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Regional metabolism analysis model based on three dimensional PIOT and its preliminary application

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Abstract

A regional metabolism analysis model based on three dimensional physical input-output tables (PIOT) was developed to analyze the intra-flows, i.e. the distribution, use and transformation of materials inside economic system. There're four major features in the design of the 3D-PIOT. The first is that it consists of a main input-output table, a series of sub-tables and supplementary tables, in which the structure of main table and sub-tables are the same, while that of supplementary tables are a little different. The second is that the material flows are measured in mixed units. The existing PIOTs are all measured in tons and those products measured in non-mass units are neglected. It is called for to use proper units to measure different kinds of products during the methodological development of PIOT, while the model in this paper is designed to meet this demand. The third is the treatment of waste. A sub-table is specially designed to record all the recycled waste flows, which describes the generation, reuse, disposal, recycle and discharge of the recycled wastes. The fourth is that the consumptions, including government and household, are regarded as sectors of intermediate use. This makes the system boundary clearer, while input-output analysis model can still be further developed based on such design. Some other problems and techniques about PIOT compilation are also discussed in this paper. Based on the 3D-PIOT, indicators of regional metabolism can be defined from different aspects and levels, such as industrial structure, techniques and socio-economic conditions. The 3D-PIOT and the derived indicators are useful to identify material metabolism and the structural characteristics of regional economic system. A planning table is also afforded in this paper for further constructing input-output analysis model to plan the natural resource use and waste discharge in a region, and to provide decision-making support for regional developmental transformation. The model was applied to Yima city for the first time, which is a pilot city demonstrating circular economy development in China. A three dimensional regional PIOT called YMPIOT2002 was compiled, which laid solid foundation for planning the circular economy development in Yima.

Keywords: Regional metabolism, Physical input-output tables (PIOT), Material flow analysis (MFA), Circular economy.

1 Introduction

Natural resources are material base of economic systems. Economic systems retrieve all kinds of natural resources from nature and discharge wastes to nature, after using and transforming these natural resources. At the same time, economic systems are open systems, connected with other economic systems outside through imports and exports[1].

In order to study the physical interactions between the economic systems and the environment, or called material metabolism, the method of MFA was developed since late 1960s (Ayres and Kneese(1969), Fischer-Kowalski(1998a)). Entering 1990s, more and more case studies of economy-wide material flow analysis (EW-MFA) on national level were carried out (Fischer-Kowalski(1998b), Eurostat(2001)). A guide of EW-MFA was published by the Eurostat in 2001 (Eurostat(2001)), which established a framework and standard for EW-MFA. However, the widely accepted model of EW-MFA is a black box, which cannot reflect the intra-flows inside the economic system. Physical input-output tables (PIOT) seem more suitable to record these intra-flows. The existing PIOTs of total mass are still relatively few, including Katterl and Kratena (1990), Stahmer et al. (1997), Pedersen (1999), Nebbia (2000), Mäenpää and Muukkonen (2001), Statistisches Bundesamt (2001). Besides, a preliminary PIOT for the European Union is based on information from the German and Danish PIOT, scaled up to EU levels (Giljum and Hubacek(2001)). A PIOT project is also currently underway in Japan at the National Institute for Environmental Studies (NIES) (Hoekstra(2006)). Some specified material, like concrete, paper, zinc, steel, etc, was also studied by using physical input-output accounting (Konijn(1995, 1997)) in the Netherlands.

Due to the relatively short history and few case studies of physical input-output accounting, there's no standard of PIOT compilation yet, and some problems still remain to be solved during the methodological development of PIOT. The first is that the existing PIOTs are all measured in tons and those physical products measured in non-mass units are neglected, which calls for using proper units to measure different kinds of material flows. The second is that the existing PIOTs of total mass are all accounting ones, which do not

[1] Commonly, imports and exports refer to trades between countries. In this paper, if not specified, imports and exports refer to trades between the economic system and its outside world.

aim at modelling, thus the advantage of input-output analysis is not manifested[2]. The third is the treatment of waste. Waste recycling is important to improve resource efficiency, especially in developing circular economy in china, but the recycled waste is not distinctly stated in the existing PIOTs. Moreover, how to treat waste properly is also very important in physical input-output analysis (Dietzenbacher(2005)). The fourth is the methodological standardization of PIOT compilation, such as avoiding double accounting (Nakamura(2007)), treatment of water and air (Mäenpää(2002)), output of agriculture (Helga(2005)), the household consumption(Eurostat(2001)), etc.

The environment problems are getting more and more serious now in China, thus circular economy is called for to deal with the problems. In order to meet the demand of developing circular economy and provide a tool for decision making and policy analysis, a regional metabolism analysis model based on three dimensional PIOT was developed. The model solves the first and the third problem by affording some amendments of the PIOT structure. The second problem, although the modeling is not discussed detailedly in this paper, a planning table is provided which is a key part of modeling and can be used to make plan for the future development of regional metabolism. Some aspects of the fourth problem are also discussed in this paper. Although the model is developed for regional economic system, it is also suitable for national economic system conceptually.

The next section, we'd like to carefully discuss regional metabolism analysis model, where conceptual model, three dimensional and two dimensional PIOT structures, balance of tables and planning table will be introduced in detail. In the third section, some material flow indicators will be derived from the three dimensional PIOT. In the fourth section, the model will be used for a preliminary application, in which Yima city was chosen for a case study. The final section is the conclusions.

2 Regional metabolism analysis model

2.1 Conceptual model

Before constructing the regional metabolism analysis model, a conceptual model was developed to conceptualize the economic system, which is shown in Figure 1. The

[2] In some literatures, e.g. Hoekstra (2006), the concept of accounting and modelling are distinguished. Besides, the terminology of planning model in this paper has the similar meaning with modelling.

conceptual model decomposes the economic system from two dimensions, one is the material dimension, and the other is the sector dimension.

From the material dimension, generally, the natural resources can be classified into biomass, fossil fuels, minerals (metal ores, industrial minerals, and construction minerals), water, and air, etc. Biomass is renewable resource, fossil fuels and minerals are nonrenewable resources. The recycled waste is also regarded as a kind of resource, although it is not a natural resource. Therefore, it is contained in the common material flow arrows and is not especially pointed out in the schematic.

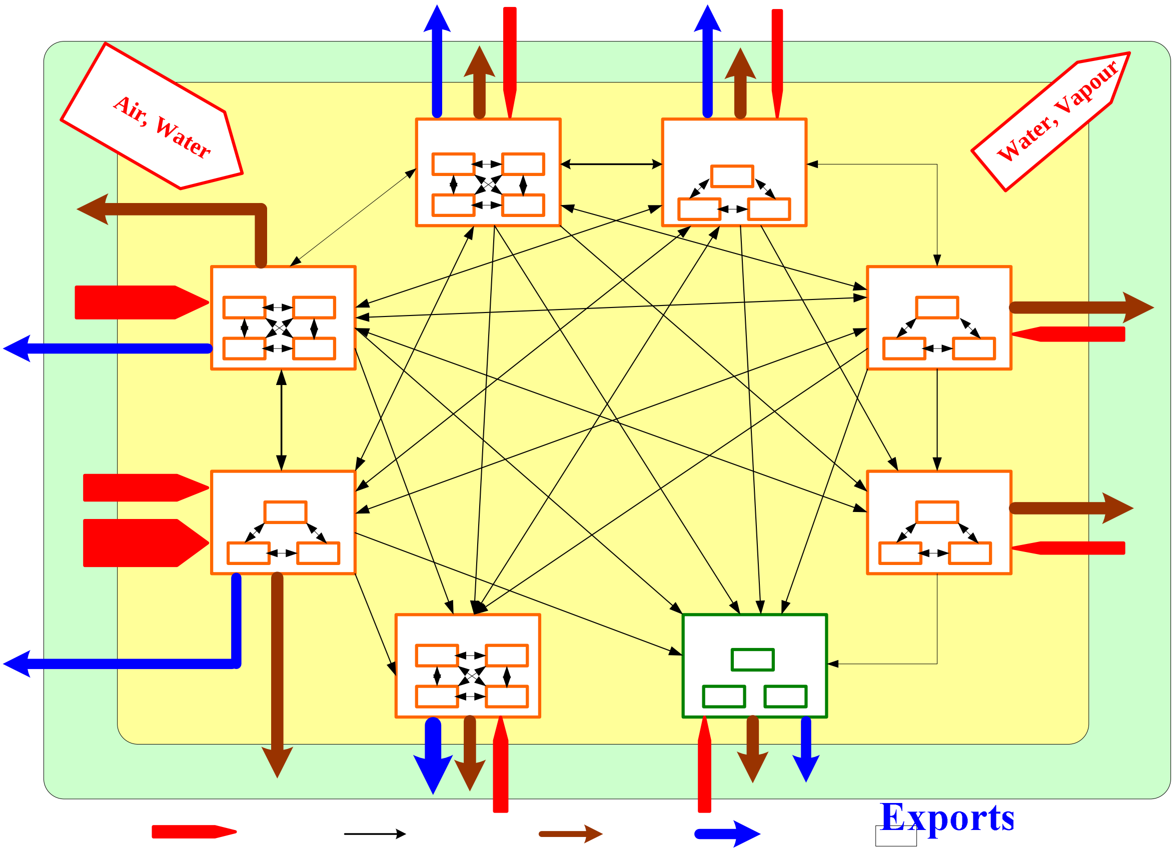


Figure 1 Schematic of conceptual model

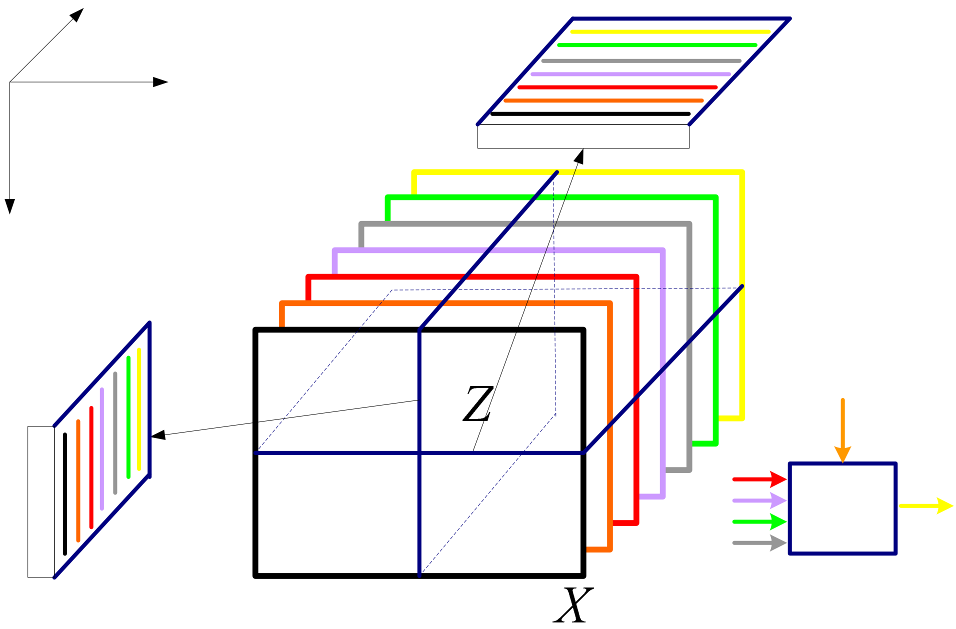
From the sector dimension, economic system is divided into eight fundamental sectors in the conceptual model, which can be further divided into more sub-sectors. The seven production sectors are agriculture, mining, manufacturing, supply of electricity, gas and water, construction, transportation, and service. The one consumption sector is household. These eight fundamental sectors, also the sub-sectors inside, are interconnected by all kinds of material flows.

The agriculture sector provides primary biomass products. The mining sector provides primary non-biomass products, mainly all kinds of fossil fuels, metal ores, industrial minerals and construction minerals. The manufacturing sector turned those primary products into all kinds of semi-manufactured and finished products. The supply of electricity, gas and water sector provides electricity, gas, water and heat, which are necessary for production and consumption. The construction sector provides buildings, transportation infrastructures, which is the foundation of economic system. The transportation sector sends the passengers and goods to the destination. The transportation sector here only includes public transportation, in which the private transportation is not included. The product of the transportation sector is freight amount or passenger amount, which should be measured by non-mass units. The service sector mainly produces immaterial products, which includes many sub-sectors such as food serving, finance, insurance, real estate, etc. The household sector consumes all the products provided by the production sectors to meet the material and immaterial demand of people. There's no material products yield in the household sector, except some recycled wastes.

2.2 Three dimensional structure

The three dimensional structure of the three dimensional PIOT is shown in Figure 2, which consists of a series of two dimensional PIOTs, i.e. one main input-output table, *m* sub-tables and two supplementary tables. The structure of main table and sub-tables are the same, while that of supplementary tables is a little different.

The main table records all the material flows and each sub-table records a certain type of material flows that measured by mass unit. Each sub-table describes the sources outside the economic system, the distribution, use and transformation of a certain type of substances among different sectors inside the economic system, and different destinations to the environment after departing from the economic system, which can be regarded as a SFA (Substance Flow Analysis) of that certain type of substances. Based on the sub-tables, further researches can be done, focusing on different certain substances. According to the classification of materials, the number of sub-tables *m* can be different. No matter how much *m* is, the wastes will always be one sub-table and also the last (i.e. *m*th) sub-table. The waste sub-table will be discussed detailedly in subsequent sections.



Source: adapted from Moriguchi (2003).

Figure 2 Schematic of 3D-PIOT

In order to record all the physical flows of economic systems, and to support the subsequent metabolism planning model, two supplementary tables of special material flows and water are designed, which describe material flows neglected by the main table and sub-tables. Air can also be constructed as a supplementary table, if it is needed in the future research, while it is not in the current design.

The special material flows mainly refer to those material flows measured by non-mass units, e.g. electricity and heat measured by energy units, freight transportation measured by ton kilometer, and passenger transportation measured by person kilometer, etc. Besides, in the landfill sector and waste water treatment sector, although the amount of landfill and waste water are measured by mass unit, such outputs are special, which are quite different from other common products. Therefore, a supplementary table is designed to record these special material flows measured by different units. These sectors are called special sectors in this paper.

Moreover, EW-MFA excludes water from the indicator of DMI (direct material input) because the amount of water is much more than other materials. However, water is also an important material flow, which cannot be ignored in the subsequent metabolism planning model. Therefore, a supplementary table is designed to record the water flows measured by mass unit.

2.3 Two dimensional structure

There're three planes in the three dimensional PIOT, i.e. plane X-Y, plane Y-Z and plane X-Z, while plane X-Y is the most important one in accounting and modelling. Therefore, the two dimensional structure refers to the structure of plane X-Y in this paper.

2.3.1 Structure of main table and sub-table

The two dimensional structure of main table and sub-tables is shown in

Table 1. There're four parts in the table. The first part is intermediate input and use, the second part is final use, the third part is primary input, and the fourth part is additional information. The former three parts (or called quadrants) are the main parts of the table, demonstrating the material flows of an economic system. The fourth part is some supplementary information related to those material flows. If not considering the fourth part, the two dimensional structure is very similar with common I/O tables.

The first part of intermediate input and use is the key part of PIOT, which reflects the physical interrelationship among sectors during the material metabolism of economic system. Let the number of total sectors, production sectors and primary production sectors be n, n_1, and n_2 respectively. When we compile PIOT for a certain region and classify the sectors, the characteristic of the region should be fully considered, because it often occurs that the industrial system is not very complete and several few industries are predominant in a certain region.

The household is incorporated into the first part of PIOT, which is different from the existing PIOT, also different from most of the existing MIOT. However, such design can make the system boundary clearer, which clarify the intermediate use and the final use. It also can avoid neglect or double accounting of NAS and waste of household. Moreover, such design will not affect the subsequent modelling, because semi-open model does exist in the input-output analysis, although it is uncommon.

Table 1 Structure of main table ($k = 0$) and sub-tables ($k = 1, 2, \ldots, m$) of 3D-PIOT

Input			Output																	
			Intermediate use					final use												Total output
			Sector 1	…	Sector j	…	Sector n	Exports	NAS	Discharged waste					Reduced waste					
										Waste 1	…	Waste j	…	Waste t_1	Waste 1	…	Waste j	…	Waste t_2	
Intermediate input	Sector 1		$Z_{1,1,k}$	…	$Z_{1,j,k}$	…	$Z_{1,n,k}$	$e_{1,k}$	$s_{1,k}$	$w_{1,1,k}$	…	$w_{1,j,k}$	…	$w_{1,t1,k}$	$\overline{\overline{w}}_{1,1,k}$	…	$\overline{\overline{w}}_{1,j,k}$	…	$\overline{\overline{w}}_{1,t2,k}$	$\overline{\overline{x}}_{1,k}$
	…		…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
	Sector i		$Z_{i,1,k}$	…	$Z_{i,j,k}$	…	$Z_{i,n,k}$	$e_{i,k}$	$s_{i,k}$	$w_{i,1,k}$	…	$w_{i,j,k}$	…	$w_{i,t1,k}$	$\overline{\overline{w}}_{i,1,k}$	…	$\overline{\overline{w}}_{i,j,k}$	…	$\overline{\overline{w}}_{i,t2,k}$	$\overline{\overline{x}}_{i,k}$
	…		…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
	Sector n		$Z_{n,1,k}$	…	$Z_{n,j,k}$	…	$Z_{n,n,k}$	$e_{n,k}$	$s_{n,k}$	$w_{n,1,k}$	…	$w_{n,j,k}$	…	$w_{n,t1,k}$	$\overline{\overline{w}}_{n,1,k}$	…	$\overline{\overline{w}}_{n,j,k}$	…	$\overline{\overline{w}}_{n,t2,k}$	$\overline{\overline{x}}_{n,k}$
Primary input	Competitive imports	Sector 1	$G_{1,1,k}$	…	$G_{1,j,k}$	…	$G_{1,n,k}$													
		…	…	…	…	…	…													
		Sector i	$G_{i,1,k}$	…	$G_{i,j,k}$	…	$G_{i,n,k}$													
		…	…	…	…	…	…													
		Sector n	$G_{n,1,k}$	…	$G_{n,j,k}$	…	$G_{n,n,k}$													
	Non-competitive imports		$f_{1,k}$	…	$f_{j,k}$	…	$f_{n,k}$													
	Domestic Extraction		$d_{1,k}$	…	$d_{j,k}$	…	$d_{n,k}$													
Total input			$\bar{x}_{1,k}$	…	$\bar{x}_{j,k}$	…	$\bar{x}_{n,k}$													
Additional information	Balancing items		$b_{1,k}$	…	$b_{j,k}$	…	$b_{n,k}$													
	Hidden flows		$h_{1,k}$	…	$h_{j,k}$	…	$h_{n,k}$													
	Value added		v_1	…	v_j	…	v_n													

The second part of final use reflects the final destination of materials, which comprises exports, net additions to stock (NAS), and emissions and wastes[3]. The NAS can further be classified into 5 categories, i.e. buildings, transportation infrastructure, machinery, endurable goods, and inventory. Each category can be listed as a column further.

In principal, the classification of emissions and wastes accords with the Eurostat Guideline, which can be classified into four groups, i.e. emissions to water, emissions to air, solid waste, and dissipative uses and losses. As for the emissions to air, both the amount including the air for balancing and that excluding the air are listed. When calculate the total output, the air should be excluded to keep the mass balance. At the same time, the waste classification should conform to the existing environmental statistical system as close as possible, so that more data can be aggregated into the PIOT and the PIOT can afford more information about the pollution and the environment problems that are most concerned currently.

There're four different concepts about waste, i.e. generated waste, discharged waste, reduced waste and recycled waste. The generated waste refers to the total amount of the waste that generated during production and consumption. The discharged waste refers to the waste that disposed to nature after reduction. The reduced waste refers to the waste that reduced by all kinds of means[4]. The recycled waste refers to the waste that recycled and reused by the economy system, which can also be regarded as by-product. The generated waste equals the sum of the discharged waste, reduced waste and the recycled waste. The data listed in the second part of the main table and all sub-tables are the discharged waste and reduced waste. Let the number of discharged waste and reduced waste are t_1 and t_2 respectively in the model.

The third part of primary input reflects the original source of the materials input into the economic system. The primary input comprises imports and domestic extraction. Imports are further divided into competitive imports and non-competitive imports. In this paper, the imports are not distinguished whether they are imported from foreign countries

[3] In some places of this paper, *emissions and wastes* is simplified as *wastes* for brevity.
[4] For example, a factory generates 100 tons SO_2 at first, while only 10 tons are finally discharged after treatment. In this case, the discharged waste and reduced waste are 10 tons and 90 tons respectively.

or from other regions in the country. Similarly, the exports are not distinguished whether they are exported to foreign countries or to other regions in the country, either. If the research focuses on the difference between home markets and international markets, the imports and exports can further be classified accordingly.

The fourth part of additional information, which is below the third part, comprises balancing items, hidden flows and value added. The balancing items include oxygen for combustion, etc, which are not included in the primary input and total input. Hidden flows refer to the movements of the unused materials associated with the extraction of raw materials, domestically and abroad, including materials that are extracted from the national environment but not actually used by the economy (so-called domestic hidden flows), and the upstream resource requirements associated to imported products (so-called foreign hidden flows) (Eurostat (2001)). The value added is used to measure the economic output of different sectors. The value added of consumption sector is zero conceptually, but may be filled with the household consumption expenditure data. The data of value added only appear in the main table, which are not decomposed into the related sub-tables.

2.3.2 Waste sub-table

Waste is carefully treated in the model, because waste recycling is very important in circular economy. A sub-table of waste is specially designed to record the recycled waste flows, which describes the generation, reuse, disposal, recycle and final destination of the recycled wastes.

The structure of waste sub-table is the same with the main table. If the recycled waste is generated in the accounting year, it is regarded as intermediate input, which occurs in the first quadrant. If the recycled waste is stored before the accounting year, or is imported, it is regarded as primary input, which should be filled in the corresponding part of the third quadrant. The exported wastes for recycling, and the wastes that become NAS are listed in the export column of the second quadrant. The discharged waste and reduced waste of the recycled waste are listed in the corresponding part of the second quadrant in this sub-table.

2.3.3 Structure of supplementary table

The structure of supplementary tables is a little different from main table and sub-tables (shown in Table 2), in which there's no third part, fourth part, and the waste columns in the second part. Since the primary input, wastes and additional information have been completely recorded in the main table and sub-tables, such information do not appear again in the supplementary tables.

Table 2 Structure of supplementary tables of 3D-PIOT

Input	Output					
	Sector 1	…	Sector n	Final use		Total products
				Exports	NAS	
Sector 1	$Z_{1,1,k}$	…	$Z_{1,n,k}$	$e_{1,k}$	$s_{1,k}$	$x_{1,k}$
…	…	…	…	…	…	…
Sector n	$Z_{n,1,k}$	…	$Z_{n,n,k}$	$e_{n,k}$	$s_{n,k}$	$x_{n,k}$

2.4 Balances of tables

The three dimensional PIOT reveals the interrelationships among sectors in the economic system during the material metabolism procedure. There exist some quantitative relationships in the main table, sub-tables and supplementary tables themselves and among them, which can be summarized as plane balance and solid balance. The balance relationships are the foundation of constructing the subsequent metabolism planning model.

2.4.1 Plane balances

The plane balances refer to the balance relationships that exist in the main table, sub-tables and supplementary tables themselves, comprising three kinds, i.e. row balance (equation（1）), column balance (equation（2）) and gross balance (（3a）~（3c）).

intermediate use + final use = total output （1）

intermediate input + primary input = total input （2）

total input = total output （3a）

sectoral total input = sectoral total output （3b） total intermediate input = total intermediate output （3c）

The above balances can be further expressed as equation （4） and （5）:

Primary input + intermediate input = intermediate use + final use （4）

Domestic extraction + imports + intermediate input
= intermediate use + exports + NAS + wastes （5）

In the main table, the total input is equal to the total output, and the sectoral total input is equal to sectoral total output in each sector. Therefore, the row balance, column balance and gross balance all exist in the main table, which can be further expressed by Equation （6）~（8） respectively.

$$\sum_{j=1}^{n} Z_{i,j,k} + e_{i,k} + s_{i,k} + \sum_{j=1}^{t_1} w_{i,j,k} + \sum_{j=1}^{t_2} \overline{\overline{w}}_{i,j,k} = \overline{\overline{x}}_{i,k} \qquad (i=1,2,\ldots,n;\ k=0,1,\ldots,m) \quad (6)$$

$$\sum_{i=1}^{n} Z_{i,j,k} + r_{j,k} = \overline{x}_{j,k} \qquad (j=1,2,\ldots,n;\ k=0,1,\ldots,m) \quad (7)$$

$$\overline{\overline{x}}_{i,k} = \overline{x}_{j,k} \qquad (i,j=1,2,\ldots,n;\ k=0) \quad (8)$$

Where, Z is the intermediate deliveries of secondary inputs, e is the exports, s is the net additions to stock, w is the discharged waste, $\overline{\overline{w}}$ is the reduced waste, r is the primary input, $\overline{x}$ is the total input, and $\overline{\overline{x}}$ is the total output.

The definition of primary input r is defined by Equation （9）.

$$r_{j,k} = \sum_{i=1}^{n} G_{i,j,k} + f_{j,k} + d_{j,k} \qquad (k=0,1,\ldots,m) \quad (9)$$

Where, r is the primary input, G is the competitive imports, f is the non-competitive imports, and d is the domestic extraction.

In the sub-tables, the total input is not always equal to the total output, and the sectoral total input is not always equal to the sectoral total output, due to the recycled waste. Therefore, only the row balance (equation （6）) and column balance (equation （7）) exist in the sub-tables, while the gross balance doesn't exist.

In the supplementary tables, only row balance exists (shown by Equation （10）), while column balance and gross balance do not exist.

$$\sum_{j=1}^{n} Z_{i,j,k} + e_{i,k} + s_{i,k} = x_{i,k} \qquad (k=m+1,\ m+2) \qquad (10)$$

Where, Z is the intermediate deliveries of secondary inputs, e is the exports, s is the net additions to stock, and x is the total product.

2.4.2 Solid balances

The solid balances refer to the balance relationships that exist between the main table and the sub-tables, which are shown as Equation （11）.

$$Z_{i,j,0} = \sum_{k=1}^{m} Z_{i,j,k},\quad e_{i,0} = \sum_{k=1}^{m} e_{i,k},\quad s_{i,0} = \sum_{k=1}^{m} s_{i,k},\quad G_{i,j,0} = \sum_{k=1}^{m} G_{i,j,k},\quad b_{i,0} = \sum_{k=1}^{m} b_{i,k},$$

$$w_{i,j,0} = \sum_{k=1}^{m} w_{i,j,k},\quad \overline{\overline{w}}_{i,j,0} = \sum_{k=1}^{m} \overline{\overline{w}}_{i,j,k},\quad \overline{x}_{i,0} = \sum_{k=1}^{m} \overline{x}_{i,k},\quad \overline{\overline{x}}_{i,0} = \sum_{k=1}^{m} \overline{\overline{x}}_{i,k},\quad h_{i,0} = \sum_{k=1}^{m} h_{i,k},$$

$$r_{j,0} = \sum_{k=1}^{m} r_{j,k},\quad d_{i,0} = \sum_{k=1}^{m} d_{i,k},\quad f_{i,0} = \sum_{k=1}^{m} f_{i,k} \qquad (i,j=1,2,\ldots,n) \qquad (11)$$

Where, Z is the intermediate deliveries of secondary inputs, e is the exports, s is the net additions to stock, w is the discharged waste, $\overline{\overline{w}}$ is the reduced waste, r is the primary input, G is the competitive imports, f is the non-competitive imports, d is the domestic extraction, b is the balancing items, h is the hidden flows, $\overline{x}$ is the total input, and $\overline{\overline{x}}$ is the total output.

2.5 Planning table and planning model

The main table measured in single mass unit cannot provide sufficient information when constructing planning model to make plan for the future development of regional metabolism. Therefore, a new framework is required to meet this demand, which is called planning table in this paper. The planning table combines the main table and the supplementary tables, which is the fundamental of constructing the subsequent regional metabolism planning model.

The structure of planning table is almost the same as supplementary table (shown in Table 3). The only difference is that the NAS in the planning table excludes the machinery. The method of transforming the main table and the supplementary tables into the planning table are as follows:

Table 3 Structure of planning table

Input	Output					
	Sector 1	…	Sector n	Final use		Total products
				Exports	NAS	
Sector 1	$Z_{1,1,k}$	…	$Z_{1,n,k}$	$e_{1,k}$	$\bar{s}_{1,k}$	$x_{1,k}$
…	…	…	…	…	…	…
Sector n	$Z_{n,1,k}$	…	$Z_{n,n,k}$	$e_{n,k}$	$\bar{s}_{n,k}$	$x_{n,k}$

Firstly, the third part, the fourth part and the waste columns in the second part are taken off from the main table, which makes the structure of the main table be the same with the supplementary table. Meanwhile, the total output is replaced by total product, which is equal to the total output minus the waste and the machinery in NAS. Secondly, the information in the rows of the special sectors in the main table is substituted by that in the corresponding rows in the supplementary table of special material flows, which is shown as Equation（12）. Finally, the information in the row of the water supply sector in the main table is substituted by that in the corresponding row in the supplementary table of water, which is shown as Equation（13）.

$$Z_{i,j} = Z_{i,j,m+1},\ e_i = e_{i,m+1},\ \bar{s}_i = \bar{s}_{i,m+1},\ x_i = x_{i,m+1} \qquad (j = 1, 2, \dots, n) \qquad (12)$$

$$Z_{i,j} = Z_{i,j,m+2},\ e_i = e_{i,m+2},\ \bar{s}_i = \bar{s}_{i,m+2},\ x_i = x_{i,m+2} \qquad (j = 1, 2, \dots, n) \qquad (13)$$

Where, Z is the intermediate deliveries of secondary inputs, e is the exports, $\bar{s}$ is the net additions to stock (excluding machinery), x is the total product, and i is the row number of those sectors whose data should be substituted.

The balance relationship also exists in the planning table, shown as Equation（14）, which is fundamental to build the metabolism planning model.

$$\sum_{j=1}^{n} Z_{i,j} + e_i + \bar{s}_i = x_i \qquad (i = 1, 2, \dots, n) \qquad (14)$$

Where, Z is the intermediate deliveries of secondary inputs, e is the exports, $\bar{s}$ is the net additions to stock (excluding machinery), and x is the total product.

The above analyses are all based on such an assumption that each sector produces one and only one output in a mutually exclusive manner. However, joint production does exist in the real economic system, and the products in one sector may even be measured in different units, e.g. the outputs of the power industry are electricity and fly ash[5], which are measured by kwh and ton respectively. In this case, the row balance is violated, which makes the planning model impracticable. Therefore, the planning table should be adjusted to deal with this problem. Several methods may be used to solve this problem, including Stone's method, etc. But this problem will not be discussed in detail in this paper, due to the length limit.

Based on the planning table and its balance relationship, the regional metabolism planning model can be developed. Based on the planning model, the method of scenario analysis, together with optimization techniques and trial-error method can be used to plan the future regional metabolism. According to different development plans, corresponding scenarios can be made by setting different model parameter values of economic and population growth, natural resource use and waste discharge, etc. The future regional metabolism can be planned, through evaluating and comparing the simulation results of these scenarios. However, the techniques about the constructing and using of planning model cannot be discussed in detail in this paper, also due to the length limit.

3 Indicators derived from 3D-PIOT

Indicators of material flows can be derived from the three dimensional PIOT to assess the regional metabolism from different aspects, such as physical size, proficiency, intensity, structure, recycling, and technical level, etc.

Indicators of physical size includes TMR (Total material requirement), DMI (Direct material input), DMC (Domestic material consumption), DPO (Domestic processed output) and DP (Domestic pollutants), which represent the material flow scales of economic system. The former four indicators are widely used EW-MFA indicators, whose definitions can be found in Eurostat Guideline (Eurostat (2001)). The indicator of DP is a new indicator defined in this paper, which only the pollutants that degrade the environmental quality are included, while the emissions are excluded. Because the pollutants are more seriously concerned in China currently[6]. Let the number of pollutant types be t, and the pollutants be $p_1 \ldots p_t$.

If the above indicators are related to GDP, the indicators of material intensity (units of material indicator per unit of GDP) or material efficiency (the mathematical inverse of material intensity) can be derived correspondingly. If the material indicators are divided by population, the intensity indicators from another aspect are derived, which represent the material flow scales per capita. The recycling indicator is recycling rate γ, which represents the recycling level.

$$GDP = \sum_{i=1}^{n_1} v_i \,,\quad DMI = \sum_{k=1}^{m-1}\sum_{j=1}^{n} r_{j,k} \,,\quad TMR = DMI + \sum_{k=1}^{m-1}\sum_{j=1}^{n} h_{j,k} \,,\quad DP = \sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{t} p_{i,j,k}$$

$$DMC = DMI - \sum_{k=1}^{m-1}\sum_{j=1}^{n_2} e_{j,k} \,,\quad DPO = \sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{t_1} w_{i,j,k} + \sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{t_2} \overline{\overline{w}}_{i,j,k} \,, \qquad (15)$$

$$\gamma = \frac{\sum_{i=1}^{n}(e_{i,m} + s_{i,m}) + \sum_{i=1}^{n}\sum_{j=1}^{t_1} w_{i,j,m} + \sum_{i=1}^{n}\sum_{j=1}^{t_2} \overline{\overline{w}}_{i,j,m}}{DMI} \qquad (k = 0,1,\cdots,m)$$

Where, TMR is Total material requirement, DMI is direct material input, DMC is domestic material consumption, DPO is domestic processed output, DP is domestic pollutants, γ is the recycling rate, v is the value added, e is the exports, s is the net additions to stock, w is the discharged waste, $\overline{\overline{w}}$ is the reduced waste, r is the primary input, h is the hidden flows, p is the pollutants, and $\overline{\overline{x}}$ is the total output.

The structure indicators include primary input ratio r_p, import ratio r_i, and sectoral indicators. Sectoral indicators include total input percentage β_t, primary input percentage β_r, DPO percentage β_w, DP percentage β_p, sectoral total input intensity T_t, sectoral primary input intensity T_r, sectoral DPO intensity T_w, sectoral DP intensity T_p.

$$r_{\mathrm{p}} = \frac{\sum_{j=1}^{n} r_{j,0}}{\sum_{j=1}^{n} x_{j,0}} \,,\quad r_{\mathrm{i}} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} G_{i,j,0} + \sum_{j=1}^{n} f_{j,0}}{\sum_{j=1}^{n} r_{j,0}} \,,\quad \beta_{\mathrm{t}} = \frac{\sum_{k=1}^{m} x_{i,k}}{\sum_{i=1}^{n}\sum_{k=1}^{m} x_{i,k}} \,,\quad T_{\mathrm{t}} = \frac{\sum_{k=1}^{m} x_{i,k}}{v_i} \,,\quad \beta_{\mathrm{r}} = \frac{\sum_{k=1}^{m} r_{i,k}}{\sum_{i=1}^{n}\sum_{k=1}^{m} r_{i,k}} \,,$$

[5] Fly ash is a kind of waste, while it is a kind of by-product when recycled.
[6] The definitions of pollutants are different in different countries, e.g. CO_2 is not pollutant in China.

$$T_r=\frac{\sum_{k=1}^{m} r_{i,k}}{v_i},\ \beta_p=\frac{\sum_{k=1}^{m}\sum_{j=1}^{t} p_{i,j,k}}{\sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{t} p_{i,j,k}},\ T_p=\frac{\sum_{k=1}^{m}\sum_{j=1}^{t} p_{i,j,k}}{v_i},\ T_w=\frac{\sum_{k=1}^{m}\sum_{j=1}^{t_1} w_{i,j,k}+\sum_{k=1}^{m}\sum_{j=1}^{t_2} \overline{\overline{w}}_{i,j,k}}{v_i},$$

$$\beta_w=\frac{\sum_{k=1}^{m}\sum_{j=1}^{t_1} w_{i,j,k}+\sum_{k=1}^{m}\sum_{j=1}^{t_2} \overline{\overline{w}}_{i,j,k}}{\sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{t_1} w_{i,j,k}+\sum_{k=1}^{m}\sum_{i=1}^{n}\sum_{j=1}^{t_2} \overline{\overline{w}}_{i,j,k}} \quad (i=1,2,\cdots,n) \qquad (16)$$

Where, r_p is primary input ratio, r_i is import ratio, β_t is total input percentage, β_r is primary input percentage, β_w is DPO percentage, β_p is DP percentage, T_t is sectoral total input intensity, T_r is sectoral primary input intensity, T_w is sectoral DPO intensity, T_p is sectoral DP intensity, v is the value added, G is the competitive imports, f is the non-competitive imports, w is the discharged waste, $\overline{\overline{w}}$ is the reduced waste, r is the primary input, p is the pollutants, and x is the total product.

The technical level indicators are direct input coefficients $\overline{a}$ and pollution discharge coefficients q, representing the materials inputs and pollutants discharge per unit product respectively, which are shown as Equation （17）.

$$\overline{a_{ij}}=\frac{Z_{i,j,0}+G_{i,j,0}}{x_j},\ q_{ij}=\frac{w_{i,j,0}}{x_j} \quad (i,j=1,2,\cdots,n) \qquad (17)$$

Where, $\overline{a}$ is the direct input coefficient, q is the pollution discharge coefficient, Z is the intermediate deliveries of secondary inputs, G is the competitive imports, w is the discharged waste, and x is the total product.

4 Preliminary application

4.1 Introduction of Yima city

Yima city is a pilot county-level city demonstrating circular economy development in China. Yima is located in middle China's Henan Province. The area of Yima is 112 km^2, with the population of about 150,000. The agriculture is only 2% of GDP, and the service is only 33%, which means that the economy mainly depends on the industry. There're several coal mines in Yima, and the mining industry is the pillar industry, accounting for about one third of Yima's GDP and nearly half of the value added of the industry. The economic structure is relatively simple and low-level. At the same time, the environmental problems are serious. The surface water, ground water and air are all heavily polluted. Large quantities of industrial wastes, including large amount of hazardous wastes are directly discharged without any treatment every year.

4.2 Compilation of YMPIOT2002

A 3D-PIOT for year 2002 was compiled, which is called YMPIOT2002. YMPIOT2002 comprises 1 main table, 7 sub-tables of biomass, fossil fuels, metal ores, industrial minerals, construction minerals, semi-manufactured and finished products, and wastes, and 2 supplementary tables of special material flows and water.

Due to the length limits, only the main table (shown in Table 4), supplementary table of special material flows (shown in Table 5) and water (shown in Table 6) are listed in this paper, while the sub-tables are not listed. Moreover, due to the space limit, the wastes are simplified into four columns, with each column denoting one group of wastes, and the non-competitive imports are simplified into one row, denoting the sum of each sector. The balancing items here refer to the air for combustion. The weight of wastes listed in the table including the air for balancing.

The economic system of Yima city are classified into 14 sectors, which are agriculture, coal mining industry, mineral mining industry, power industry, chrome chemical industry, grinding material industry, coal gas industry, water supply industry, other industries, construction, freight transportation, passenger transportation, service and household.

The emissions and wastes are classified into 4 groups, 19 categories. Emissions to water include 3 categories, i.e. COD, ammonia nitrogen, and other emissions. Emissions to air include 5 categories, i.e. SO_2, flue dust, industrial dust, CO_2 and other emissions. Solid wastes include 7 categories, i.e. hazardous waste, metallurgical slag, fly ash, boiler slag, coal gangue, mine tailings and other solid waste. The dissipative uses and losses include 4 categories, i.e. fertilizer, pesticide, manure and others.

Table 4 Main table of YMPIOT2002 (thousand tons)

		Intermediate use															Final use							Total Output
		A	CM	MM	P	CC	GM	CG	WS	OI	C	FT	PT	S	H	sum	Exports	NAS	Emissions & Wastes					
																			e.w.	e.a.	s.w.	d.u.l.	Sum	
Intermediate Input	A	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	2.7	0.0	0.0	1.0	18.5	28.8	0.3	0.0	3.0	5.7	9.5	8.6	26.9	55.0
	CM	0.3	7.3	0.9	575.6	8.2	33.8	113.4	0.2	10.1	5.1	0.4	0.8	19.4	73.8	849.5	3958.6	0.5	0.1	18.1	248.4	0.5	267.2	5062.8
	MM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	447.5	0.0	0.0	0.0	0.0	447.5	0.0	0.5	0.0	2.1	45.0	0.5	47.6	494.2
	P	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	20.0	50.6	0.0	0.0	1309.4	250.6	0.0	1560.0	732.8
	CC	0.0	0.0	0.0	0.0	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	15.2	0.0	0.0	96.3	36.9	0.0	133.2	99.8
	GM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	65.0	0.0	0.0	122.5	58.0	0.0	180.5	156.8
	CG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.4	14.4	51.0	0.0	0.8	84.4	26.8	0.0	111.9	116.1
	WS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.0	0.6	0.2
	OI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.1	3.4	1.7	0.0	0.1	25.6	4.7	0.0	30.4	17.5
	C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	668.8	0.0	12.1	11.5	0.0	23.6	683.9
	FT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	30.3	0.1	0.0	30.5	8.9
	PT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	5.5	0.2	0.0	5.8	2.3
	S	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.1	0.0	0.1	0.9	45.8	6.8	0.0	53.4	23.5
	H	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	11.7	293.9	38.1	2.2	345.8	151.2
	Sum	3.0	7.3	0.9	575.6	18.0	33.8	113.4	0.2	14.1	475.3	0.4	0.8	20.8	111.8	1375.4	4142.4	672.2	16.6	2052.3	736.7	11.9	2817.4	7605.1
Primary Input	C. Im.	9.5	0.0	0.0	154.8	17.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	24.9	209.1								
	N. Im.	2.7	1.0	1.0	2.5	64.0	123.0	2.7	0.0	3.4	208.6	8.5	1.5	0.6	14.5	433.9								
	D.E.	39.8	5054.5	492.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5586.6								
	Sum	52.0	5055.5	493.3	157.3	81.8	123.0	2.7	0.0	3.4	208.6	8.5	1.5	2.7	39.4	6229.6								
Total input		55.0	5062.8	494.2	732.8	99.8	156.8	116.1	0.2	17.5	683.9	8.9	2.3	23.5	151.2	7605.1								
Additional information	B.I.	1.1	12.9	1.5	897.7	58.4	88.7	61.2	0.4	18.0	8.5	22.0	4.0	32.1	196.0	1206.4								
	V.A.(MY)	24.6	297.3	15.8	63.8	18.2	13.9	23.9	1.0	75.6	89.4	68.3	45.5	336.9	600.4	1074.3								

Note: A=agriculture, CM=coal mining, MM=mineral mining, P=power, CC=chrome chemical, GM=grinding material, CG=coal gas, W=water supply, OI=other industries, C=construction, FT=freight transportation, PT=passenger transportation, S=service, H=household, e.w.=emissions to water, e.a.=emissions to air, s.w.= solid waste, d.u.l.=dissipative uses and losses, D.E.=domestic extraction, C. Im.= competitive imports, N. Im.= non-competitive imports, B.I.=balancing items, V.A.=value added

Table 5 Supplementary table of special material flows of YMPIOT2002

		Intermediate use															Final use		Total products
		A	CM	MM	P	CC	GM	CG	WS	OI	C	FT	PT	S	H	sum	Exports	NAS	
Intermediate Input	A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	P(Gwh)	5	185	2	17	8	130	69	0	4	5	1	0	18	9	452	128	0	580
	CC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	GM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	CG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	WS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	OI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	FT(Mt·km)	7	39	6	13	6	9	4	1	17	18	1	0	55	9	184	0	0	184
	PT(Mp·km)	0.2	2.0	0.0	0.2	0.2	0.0	0.1	0.0	1.0	0.3	0.1	0.0	2.7	60.9	67.7	0	0	67.7
	S	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Note: A=agriculture, CM=coal mining, MM=mineral mining, P=power, CC=chrome chemical, GM=grinding material, CG=coal gas, W=water supply, OI=other industries, C=construction, FT=freight transportation, PT=passenger transportation, S=service, H=household

Table 6 Supplementary table of water of YMPIOT2002 (million tons)

		Intermediate use															Final use		Total products
		A	CM	MM	P	CC	GM	CG	WS	OI	C	FT	PT	S	H	sum	Exports	NAS	
Intermediate Input	A	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CM	0.00	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	0.00	0.44
	MM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P	0.00	0.00	0.00	10.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.76	0.00	0.00	10.76
	CC	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.05
	GM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CG	0.00	0.00	0.00	0.00	0.00	0.00	118.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	118.53	0.00	0.00	118.53
	WS	0.81	2.47	0.05	3.34	0.08	0.00	1.26	0.00	0.20	0.15	0.00	0.00	0.50	1.48	10.34	0.00	0.00	10.34
	OI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	FT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	PT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Sum	0.81	2.91	0.05	14.10	0.13	0.00	119.79	0.00	0.20	0.15	0.00	0.00	0.50	1.48	140.12	0.00	0.00	140.12

Note: A=agriculture, CM=coal mining, MM=mineral mining, P=power, CC=chrome chemical, GM=grinding material, CG=coal gas, W=water supply, OI=other industries, C=construction, FT=freight transportation, PT=passenger transportation, S=service, H=household

The data were collected mainly from four kinds of sources. The first data source is the statistic data from statistic bureau of Yima city. The second is the statistic data from environmental protection bureau of Yima city. The third is the data investigated from the important corporations in Yima city. The fourth is the data investigated from coal bureau, water resource bureau, construction bureau and other governmental administrations of Yima city.

4.3 Analysis and discussion

4.3.1 General structure analysis

In the year of 2002, the total input of Yima city was 7.61 Mt, of which the primary input and intermediate input were 6.23 Mt and 1.38 Mt respectively. The primary input ratio was 81.9%. Among the primary input, the domestic extraction and the import were 5.59 Mt and 0.65 Mt respectively. The import ratio was low as only 10.4%, which reveals that the economic growth of Yima city mainly depended on its domestic natural resources. Furthermore, in the condition of such low import ratio, the high primary input ratio implies that the industrial chain was short and the economic structure was low-level in Yima city.

In the year of 2002, the total output of Yima city was 7.61 Mt, of which the intermediate use and final use were 1.38 Mt and 6.23 Mt respectively. Among the final use, the exports, NAS, and wastes were 4.14 Mt, 0.67 Mt, and 1.42 Mt respectively, with the ratio of 66: 11: 23. This result reveals that after the use of the economic system, the primary input mainly became exported goods, and a quite large amount turned into wastes, while only a small percentage became stocks that remained inside the economic system of Yima city.

4.3.2 Material structure analysis

The data of amount and percentage of each type of materials are listed in Table 7. The fossil fuels constituted most of the primary input, exports, wastes and pollutants of Yima city, with high percentages of 84.2%, 96.7%, 77.4%, and 68.4% respectively. Therefore, the fossil fuel was the dominant type of material flows in the material metabolism of Yima city.

The waste was zero in the primary input, which means that the economic system of Yima city neither disposed the wastes historically stocked inside it, nor disposed the wastes outside it. At the same time, only very few wastes were exported. If this situation continues, there will be more and more wastes in Yima city, which will bring higher risk to the environment.

Table 7 Material structure data of Yima city in Year of 2002

	Amount (thousand tons)					Percentage (%)				
	Primary Input	Exports	NAS	Wastes	Pollutants	Primary Input	Exports	NAS	Wastes	Pollutants
Biomass	87	0.3	13	73	46	1.4	0.01	2.0	5.2	5.5
Fossil fuels	5,245	4,007	0	1,095	578	84.2	96.7	0.0	77.4	68.4
Metal ores	164	80	14	70	70	2.6	1.9	2.1	4.9	8.2
Industrial minerals	30	0	0	30	16	0.5	0.0	0.0	2.1	1.9
Construction minerals	492	0	448	45	45	7.9	0.0	66.6	3.2	5.3
Semi-finished and finished products	212	4	177	30	30	3.4	0.1	26.4	2.1	3.6
Wastes	0	51	20	72	60	0.0	1.2	3.0	5.1	7.1

4.3.3 Sectoral structure analysis

Because Yima city is a small city, its industries are relatively few. Many of the elements of the first quadrant of YMPIOT2002 are zero, which means that the interrelationship between industries in Yima was relatively weak. In detail, only some products of coal mining, power, water supply, coal gas, freight transportation, passenger transportation and service were provided for domestic use. At the same time, the material inputs of water supply, freight transportation, passenger transportation and service mainly depended on imports, the power industry also needed some raw materials imported. The consumer goods mainly depended on imports, except fuels of household. One third of raw materials of construction were also imported. For chrome chemical, grinding material, even all the raw materials except fuels were directly imported, and all the finished goods were directly exported. Especially, most of the domestically extracted coals, the dominant material type, were directly exported, while the remains were only simply used as fuels or to produce coal gas, without further manufacturing. This also reveals that the industrial chain was too short.

The main sectoral indicators of material flows are listed in Table 8. According to these indicators, the coal mining industry was the key sector of the amount and intensity of the primary input, while it was not the key sector of amount and intensity of wastes and pollutants. Although the power industry was not the main cause of the large amount and high intensity of the primary input, it was the key sector of amount and intensity of wastes and pollutants in Yima city. Altogether, the power industry and the coal mining industry were the key sectors of material flows in Yima city. These two sectors were both related to the coal, which accords with the above analysis that the fossil fuel was the dominant type of material flows in the material metabolism of Yima city. According to more detailed pollutants data of YMPIOT2002, the chrome chemical industry which discharged large amount of hazardous wastes should also be paid enough attention to.

Table 8 Sectoral material flow indicators of Yima City in Year 2002

	Percentage (%)					Intensity (t/KY)			
	GDP	Total input	Primary input	Wastes	Pollutants	Total input	Primary input	Wastes	Pollutants
Agriculture	2.3	0.7	0.8	1.8	2.4	2.2	2.1	1.0	0.9
Coal Mining	27.7	66.5	81.1	17.9	29.0	17.0	17.0	0.9	0.8
Mineral Mining	1.5	6.5	7.9	3.3	5.3	31.3	31.3	2.9	2.9
Power	5.9	9.6	2.5	46.7	39.1	11.5	2.5	10.4	5.3
Chrome Chemical	1.7	1.3	1.3	5.4	6.4	5.6	4.6	4.2	3.0
Grinding Material	1.3	2.1	2.0	6.5	6.8	11.3	8.8	6.6	4.2
Coal Gas	2.2	1.5	0.0	3.6	1.4	4.9	0.1	2.1	0.5
Water Supply	0.1	0.0	0.0	0.1	0.1	1.2	1.0	1.2	1.1
Other Industries	7.0	0.2	0.1	0.9	0.6	0.2	0.0	0.2	0.1
Construction	8.3	9.0	3.3	1.1	1.4	7.7	2.3	0.2	0.1
Freight Transportation	6.4	0.1	0.1	0.6	0.0	0.1	0.1	0.1	0.003
Passenger Transportation	4.2	0.0	0.0	0.1	0.0	0.05	0.03	0.04	0.007
Service	31.4	0.3	0.0	1.5	1.0	0.07	0.006	0.06	0.03
Household	—	2.0	0.7	10.7	6.4	—	—	—	—

4.3.4 Technical level analysis

The structure analysis has identified the power industry and coal mining industry as the key sector of the material metabolism of Yima city. The technology level of these two sectors will be further analyzed in this section.

The power plants in Yima were on small scale, which were from 6 to 30 MW, and the technology was low-level, which leaded to the low resource productivity and large amount of pollution discharge. The coal consumption of Yima's power industry is 1135 g/kWh, which is 2.9 times of the average level in China. Besides, the heat value of coal was very low, which was also an important cause of the large amount of coal consumption. All these made the primary input intensity very high, and furthermore the waste intensity very high.

The main wastes of power industry were fly ash and boiler slag. The percentage of ash to coal was 30%~40%, which leaded to large amount of fly ash and boiler slag generated. At the same time, the recycling rate of fly ash and boiler slag was only 24%, which was very low. Therefore, large amount of fly ash and boiler slag were discharged to nature. While in the year of 2001, the recycling rate of fly ash and boiler slag in Jiangsu Province reached 103.8% and 94.7% respectively (DESE(2003)). Therefore, the reduction potentials of the resource use and pollution discharge of Yima were still very high.

As for the coal mining industry, the comprehensive electricity consumption of coal producing was 39 kwh/t, which was relatively high. Electricity was one of the main costs of coal mining, which means that reducing the comprehensive electricity consumption can reduce the costs and improve the benefits, so that the primary input intensity can be lower. Therefore, the potential of reducing primary input intensity of the coal mining industry of Yima still existed.

The main waste of the coal mining industry was the coal gangue. The coal gangue generation ratio was 0.067t/t, which was not very high. However, the recycling rate of the coal gangue was only 26.8%, which leaded to large discharge amount of the coal gangue. While in the year of 2001, the recycling rate of the coal gangue in Jiangsu province reached 89.5% (DESE(2003)). Therefore, the potential of reducing pollution discharge of the coal mining industry of Yima remained high.

4.3.5 Macro comparison

According to YMPIOT2002, the DMI, DMC, DPO, DP and recycling rate were 6.23 Mt, 2.28 Mt, 1.42 Mt, 0.86 Mt, and 2.5% respectively. Divided by the data of GDP and population, intensity indicators can be derived as follows. The DMI per capita, DMC per capita, DPO per capita, DP per capita were 40.5t, 14.8t, 9.2t, 5.6t, respectively. DMI intensity, DMC intensity, DPO intensity, DP intensity were 5.8 t/KY, 2.1 t/KY, 1.3 t/KY, 0.8 t/KY, respectively.

The Guiyang city, which was also a resource type city, DMI per capita, DP per capita, DMI intensity, DP intensity and recycling rate were 6.7t, 1.3t, 1.1t/KY, 0.2t/KY, and 11.0% respectively (Xu et al. (2004)). These indictors, Yima were 6.0 times, 4.2 times, 5.3 times, 3.7 times and 22% of Guiyang respectively. Compared with Guiyang, the material intensity were higher while the recycling rate is lower in Yima, which reveals that the resource productivity of Yima was lower.

4.3.6 Scenario analysis

In order to complete the industrial transformation and establish a circular economy in Yima, at least the following three measures can be taken. The first one is to optimize and upgrade the economic structure, among which developing high value-added industries, extending the industrial chain are good choices. Since the fossil fuel (mainly coal) was identified as the dominant material type, the emphasis of such efforts could be laid on the coal. The second one is to improve the technology and equipment. The power industry and coal mining industry were identified as the key sectors of current material metabolism in Yima, the technology and equipment improvement should be focused on these two sectors to improve the resource productivity. The newly established industries should also adopt advanced and appropriate technologies. The third one is to improve the recycling rate. Efforts can be made to establish some new industries which use the recycled wastes as raw materials, such as construction material industry which can reduce fly ash and boiler slag. In this way, the wastes can be remarkably reduced, while more economic outputs can be produced.

The goal of economic growth has been set by the government of Yima city. Three scenarios were designed to help forming the plan of circular economy development in Yima city, which can reduce the pressure on natural resource and environment while reach the goal of economic growth. All the three scenarios require production enlargement, but in different ways. The first scenario is *business as usual*, that is keeping the industries, products, techniques and recycling rates the same as those in year 2002. The second scenario is *half improvement*, keeping the industries and products almost the same as those in year 2002, while improving the techniques and recycling rates remarkably. The third scenario is *full improvement*, that is not only improving the techniques and recycling rates greatly, but also upgrading the economic structure and extending the industrial chains. Due to the length limit, the scenarios cannot be discussed in detail in this paper.

5 Conclusions

A regional metabolism analysis model based on three dimensional PIOT was developed to meet the demand of developing circular economy and provide a tool for decision making and policy analysis. There're four major features in the design of the 3D-PIOT. The first is that it consists of a main input-output table, a series of sub-tables and supplementary tables, in which the structure of main table and sub-tables are the same, while that of supplementary tables are a little different. The second is that the material flows are measured in mixed units, which records all the material flows measured in mass unit and non-mass units. The third is the treatment of waste. A sub-table is specially designed to record all the recycled waste flows, which describes the generation, reuse, disposal, recycle and discharge of the recycled wastes. The fourth is that the consumptions, including government and household, are regarded as sectors of intermediate use. This makes the system boundary clearer, while physical input-output analysis model can still be further developed based on such design.

On the basis of the three dimensional PIOT, some indicators of material flows were developed to assess the regional metabolism. Based on the planning table derived from 3D-PIOT, planning model can be further developed, which can be used to make plan for the future development of regional metabolism.

Yima city was chosen for the first application of the model. A 3D-PIOT called YMPIOT2002 was compiled, and the economic growth style and material metabolism of Yima city was analyzed and discussed preliminarily. The analysis based on YMPIOT2002 reveals that the economic growth style in Yima was a linear one of "natural resource—products—waste", and the resource productivity of Yima was very low. The low-level economic structure and the backward technology and equipment of Yima were the main reasons of such a linear economy and low resource productivity, which calls for the circular economy of "natural resource—products—waste/recovered resource", aiming at *less material input, more economic output, and less pollution discharge*. Moreover, three scenarios representing different economic growth styles were made, which helps to plan the future material metabolism in Yima.

At the same time, the application of the regional analysis model to Yima city is only a preliminary one, further analysis can be done, e.g. the analysis of some specific pollutants such as SO_2, COD, etc. Besides, the economic structure is not very complex in Yima, the model could be applied to some other economic systems with more complex structures and more complete industrial systems in the future work.

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