analysis for sustainability study, the physical input monetary output (PIMO) model, is presented.

## 2. Input-output economics

*“It is not too early to predict that any list of the four or five major advances in economics during the twentieth century will include input-output analysis. Input-output analysis is the creation of a single person with a unique endowment of talent, training, vision, and persistence.” (Dorfman, 1995)*

### 2.1 History of input-output economics

Although the earliest insight can be traced back to François Quesnay (1694-1774), input-output economics was founded and popularized by the 1973 Nobel Laureate in economics, Wassily Leontief (1905-1999). Leontief was originally from Russia, and resided in the United States. In 1932, at Harvard University he developed the first economic input-output table, containing 500 U.S. economic sectors (Leontief, 1936; 1941; 1951). Inspired by his work, a group of

economists and professionals has continued to work on input-output analysis, developing it to be a powerful technique for quantitative economic study.

In 1988, the International Input-Output Association (IIOA)<sup>1</sup>, a scientific non-profit organization dedicated to the advancement of knowledge in the field of input-output analysis, was founded. IIOA has now grown into a world-wide network of economists, government officials, engineers and managers with interests in input-output analysis. In academia, there are a range of peer-reviewed journals, such as *Economic Systems Review*, *Structural Change and Economic Dynamics*, and international and regional conferences setting up a world-wide network on input-output analysis. In particular, the International Input-output Conference, the most important event in the academic input-output community, has a long history of more than 50 years.

Another major party involved in input-output economics is government statistical agencies. After Leontief constructed the first input-output table for the U.S. in the early twentieth century, governments of major industrialized countries, including the U.S., Japan, and some European countries, began to develop national input-output tables. At this point, most of economically important countries, including both industrialized and developing ones, have developed and used input-output tables for years. For instance, the Organisation for Economic Co-operation and Development (OECD) has input-output tables harmonized from various sources for its member countries and other major countries such as China and Russia (Yamano and Ahmad, 2006).

Due to its comprehensive but easy-to-understand description of complex economic systems, input-output analysis has been one of the major statistical tools for most economically important countries in the world for years. As a result, almost free input-output databases are available for researchers and professionals working on economic analysis and related fields. This is a main practiced reason why input-output analysis has always been popular.

## 2.2 General terms

Generally, input-output analysis divides the economic system into a number of sectors, and considers the flows of commodities and services in and out of each sector. Because each sector can have flows to and from any other sector, the amount of information such a model contains increases rapidly as the number of sectors in the system is increased. Obviously, the processing and cost of data collection will also be harder and more expensive.

In practice, the basic framework of input-output analysis consists of two models, a quantity model and a price model. The quantity model can use either physical units such as tons steel or number of computers, or monetary units. In the latter case, it is easy to confuse the price input-output model and the monetary input-output model. Those two terms, however, are not the same; the latter one is just one form of quantity input-output model (Duchin, forthcoming). The most widely used input-output model is in fact the monetary model because it forms the basis of national economic accounting systems. Thus, Monetary Input-Output Tables (MIOTs), are available for most countries today (Hubacek and Giljum, 2003). In the following sections, the general and computational structures of IOT are introduced.

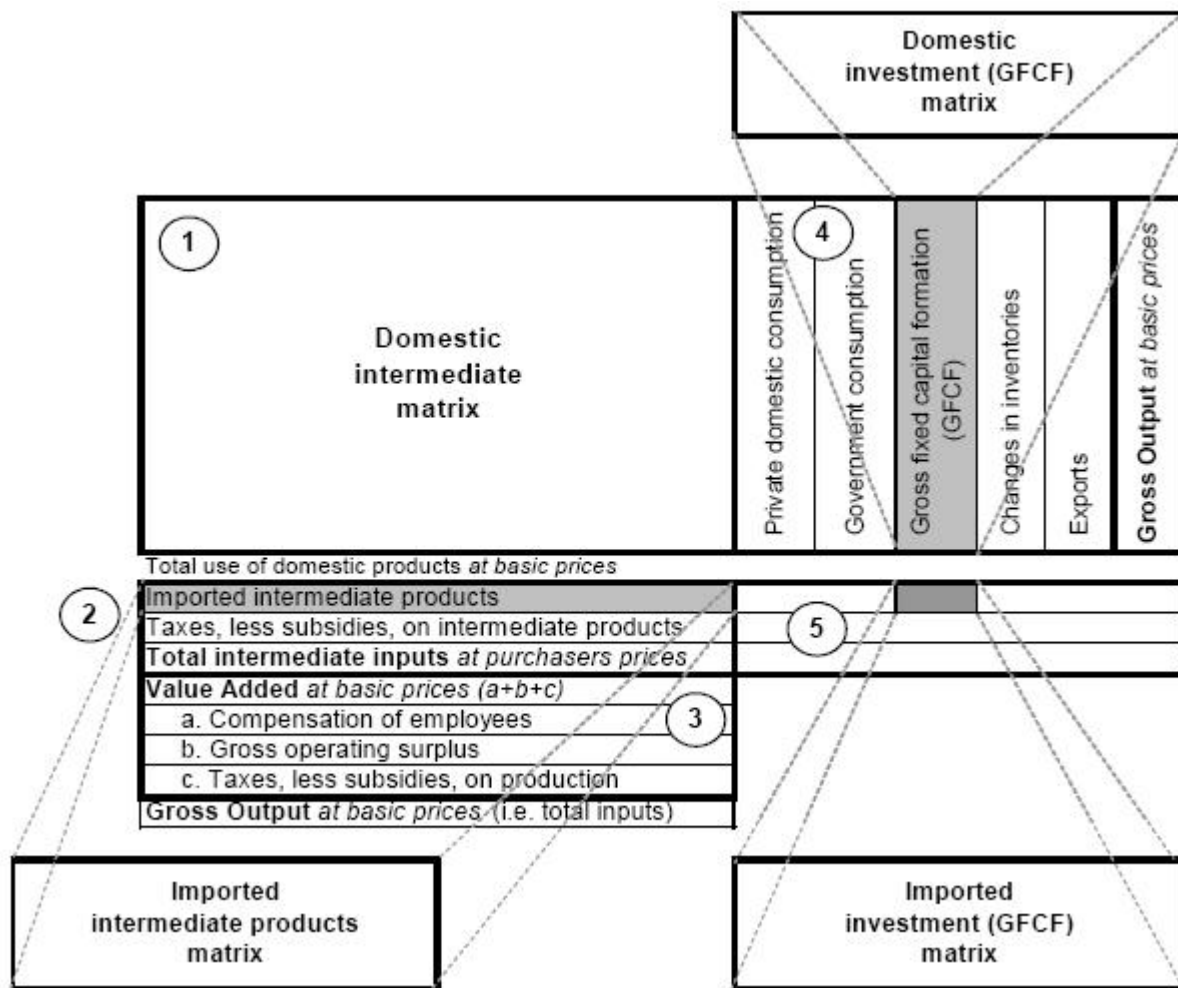
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<sup>1</sup> <http://www.iioa.org>

### 2.3 Input-output tables

Essentially, the basic layout of input-output tables is in rows and columns. The rows represent the outputs of a sector, and the columns indicate the destination of inputs. Therefore, the matrix represents an economic system in two-way recording, namely that the total input and output of any sector are equal to each other. In research practice, especially for sustainability research, simplified input-output matrices are commonly adopted, which contain the information and data about interactions between each pair of sectors.

In general, an input-output table, most typically for national economic system, contains five sections, as illustrated in the Figure 1.



**Figure 1.** The basic structure of an input-output table (source: Wixted *et al.*, 2006)

The first section is the domestic intermediate matrix, which is a square matrix with equal number of supplying and using sectors. The domestic intermediate matrix provides the data about interactions between each pair of domestic sectors of domestically processed raw materials, semi and final products, and services, quantified as prices.

The second section contains imports of intermediate goods and services, taxes less subsidies (net taxes) and import duties paid on intermediate products. This section is used to adjust differences between the total domestic intermediate inputs (at basic prices) and total intermediate inputs (at purchaser's prices)<sup>2</sup>.

The third section consists of value added at basic prices such as wages, salaries, and gross operating surplus.

The fourth section comprises of goods and services which are not consumed by domestic sectors. Those products include final consumption both households and governments, gross fixed capital formation (investment) and exports.

The last section contains imported goods for final use and the associated taxes less subsidies, which can be added to the fourth section to provide total final use at purchaser's prices.

#### 2.4 Computational structure

In this section, a simplified table is used to represent the computational structure of input-output analysis. Both of the models of input-output computation, the quantity model and the price model, use the same mathematic base.

**Table 1.** Simplified input-output table

Input		Output	Intermediate Output				Final Demand	Total Output
			Sector					
			1	2	...	n	Y	X
Intermediate Input	Sector	1	$x_{11}$	$x_{12}$		$x_{1n}$	$Y_1$	$X_1$
		2	$x_{21}$	$x_{22}$		$x_{2n}$	$Y_2$	$X_2$
		...						
		n	$x_{n1}$	$x_{n2}$		$x_{nn}$	$Y_n$	$X_n$
Value-added		V	$V_1$	$V_2$		$V_n$		
Total Input		X	$X_1$	$X_2$		$X_n$		

As illustrated in Table 1, an economic system consists of  $n$  sectors. The product or service flow from sector  $i$  to sector  $j$  is expressed by element  $x_{ij}$ . The final demand of sector  $i$ , which means the sector's products finally consumed by consumers, is presented as  $Y_i$ .  $V_i$  represents value-added of sector  $i$ . There is input-output balance for each sector, which means the total input of a sector is equal to its total output. In the input-output table, the total output of sector  $i$  expressed as  $X_i$  is equal to the summation of all intermediate products and the final demand of that sector. The total input of sector  $i$ ,  $X_i$ , is equal to the summation of all intermediate inputs and the value-

<sup>2</sup> The terms of basic price and purchaser's price can be reached in common economics textbooks. See also United Nations (1999).

added of that sector. It should be noted that one can also include flows of import from and export to the outside of the system, which is not expressed in this simplified input-output table.

### Input-output quantity model

Based on the input-output table, one can derive the matrix of input-output coefficients, so called technical coefficients, by dividing the matrix of  $x_{ij}$  by total outputs  $X_j$ :

$$a_{ij} = x_{ij} / X_j \quad (1)$$

Express the  $n \times n$  matrix of  $a_{ij}$  as  $A$ , which is called the technical coefficients matrix. The technical coefficient represents the share of input from each sector required to produce one unit of sectoral output. Consequently, the general equation for this input-output model is:

$$X = (I + A + A \times A + A \times A \times A + \dots)Y = (I - A)^{-1}Y \quad (2)$$

with  $X$ ;  $n \times 1$  vector of total outputs,  $I$ ;  $n \times n$  identity matrix,  $Y$ ;  $n \times 1$  vector of final demands. In this equation, the terms represent the total input required by final demand itself ( $I \times Y$ ), contributions from the direct or first level suppliers ( $A \times Y$ ), the second level indirect supplies ( $A \times A \times Y$ ), etc. The complete input required by final demand is expressed by this infinite series of the supply chain which can be substituted by  $(I - A)^{-1}$ .

The technical coefficient is also called direct consumption coefficient. Besides, there are also indirect effects of final consumption in the input-output economic systems, represented by  $A \times Y$ ,  $A \times A \times Y$ , etc. The cumulative effect of direct and indirect consumption can be expressed as following:

$$b_{ij} = 1 + a_{ij} + \sum_{k=1}^n a_{ik} a_{kj} + \sum_{i=1}^n \sum_{r=1}^n a_{ik} a_{kr} a_{rj} + \sum_{i=1}^n \sum_{r=1}^n \sum_{t=1}^n a_{ik} a_{kr} a_{rt} a_{tj} + \dots, \quad (i, j = 1, 2, \dots, n)$$

where  $b_{ij}$  is called cumulative input coefficient. Rewrite the above equation to matrix format:

$$B = I + A + A^2 + A^3 + A^4 + \dots = (I - A)^{-1} \quad (3)$$

where  $B$  is called cumulative input coefficient matrix which expresses the cumulative effects of economic output of one sector on other sectors.

### Input-output price model

Even if monetary units are used, the quantity input-output model cannot deal with price issues. Therefore, the price model is developed based on the same balance idea, represented by the following equation.

$$(I - A')p = V \quad (4)$$

where  $p$  is  $n \times 1$  vector expressing the unit price of output in each sector.  $V$  is also  $n \times 1$  vector representing the value-added of each sector. For sectors whose output are measured in monetary units, for example business services, the corresponding unit price in vector  $p$  is simply 1.0. This equation can be used to compute impacts on unit prices caused by changes of technology coefficient ( $A$ ) and value-added of each sector ( $V$ ).

From equations (2) and (4), one can deduce the income equation as following, which ensures that the value of final demand is equal to the total value-added.

$$p'Y = V'X \quad (5)$$

### 3. Input-output analysis for studying sustainability

The basic computational structure of input-output analysis discussed above is most commonly used in applications involving national accounting, statistics and development, and structural economics. However, as early as 1990s, input-output analysis was being adopted to research on sustainability. In this section, the applications of input-output analysis for studying sustainability are introduced.

Generally, there are two main areas in which input-output analysis is applied in the study of sustainability. One methodology involves the development of Physical Input-Output Tables (PIOT), which present input and output material flows for each sector of an economic system in physical units. The other application is mainly based on the widely available Monetary Input-Output Tables (MIOTs), which is used to represent connections between sectors of an economic system. MIOT-related research is more widely used because its data availability is better than PIOT-related research.

#### 3.1 Physical input-output table (PIOT)

The foundation of PIOT research, which mainly focuses on ecological-economic systems, was first made by Kneese *et al.* (1970) who applied material balance approach to economic analysis. However, only a small number of PIOTs have been compiled to date. Examples of PIOTs can be found in Kratterl and Kratena (1990); Kratena *et al.* (1992); Konijn *et al.* (1997); Stahmer *et al.* (1997); Pedersen (1999); Nebbia (2000); Stahmer (2000); Mäenpää (2002); and Hoekstra (2003).

Based on the principles of input-output analysis, PIOT conducts physical data to present material relationship between economic sectors, which makes more accurate approximation to real material flows in the economic system than analysis based on MIOT. However, because of the relatively young history of physical input-output accounting, there are not yet standard methods for PIOT compilation. Therefore, existing PIOTs differ from each other in conventions and definitions, and also differ from MIOTs which have become much more standardized due to several decades of experience. This lack of standardization for PIOT can lead to misunderstanding and confusions, for example Hubacek and Giljum (2003); Suh (2004); Giljum *et al.* (2004); Weisz and Duchin (2006). As a result, it is clear that a major application bottleneck for PIOT is the lack of standard compiling method. Recently, ecological economists have been taking the lead to trying to break through the bottleneck by forming a standardized framework for PIOT compilation (Dietzenbacher, 2005; Suh, 2007). However, if PIOT methodologies are to flourish, it is likely that strong participation from governmental statistic departments, which have enough resources and capability to compile PIOTs, will be necessary.

#### 3.2 MIOT with extensions and EIO-LCA

Most input-output analysis applications in the area of sustainability use existing MIOTs with different extensions for corresponding issues of concern. Hubacek and Sun (2001), for example, studied China's land use accounting by extending MIOTs. The land use data were attributed to the different categories of final demand of MIOTs. This method is useful for the calculation of both directly and indirectly appropriated land areas of production and consumption activities. It can also be used to study other issues of concern, such as waste generated, energy consumption, water requirements, and so on.

One of the important applications of MIOT with extensions has combined Life Cycle Assessment (LCA) which is a quantifying tool to evaluate the environmental impacts of a product or service over the course of its entire life-cycle (Guinée, *et al.*, 2002; ISO, 2006). The most recent and also one of the most important works in this area is the Environmental Input-Output Life Cycle Assessment (EIO-LCA) methodology developed at Carnegie Mellon University (Hendrickson *et al.*, 2006). The methodology of EIO-LCA involves three basic steps. First, the output changes to final demand are estimated by sectors. Once the output changes to final demand are specified, all the direct and indirect requirements are secondly assessed. The first two steps are finished by traditional input-output analysis, using MIOTs. Finally, the EIO-LCA model computes the environmental discharges resulting from the direct and indirect economic changes. There is one significant parameter called environmental burdens vector ( $b_i$ ), which represents the environmental impacts for each sector. One can define  $b_i$  as whatever issues they are interested in, such as resource inputs (electricity, fuels, ores, land uses, *etc*) and environmental outputs (hazardous waste generation, air pollutant emissions, *etc*). There are two significant advantages for EIO-LCA. First, it is conclusive in that it covers the entire economy, including all the material and energy inputs. Second, it is a quick and cheap methodology. However, it also has a disadvantage in that it provides results at an aggregate level which does not allow doing detailed research.

In general, EIO-LCA and other similar approaches utilize MIOTs separately to illuminate both direct and indirect relationship between final demands and economic changes. Those economic changes are then translated into ecological indices to represent environmental impacts. Because economy-wide MIOTs are available in most important counties for a relative long time period, this kind of method is a cheap and relatively effective method to study an entire economic system. However, it is hard to properly translate economic data into data which can present environmental impacts. The ways to convert economic information to ecological information differ depending on desired goals and the environmental concerned issue. Additionally, the most LCA methods, the results reflect environmental concerns much more than social ones, and so much be augmented with additional social analysis to truly be sustainability analysis. Thus, MIOTs with extensions are mostly used to study large scale systems, such as an entire economy, with an aggregate level of concerns.

On the other hand, PIOTs have one major drawback, a lack of data, although there is no necessary to translate economic information into ecological information. It still needs a relative long time to form standard PIOT framework and accumulate PIOT data. Thus, currently, PIOT has limited application in relative small scale systems whose physical input-output data are few enough to be able to compile.

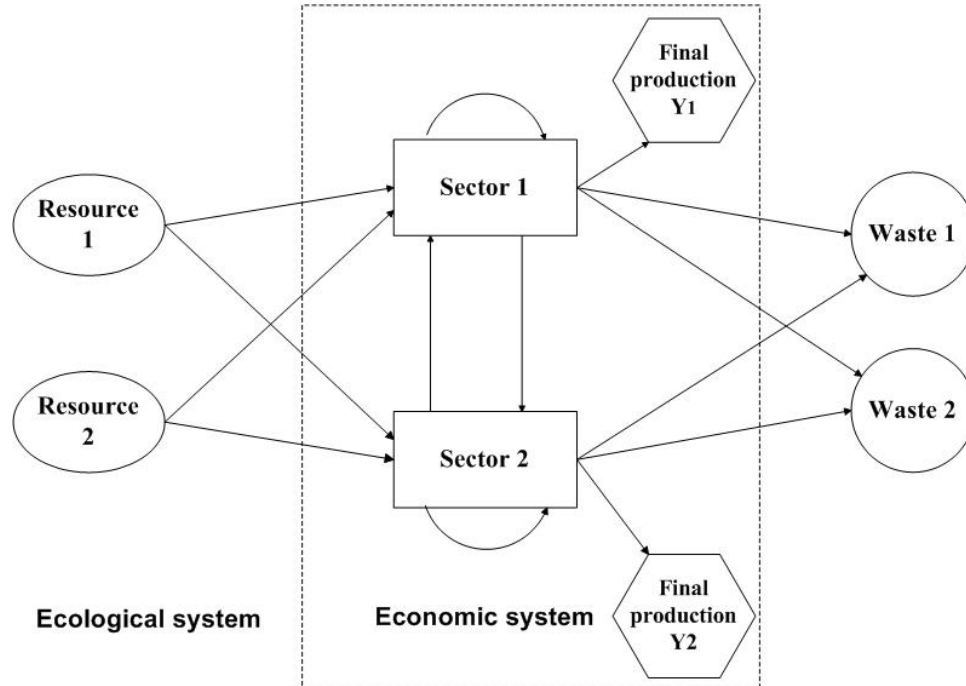
In next section, a case study of input-output analysis for sustainability study is presented. The model is relatively easy to implement using a relatively standard compilation framework. It uses ecological-economic coefficients (e-coefficient) to connect ecological information and economic information, and thus provides new tools for sustainability research and related fields.

#### 4. Case study: Physical Input Monetary Output (PIMO) model

The model in this case study is named the Physical Input Monetary Output (PIMO) model. It focuses on an economic system which can be divided into several sectors. The surrounding ecological system exchanges materials with this economic system. In this section, the conceptual basis, conceptual model, parameter definitions, PIMO table, and equations of the PIMO model are discussed.

##### 4.1 Conceptual model

A conceptual model of material metabolism for an ecological-economic system is illustrated in Figure 2. Conceptually, the ecological-economic system contains two sectors, each of which extracts two kinds of resource from the ecological system, and emits two kinds of waste to the ecological system. The terms “resource” and “waste” mean raw materials, such as mineral ores and crude oil, extracted directly from the ecological system, and “pure” materials emitted finally to the ecological system without any further treatment.



**Figure 2.** Conceptual model for material metabolism of an ecological-economic system

Therefore, the economic system can be illuminated by input-output analysis if the material exchange with the ecological system is ignored. Thus, it is possible and reasonable to

quantitatively represent relationships between sectors by MIOTs and relationship between the ecological system and the economic system by material flow accounting and analysis (MFA).

To make the PIMO model easier to compile, the above conceptual model is modified as illustrated in Figure 3. In the PIMO conceptual model, wastes emitted by the economic system are regarded as "non-positive" input from the ecological system, while resources are known as "positive" input to the economic system. Hence, there are only physical flows in the input side and only monetary flows in the output side, which is also the reason why the model is described as physical input and monetary output.

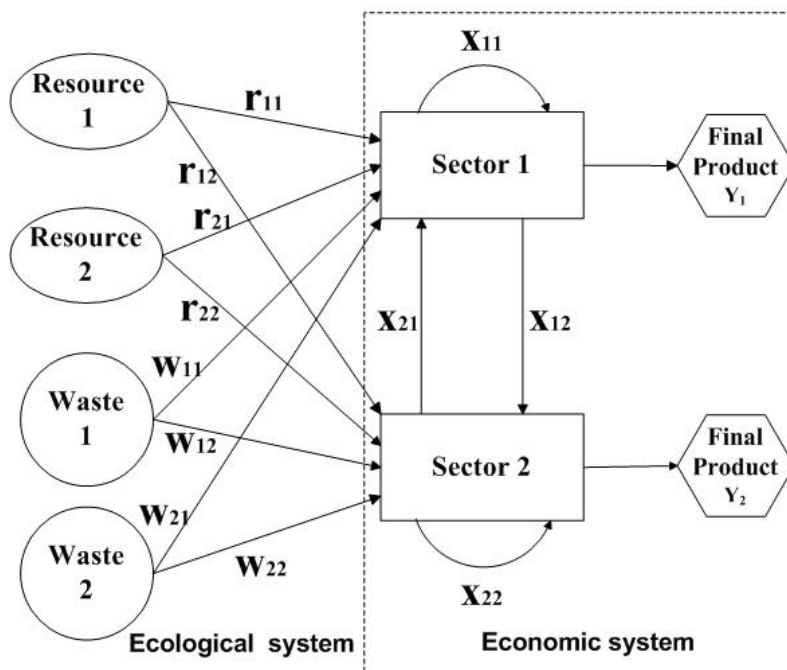


Figure 3. Conceptual model of PIMO

#### 4.2 Parameter definitions

Define the following parameters:

- $n, m, k$ : the ecological-economic system has  $n$  economic sectors,  $m$  categories of resources,  $k$  categories of wastes;
- $x_{ij}, a_{ij}, A, X_i, Y_i, V_i$ : parameters from monetary IOA and MIOT;
- $r_{ij}$ : the amount of physical resource input to sector  $j$  from resource category  $i$ ,  $r_{ij} \geq 0$ ;
- $R_i$ : the total amount of input to the economic system from resource category  $i$ ,

$$R_i = \sum_{j=1}^n r_{ij} \geq 0;$$

- $w_{(m+i)j}$ : the amount of physical waste output from sector  $j$  to waste category  $i$ ,  $w_{(m+i)j} \leq 0$ ;
- $W_{m+i}$ : the total amount of output from the economic system to waste category  $i$ ,

$$W_{m+i} = \sum_{j=1}^n w_{(m+i)j} \leq 0;$$

- $e_i$ : ecological-economic coefficient (e-coefficient), physical quantities per unit price of product of sector  $i$ ;
- $e$ : e-vector,  $e=(e_1, e_2, \dots, e_n)^T$ ;
- $p_{ij}$ : material production coefficient, the physical amount of materials from resource or waste category  $i$  required to produce per unit of economic output of sector  $j$ ,

$$p_{ij} = \begin{cases} \frac{r_{ij}}{X_j}, & i = 1, 2, \dots, m \\ \frac{w_{(m+i)j}}{X_j}, & i = 1, 2, \dots, k \end{cases};$$

- $P$ : material efficiency coefficient matrix,  $P=(p_{ij})_{(m+k) \times n}$ ;
- $d_{ij}$ : material distribution coefficient, the portion of physical materials from resource or waste category  $i$  input to sector  $j$  in total amount of that kind of resource or waste input to the entire economic system,

$$d_{ij} = \begin{cases} \frac{r_{ij}}{R_i}, & i = 1, 2, \dots, m \\ \frac{w_{(m+i)j}}{W_{m+i}}, & i = 1, 2, \dots, k \end{cases};$$

- $D$ : material distribution coefficient matrix,  $D=(d_{ij})_{(m+k) \times m}$ ;
- $T$ :  $(m+k) \times 1$  vector of total amount of materials input, including  $m$  kinds of resource and  $k$  kinds of waste,  $T=(R_1, R_2, \dots, R_m, W_{m+1}, W_{m+2}, \dots, W_{m+k})^T$ .

Using the parameters defined above, a set of equations can be derived.

### 4.3 PIMO table

Extra rows and columns can be added to extend MIOT to become a PIMO table. Table 2 is the basic structure of PIMO table. From top to bottom, the PIMO table can be divided into three parts. The first part is the traditional MIOT matrix, which presents the structure of the economic system. The following part is the resources input table and the last part is the waste output table. The latter two parts represent the relationship between the ecological system and the economic system. One can create different classification for economic sectors and resource or waste categories according to different research goals. In particularly, the most common classification should be based on economic sector classifications which are already used widely to compile MIOT, especially for national economies, such as System of National Accounts (SNA) and System of Environmental and Economic Accounts (SEEA) provided by United Nations (1993; 2003).

Symbols in the first part of PIMO table are the same as those in MIOT. Other symbols will be introduced in next section together with the basic equations of PIMO analysis.

### 4.4 Equations

First, derive mass balance for the entire economic system:

$$\sum_{i=1}^m R_i + \sum_{i=1}^k W_{m+i} = \sum_{i=1}^n e_i Y_i \quad (6)$$

where the left side of the equation presents net physical amount of materials input to the economic system, while the right side is the physical value of economic output (final demands).

**Table 2.** PIMO table

Monetary Input		Monetary Output	Intermedia Monetary Output				Final Demand	Total Output
			Sector					
			1	2	...	n	Y	X
Intermedia Monetary Input	Sector	1	x <sub>11</sub>	x <sub>12</sub>		x <sub>1n</sub>	Y <sub>1</sub>	X <sub>1</sub>
		2	x <sub>21</sub>	x <sub>22</sub>		x <sub>2n</sub>	Y <sub>2</sub>	X <sub>2</sub>
		...						
		n	x <sub>n1</sub>	x <sub>n2</sub>		x <sub>nn</sub>	Y <sub>n</sub>	X <sub>n</sub>
Value-added		V	V <sub>1</sub>	V <sub>2</sub>		V <sub>n</sub>		
Total Input		X	X <sub>1</sub>	X <sub>2</sub>		X <sub>n</sub>		
Physical Input			Physical Input Distribution				Total Physical Input	
			Sector					
Resource	Category	1	r <sub>11</sub>	r <sub>12</sub>		r <sub>1n</sub>	R <sub>1</sub>	
		2	r <sub>21</sub>	r <sub>22</sub>		r <sub>2n</sub>	R <sub>2</sub>	
		...						
		m	r <sub>m1</sub>	r <sub>m2</sub>		r <sub>mn</sub>	R <sub>m</sub>	
Waste	Category	m+1	W <sub>(m+1)1</sub>	W <sub>(m+1)2</sub>		W <sub>(m+1)n</sub>	W <sub>m+1</sub>	
		m+2	W <sub>(m+2)1</sub>	W <sub>(m+2)2</sub>		W <sub>(m+2)n</sub>	W <sub>m+2</sub>	
		...						
		m+k	W <sub>(m+k)1</sub>	W <sub>(m+k)2</sub>		W <sub>(m+k)n</sub>	W <sub>m+k</sub>	

Consider each sector as a control system, and derive mass balance for sector  $j$ :

$$\sum_{i=1}^m r_{ij} + \sum_{i=1}^k w_{(m+i)j} + \sum_{i=1}^n e_i x_{ij} = e_j \sum_{i=1}^n x_{ij} + e_j Y_j$$

where the left side of the equation is the summation of materials input to sector  $j$  from resources, wastes, and other sectors, while the right side is the output summation from sector  $j$ . In the output side, using equation (2) from input-output analysis a substitution can be made as following:

$$\sum_{i=1}^m r_{ij} + \sum_{i=1}^k w_{(m+i)j} + \sum_{i=1}^n e_i x_{ij} = e_j X_j \quad (7)$$

From the definition of the material efficiency coefficient matrix and the material distribution coefficient matrix, the relationship between  $P$ ,  $D$ , and  $M$  can be represented as following:

$$PX = Di = T \quad (8)$$

where  $X$  has the same meaning as it in input-output analysis and MIOT,  $n \times 1$  vector of total outputs, and  $i = (1, 1, \dots, 1)^T$  is  $n \times 1$  unit vector. Rewrite sector mass balance equation (7) into matrix format:

$$D'PX + (\hat{A}'e)X = \hat{e}X \quad (9)$$

where  $A$  has the same meaning as it in input-output analysis and MIOT,  $n \times n$  technical coefficients matrix, and  $\hat{e}$  means the  $n \times n$  diagonal matrix with the vector  $e$  down the diagonal.

From the definition of material production coefficient, one can get:

$$r_{ij} = X_j p_{ij}, \quad (i=1, 2, \dots, m);$$

$$w_{(m+i)j} = X_j p_{(m+i)j}, \quad (i=1, 2, \dots, k);$$

substitute above equations into sector mass balance equation (5) and derive:

$$P'i + A'E = E \quad (10)$$

Equation (10) and equation (9) are both derived from sector mass balance equation (7), and are equivalent. However, equation (10) is much easier for effective computation because it does not need the material distribution matrix  $D$  which is required in equation (9).

Similar to input-output analysis, there are also cumulative effects in PIMO model on materials input. Define  $f_{ij}$  as material cumulative input coefficient, which means the cumulative material input of category  $i$  caused by per unit of output of sector  $j$ .  $f_{ij}$  can be calculated as following:

$$f_{ij} = \sum_{t=1}^n p_{it} b_{tj}$$

Rewrite the above equation to matrix format as following:

$$F = PB \quad (11)$$

Those 6 equations, together with equations from input-output analysis and the PIMO table compose the basic framework of PIMO analysis. One can compile a PIMO table based on an existing MIOT, and then conduct the analysis using selected parameters and equations. In the following section, a case study of PIMO application based on China's 1997 MIOT is carried out.

#### 4.5 PIMO example

Based on the MIOT for China in 1997 which has 128-sector format, a PIMO table for China was compiled. In the PIMO table, economic sectors were combined into 43 sectors, with a special concentration on manufacturing industries. Data about materials input to, and output from, the

economic system are gained from related research (Xu and Zhang, 2007). Materials following into the economic system were divided into 15 categories, including agriculture products, fossil fuels, important minerals, fresh water, waste water, solid wastes, sulfur dioxide, and so on. In the waste water category, a more detailed sub-classification was provided for hazard contaminants, such as Chemical Oxygen Demand (COD), lead, volatile phenols, mercury, and so on. Following the structure and equations of PIMO model, the PIMO table, which has 43 economic sectors, 10 sorts of materials input, and 5 sorts of materials output, was used to evaluate and access the environmental impacts of China's economy in 1997.

Generally, the PIMO model results show that China consumed 2.06 kg of coal equivalent to produce one dollar of Gross Domestic Product (GDP) in 1997. The sector of *Electricity, Gas & Water Supply* had the lowest efficiency of water consumption, which needed 474.16 kg of fresh water to produce one dollar of GDP. Additionally, the *Electricity, Gas & Water Supply* sector also emitted the most amount of sulfur dioxide among all 43 sectors. For other material categories, it was generally the case that one or a few number of sectors consumed or emitted most of resources or wastes.

From the point of view of cumulative effects, a table of material cumulative input coefficients was compiled by PIMO analysis, which contained 25 rows, 43 columns, and correspondingly 1075 coefficient elements. For example, one dollar GDP of the sector of *Smelting and Pressing of Ferrous Metals* needed to consume 8.27 kg coal, 8.48 kg nonmetal minerals, and 93.25 kg fresh water, to emit 41.71 kg waste water, 0.14 kg solid wastes, and so on.

The application of PIMO analysis can also be used to create different scenarios of material metabolism. In the case study of China, 15 scenarios were set to simulate the change of economic structure and the level of production technologies. The scenario analysis using PIMO model showed that only some material categories can be effectively influenced by changes of economic structure. The amount of materials input and output for most categories are controlled only by production technologies. Further details of this analysis can be found at (**forthcoming**).

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