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A three-dimensional model featuring material flow, value flow and organization for environmental management accounting

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ABSTRACT

In the context of sustainable development, environmental considerations embedded in the life cycle of a product cannot be separated from the environmental management accounting of product and waste costs, or from the quantification, monitoring and evaluation of external environmental damage. In this paper, a three-dimensional model for environmental management accounting is built that takes into consideration the dimensions of material flow, value flow and organization; this model is based on material flow cost accounting and the traditional life cycle theory. On this basis, this paper explains the basic principles of the resource value flow analysis method, and it dissects the internal mechanism of the three-dimensional model from the perspective of the enterprise, the industrial park and the nation. Then, using aluminum production as a case study, this paper briefly expounds on the implementation of resource value flow analysis from the perspective of the organization. This three-dimensional model expands the organizational boundaries of material flow cost accounting, providing guidance for tracking and quantifying the environmental impact of material flow over the entire life cycle of the enterprise, and evaluating the efficiency of the objective of material flow.

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1. Introduction

Given the deterioration of the ecological environment in recent years, the sustainable development of society is facing enormous challenges (Enríquez-de-Salamanca et al., 2017; Rodell et al., 2018). Many questions have arisen as to how to establish a new order of modern human civilization, guided by the rational development of resources and focusing on sustainable development as a central element; this challenge exists at all levels and for all types of organizational entities, including enterprises, industries, industrial parks, regions and even nations. Since the time that the idea of an “ecological civilization strategy” was established, the concepts of “green development,” “low-carbon development” and “circulating development” have revealed ways and means by which we may achieve an “ecological civilization.” Regarding the implementation of a specific strategy, after Germany developed its “Industry 4.0” concept, and the United States developed the “Industrial Internet of Things (IIOT),” China promulgated the “Made in China (2025)” directive. While these countries have different historical backgrounds, they share many common goals, including evolving a green manufacturing system and reducing energy consumption. Since the time that accounting was integrated into environmental problems, accountants contributed greatly to issues of sustainable development. Indeed, accounting systems have become data information support systems by means of evaluating the complex interactive impact that accounting has on an organization and on the larger economy, society as a whole and the environment (Gray, 2002; Hopwood, 2009; Ogilvy et al., 2018). Given people's attention to environmental responsibility, we find indications that demand for accounting systems and accounting information flow is increasing. From the perspective of strategy implementation, there is an inseparable link between an organization and the larger economy, the society and the environment, especially as sustainability becomes an important metric of the output performance of an organization (Bebbington and Larrinaga, 2014).

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Environmental accounting, which is a tool that may be used to monitor and reflect environment-related economic activities, has been researched by many scholars according to various topics, including sustainable development accounting, environmental financial accounting and environmental management accounting (Deegan, 2017; Gray, 2010; Jasch, 2006; Wang and Jiang, 2014; Xiao, 2010). Some have discussed the challenges that environmental accounting faces in meeting the needs of sustainable development strategies and building the institutions of an ecological civilization (Killian and O'Regan, 2016; Shen and Liao, 2014; Tregidga et al., 2014; Zhou and Tao, 2012). The following is a selected list of environmental management accounting studies that have appeared in the past ten years: the *United Nations Division for Sustainable Development* (UNDSD) has issued two workbooks on environmental management accounting (UNDSD, 2001, 2002), and the *International Federation of Accountants* (IFAC) has issued international guidelines for environmental management accounting. In terms of the management tools used for environmental accounting, material flow cost accounting (MFCA), which first originated in Germany, is a highly regarded and respected method. MFCA can be used to track and quantify the material flow and inventory of the respective physical units of organizations, and it may further be used to improve the transparency of corporate consumption of materials and energy. Since the *International Organization for Standardization* (ISO) published the ISO14051:2011 "*Environmental management-Material flow cost accounting-General framework*" (ISO, 2011), MFCA has been widely promoted and applied in Germany, Japan and other countries and regions, and many enterprises have expressed strong interest in its production practices (Christ and Burritt, 2015; Kokubu and Kitada, 2015; Wagner, 2015). In recent years, some researchers have begun to explore how to systematically integrate the MFCA visualization tool with ERP (Enterprise Resource Planning) into industries that have a low-carbon supply chain, as well as into other systems, to obtain more information about cost savings (Fakoya and van der Poll, 2013; Nakajima et al., 2015; Prox, 2015).

Based on MFCA, a research team led by professor Xiao has been expanding MFCA from the perspective of the circular economy. Xiao has established a "material flow"- "value flow" two dimensional (2D) accounting system based on resource flows (Xiao and Jin, 2008; Xiao and Liu, 2014; Xiao and Xiong, 2015). The 2D accounting system aims to solve the problem of "uneconomic recycling," which is a situation faced by some enterprises as they navigate the process of applying circular economy technology. The 2D accounting system also aims to eliminate the common errors that occur with most current accounting systems. These problems mainly exist in the case of a product cost accounting system that does not reflect the economic value of "external environmental cost internalization" that occurs during the operation of a circular economy, and that does not properly estimate the waste cost information of the production process or the monetary evaluation of the environmental effects (Li et al., 2019). To this end, Xiong et al. (2015) and Zhou et al. (2017) introduced the connotation of the 2D analysis, and they used concrete case studies (*e.g.* CHINALCO and *L* Steel) to illustrate the application of this method at the enterprise level. 2D analysis of environmental management accounting is a tool that can identify and estimate potential points during production at which improvements can be made, and it can also measure the effectiveness of such measures before and after these improvements, ultimately contributing to the business activity of circular economy practices.

However, with continuous in-depth research, we found that the 2D analysis method can be further developed in terms of the function and application of boundaries. First, current environmental management accounting takes the enterprise as the research object and focuses solely on the cost savings of a particular enterprise; it does not extend to the upstream and downstream enterprises that may exist in the supply chain. Second, environmental management accounting focuses on the material and value flows of product manufacturing, which ignores the material metabolism mechanism. This mechanism is the ecological industrial system which, according to the principles of biology, can be viewed as a food chain made up of producers, consumers, disintegrators and the abiotic environment, and which involves a metabolic process that turns raw materials and energy into products and wastes. The material metabolism mechanism of the ecological industry takes a full life cycle perspective, and it blocks the continuous optimization of inter-organizational material flow. Third, "the micro-cycle (enterprise)", "the meso-cycle (industrial park)" and "the macro-cycle (region or nation)" elements of the practice of a circular economy pose a challenge for the applicable boundaries of 2D analysis (Geissdoerfer et al., 2017; Winans et al., 2017). Therefore, an expansion from the micro level to the meso and macro levels is needed. In other words, 2D analysis should be extended to multi-level organizations based on a full life cycle perspective. In view of this, this paper builds a "material flow"-"value flow"—"organization" three-dimensional (3D) model for environmental management accounting. Compared with existing research, the important new aspects presented in this paper are reflected in the following observations:

1) Available literature on MFCA poses more questions than solutions; some studies consider cases based on actual organizational behavior, but theoretical research on MFCA is rare (Christ and Burritt, 2015; Schaltegger et al., 2012; Wagner, 2015). This paper conducts basic theoretical research on environmental management accounting and facilitates the search for theoretical explanations to promote the organizational practices of MFCA.
2) ISO indicates that MFCA is applicable to any organizational level (cost centers, factories, enterprises, industries, regions, etc.), but MFCA adopters are still mainly standalone enterprises, and the main obstacle facing MFCA implementation is its inability to share information about internal economic systems that exist between organizations (Nakajima et al., 2015). The aspects of volume and value reveal the material structure and loss of efficiency from the entire life cycle perspective; this helps to achieve the sharing of information about waste costs and environmental damage, which in turn provides the basis by which the government may determine the corresponding cost-sharing standards and economic support measures.
3) Standardization is an important undertaking for improving resource efficiency, reducing pollutant emissions and disseminating technology. In addition, the application of environmental management accounting tools requires standardized criteria and processing systems (Christ and Burritt, 2016; Xiao and Xiong, 2015). This paper intends to provide a top-level architectural design for value flow network mapping and organizational boundary demarcation that will help to standardize resource value flow analysis (RVFA).

The remainder of this paper is organized as follows: Section 2 provides a basic theory review; Section 3 presents the construction of the 3D model; Section 4 presents the application mode of the 3D model for enterprises, industrial parks and nations; Section 5 lists and discuss the conclusions drawn from this study.

2. Theoretical background

Throughout the history of accounting, the capital movement theory has been based on material transfer (Xiao and Xiong, 2015). Monetary information and material flow information are linked and interact with each other, and the circulation form can be represented as "cash → raw materials → finished-product → accounts receivable → cash." 2D analysis is a series of management activities based on currency as the main unit of measurement, as well as on the material flow analysis (MFA) of a circular economy. MFA includes factors such as value validation, measurement, reporting, analysis and evaluation of the displacement of resources and energy in different spaces within the organization, and it allows for participation in the control of, and decision-making about, the circular economy (Xiao and Jin, 2008).

If only at the enterprise level, material flow passes through different sectors (such as quantity centers, workshops, factories, etc.) in different forms, including raw materials, intermediate products, finished products and other physical forms. Correspondingly, materials have different values that are manifested as fees or costs, including output value, added value and other monetary forms. However, current 2D analysis within the boundary of the enterprise could be improved. MFA in economic systems is performed throughout the entire life cycle of the material, including material extraction, production, manufacturing, usage and disposal into recycling and other processes. However, material flow and inventory behaviors at different stages are led by a particular organization, and each stage will produce waste and involve environmental damage. The 3D model that this paper intends to construct involves the integration of content related to multi-disciplinary fields. To further identify and define the developmental potential of this tool, this paper reviews existing theories from two aspects: MFCA and the life cycle theory.

2.1. Material flow cost accounting (MFCA)

In the late 1980s, MFCA originated out of an environmental management project conducted by the *Kunert Textile Company* in Germany. Wagner developed MFCA into an environmental management accounting tool, into which certain other concepts have successively been incorporated, such as "flow accounting," "flow cost accounting" and "environmental cost accounting" (Wagner, 2015). In Japan, based on Wagner's work, the material flow model was set up using input terminals (e.g., material, energy and system costs) and output terminals (e.g., positive products and negative products) according to the principle of "input-output" material balance. The material flow model was divided into different quantity centers according to production operation units, and the total cost of each quantity center was assigned between the positive and negative products. MFCA has gradually become an important branch of environmental management accounting, and the promulgation of ISO14051 was a catalyst that promoted the use of MFCA in wide practice.

MFCA is a kind of visualization tool that can quantify (with material units and monetary units) and track the flow and inventory of raw materials, energy and system costs during the production process. It can also reveal any inefficient steps that occur during the production process (ISO, 2011). The material balance principle is the theoretical basis of MFCA, and this principle holds that "raw material + new inputs = positive products + negative products." As shown in Fig. 1, material circulation at the enterprise level can be divided into several quantity centers, and the positive and negative product costs can be calculated according to the sequential movement of materials and energy within the different quantity centers. Compared with traditional cost accounting, the difference with MFCA lies in the identification of waste. MFCA considers all material losses as waste or non-product output, while traditional cost accounting systems do not include loss that exceeds certain established criteria (Kokubu et al., 2009). Specifically, MFCA costs can be divided into material costs (material purchase price × inputs), energy costs (average unit price × consumption), system costs (expense ratio × work-hour × unit price) and waste costs (using the LIME index).

MFCA can be applied to a single process manufacturing enterprise, and it may also be extended to multiple enterprises or organizations by means of the supply chain. MFCA can be used to develop an integrated method for more efficiently consuming raw materials and energy (ISO, 2011). A 2D analysis from the perspective of a multi-level organization transcends the boundaries of individual organizational and expands the material transfer forms (i.e., from product/waste to consumption, waste collection, recycling and other links), using the principle of "input—output" material balance. Along with the added-value process of material flow, the participants are expanded from the enterprise to the process of industrial symbiosis (an industrial organization in which waste from a production process can be used as a raw material for another production process), as well as to industrial parks, countries (or regions) and other economic systems.

2.2. Life cycle theory

The concept of the "life cycle," which originated in the field of ecology, considers the entire life process of an entity, from birth to growth, maturity, recession, and finally death—in other words, from "cradle to grave"—and it refers to the regularity of natural things. The life cycle theory as applied to industrial ecology refers to the metabolic processes of the industrial ecosystem. The life cycle of a product includes raw materials, processing, manufacturing, transportation, consumption, disposal, recycling and reutilization. In addition, during sustainable development decision-making, life cycle cost (LCC) and life cycle assessment (LCA) are methods that are commonly used to assess products and evaluate the economic and ecological impacts of a production system (Lim and Park, 2007; van Boxtel et al., 2015). LCC focuses on the assessment of economic consequences (such as costs, revenues and cash flows), and LCA focuses on the identification and quantification of the ecological impact of economic activities (ISO, 2006).

MFA is a tool used to study the material resource transportation, transformation and inventory of a specific system (Brunner and Rechberger, 2004). It is an important method for quantitatively evaluating the development of a circular economy by studying the metabolism of the material resources used in economic activities. MFA in the context of a circular economy, and indeed throughout the entire life cycle of the materials, is a closed-loop model that is useful for evaluating "resources-products-waste-renewable resources." Certainly, industrial metabolism at different stages comes to completion within different economic sub-subsystems or organizational stages. Still, the logical starting point of MFA can be summed up according to three aspects: 1) the economic system is considered to be an organism with the capability of metabolism; 2) the material inputs and outputs of an economic system follow the regularity of mass conservation; and 3) resource acquisition and waste emissions generate environmental perturbations (Eurostat, 2001). Thus, to clarify the scale of 2D analysis, we need to accurately define the boundaries of the economic system (organization) based on the life cycle stages during which the materials being evaluated are used. However, the practice of a circular economy also includes three patterns: the micro-cycle, the meso-cycle and the macro-cycle. The micro-cycle is the metabolic process of the "resources—product" from a life-cycle perspective, and it is also the process by which byproducts (or wastes) from upstream companies become the raw materials used/processed by downstream

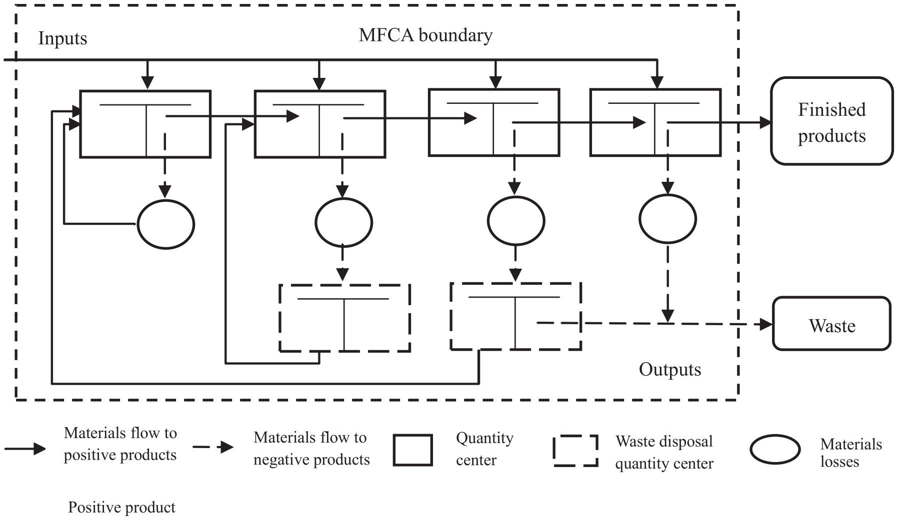


Fig. 1. Material balance of MFCA.

companies in the symbiotic industrial chain. Therefore, the boundary of 2D analysis should be extended to include the meso-cycle (circulation among symbiotic enterprises) and the macro-cycle (circulation between production and consumption).

3. The 3D model design

3.1. Objectives and principles

The objective of constructing a 3D model is to identify the rule of material circulation among intra-organizational and inter-organizational points, as well as the corresponding cycles of monetary flow and environmental impact. Specifically, the model will help an enterprise:

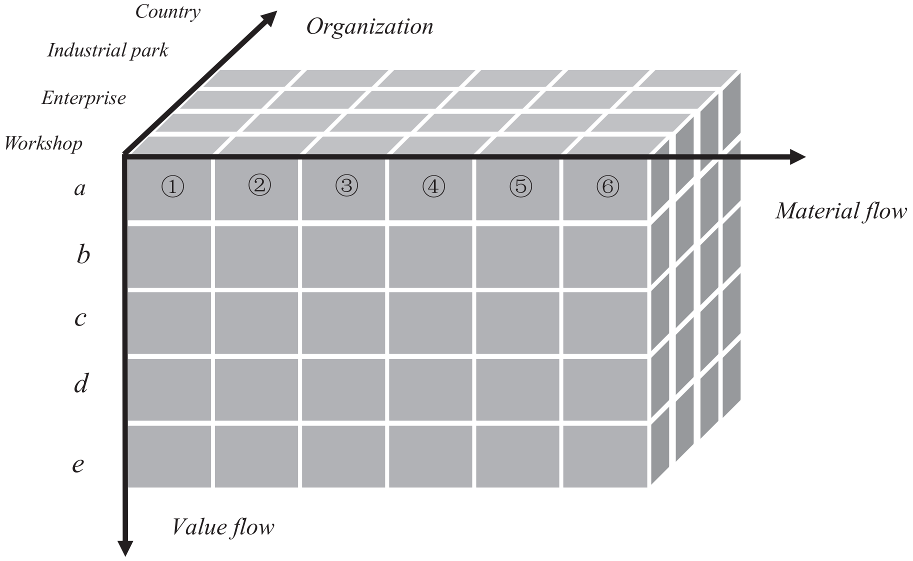
1) Quantify the value of lost resources and explore potential links that may be improved. In defining an organization's boundaries, this model visualizes material loss and other costs incurred during the life cycle in terms of both quantity and value, so as to locate the relevant links and costs and depict costs flows (including path and quantity) across the entire life cycle.
2) Identify the cost structure of lost resources and discover any inefficient steps. This value calculation, along with the lifecycle of resource transfer, covers direct costs and indirect costs, and the structure of lost resources is refined. Moreover, the value calculation matches with the corresponding objects, such as the organization of both technology and management. This eventually lays a good foundation for improving resource efficiency and reducing environmental impact.

During the process of constructing the 3D model, two basic principles are followed. First, a systematic principle: material circulation from a lifecycle perspective exceeds the boundaries of a single organization; accordingly, it is necessary to regard “raw material-product-recycling” as a metabolic process within an economic system. Additionally, the model reflects the systematic integration of accounting, industrial ecology and resource science, and its data integration requires the convergence of each module. Second, a principle is needed to extend the producer's responsibilities: resources value flow accounting is considered from a lifecycle perspective, considering more than just the value of external damages caused by production processes; rather, the scope of an organization's environmental responsibilities must be extended to product consumption, recycling and clean-up.

3.2. Model construction

Combining the process system and application mode of the RVFA, in this study, a 3D model was constructed using the dimensions of material flow, value flow and organizational hierarchy (Fig. 2). The essence of the model is to realize the vertical integration of enterprises, industrial parks and nations, while allowing for the horizontal integration of the cross-organizational value network and the end-to-end integration of the entire life cycle of materials. This model has an important reference value in terms of recognizing the internal and external relationships of the RVFA, where the objects, boundaries and relationships among different organizations are concerned.

The model is constructed in three dimensions: material flow, value flow and organization, as shown in Fig. 2. The material flow dimension is based on the principle of a whole life-cycle, consisting of a series of value-creating activities including resources, manufacturing, transport, use, disposal and recycling. The material flow activities in the lifecycle are interrelated and influence each other mutually. The lifecycles of different industries are different, and different organizations focus on different stages of the life cycle. The value flow dimension relies on material inputs (such as raw materials and energy) into an organization, and this reflects the value transfer of the resources. Specifically, the category of “positive products” refers to products or semi-finished products that can be sold directly or moved to the next process. “Negative products” refer to waste, which can bring value to an enterprise but may also have a negative impact on the environment and should be reduced as much as possible in the production and operation processes. “System costs” are costs incurred in the course of the in-house handling of material flows, except for material, energy and waste management costs, such as the cost of labor, depreciation and maintenance, transport and so on. “Environmental damage costs of wastes” represent the pollution and damage caused to the external environment by waste discharge; such costs are quantified by their monetary value. “Added economic value” refers to the increment of product value formed by resources flowing through each link. Value flow here is considered in a way that goes beyond the traditional scale of an accounting system (prices, costs and income),



Value flow: *a*. positive products, *b*. negative products, *c*. system costs, *d*. environmental damage costs of wastes, *e*. added economic value.

Material flow: ①resource, ②manufacturing, ③logistics, ④use, ⑤dispose, ⑥recycle.

Fig. 2. The 3D model.

and environmental damage costs are included. The organizational dimensions, from bottom to top, are divided into four levels: workshop, enterprise, industrial park and country. The definition of the organization in terms of RVFA emphasizes the idea of industrial symbiosis. The input and output processes of an industrial system can be regarded as an organism metabolism.

3.3. *Systematic framework*

The framework of the 3D model is shown in Fig. 3 and includes three components: common basis, methodology and application mode.

Specifically:

1) The “PDCA (plan-do-check-act) cycle” management model summarizes all aspects of the RVFA, which includes content, application, debugging and improvement. The 3D analysis from the whole life cycle perspective also follows the PDCA cycle. The “material flow of the whole life cycle” indicates that the LCA can be applied to a RVFA, and that the 3D analysis should be a “cradle to grave” evaluation that begins from the angle of the production system and emphasizes the environmental impact of each sector.
2) In the methodology module, the analytical framework of the “internal loss of resource flow-external damage of waste” has been introduced, the core principle of which is to calculate the cost of resource transfer. This includes two aspects: (1) by collecting information about costs, outputs may be divided into positive product costs (effective utilization cost of resources) and negative product costs (waste costs); and (2) waste occupies an important position that allows the external damage costs of the resource flows to be calculated by assessing any environmental damage that may be caused by the waste.
3) In the application mode, RVFA applied in industrial parks and at the country level represents a further development of enterprises' current practices. The RVFA application in an industrial park relies on an “economy-environment” integration evaluation (note that in the accounting of the economic benefits of resource flows, the environmental damage caused by waste is also evaluated) of material flow, energy flow integration, water integration and waste integration. However, the application of resource value flow analysis at the country level is based on the analysis of material input, material output, inventory and consumption, as well as on the environmental impact of all economic systems in a certain geographical area.

4. 3D model analysis

To gain a deeper understanding of the 3D model and reveal its underlying mechanisms and functions, we expound upon the basic principles of the 3D model and explain the thinking path from different organizational boundaries.

4.1. *Fundamentals of the 3D analysis*

Resource value flow accounting is based on flow management theory, and it incorporates theories about industrial ecology, such as energy flow analysis, MFA, and ecological efficiency. Given the gradual carry-over processing method used in cost accounting, and the tracking of changes in resources, resource value flow accounting considers the entire process of material information and value information to the organization (Xiao and Jin, 2008). Resource value flow accounting was inherited and expanded from Germany's MFCA, which calculates the costs of positive products and negative products. It also draws lessons from Japan's resource flow cost accounting, which added an environmental damage value that was evaluated using MFCA.

According to the interaction between material flow and value flow, and the method system module displayed in Fig. 3, the accounting equation for the resource value flow is shown as Eq. (1)

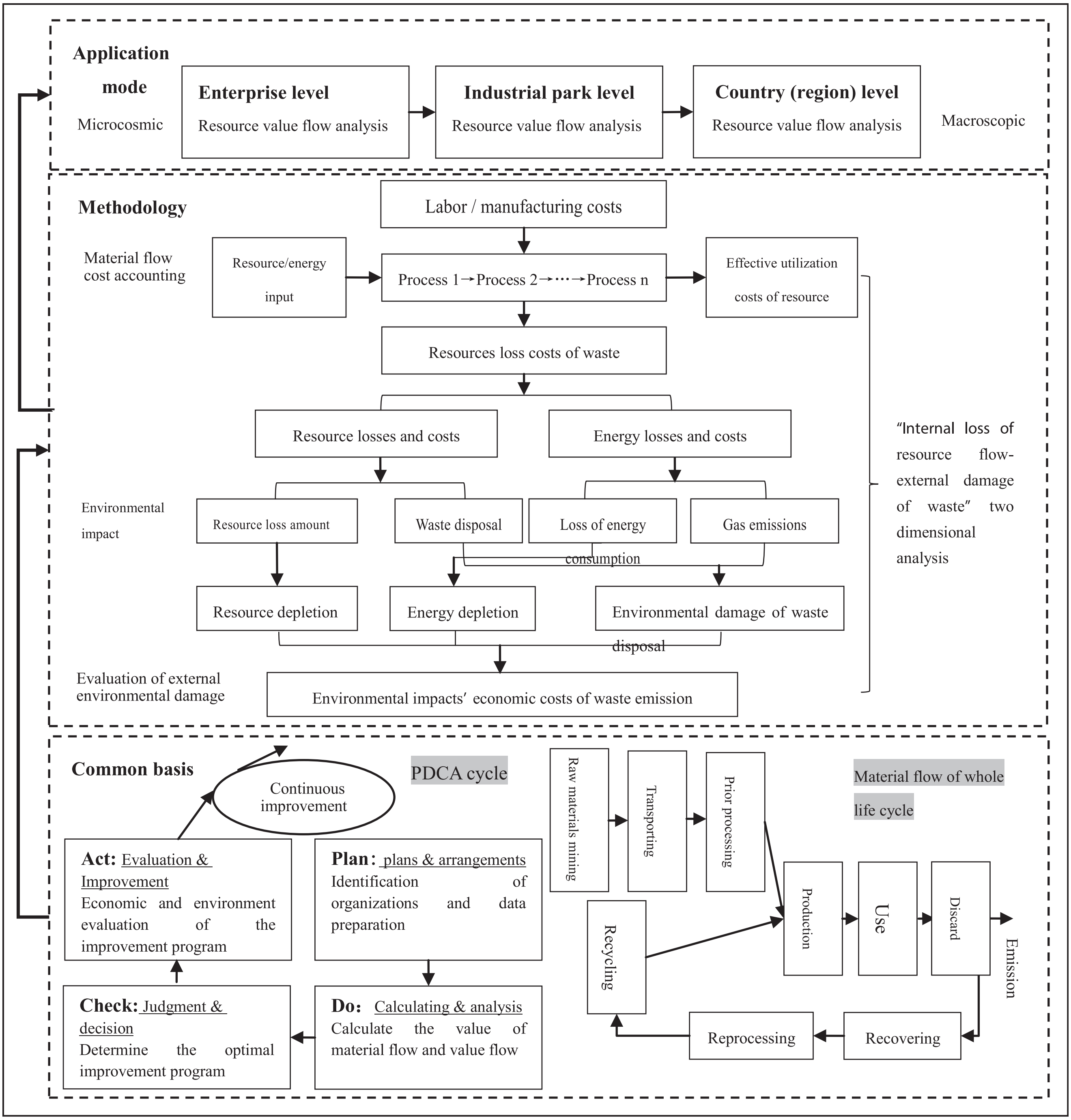


Fig. 3. Framework of the 3D model.

(Zhou et al., 2017; Zhou and Xiao, 2013).

$$RV_i = RAV_i + RUV_i + RLV_i + WEV_i \tag{1}$$

where, in the ith process, RV_i represents the value flow; RAV_i refers to the added value flow; RUV_i is the value flow of effective use; RLV_i is the internal resource flow loss, and the resource consumption and external environmental costs are represented by WEV_i. When $RV_i = RUV_i$, the impact of the economic, environmental and societal effects are optimized.

According to this accounting method, Eq. (1) can be further decomposed into Eq. (2), Eq. (3), and Eq. (4).

$$RUV_i = \frac{MC_i + EC_i + SC_i + OC_i}{QP_i + QW_i} \times QP_i \tag{2}$$

$$RLV_i = \frac{MC_i + EC_i + SC_i + OC_i}{QP_i + QW_i} \times QW_i \tag{3}$$

$$WEV_i = \sum_{i=1,j=1}^{m,n} WEI_{ij} \times UEV_{ij} \tag{4}$$

where, in the ith process, MC_i, EC_i, SC_i, and OC_i represent, respectively, the input costs of the material, the input costs of energy, the system cost and the cost of other expenses; QP_i and QWi refer to the weight or element content of the qualified products and wastes; WEI_{ij} is the waste of j's environmental impact on the process i; and UEV_{ij} is the environmental damage index (i.e., the external cost of the unit environmental load); and the UEV_{ij} is usually calculated using Japan's LIME (life-cycle impact assessment method based on endpoint modeling) method.

Eq. (5) can be used for an integrated evaluation of resource input, consumption cycle and output (Xiong et al., 2015):

$$RW_i = RP_i \times VP_i \times EP_i \tag{5}$$

where, in the ith process, RW_i is the environmental load rate of the unit resources (environmental damage value/resources input); RP_i is the resource productivity (output value/resources input), which indicates the relative savings of resource inputs and reflects the principle of "reduction"; VP_i is the output rate of added value (industrial added value/output), which represents the relative output ratio of added value due to resource flow circulation and indicates the principle of "reuse"; and EE_i is the environmental efficiency (environmental damage value/industrial added value), and this factor combines the pollution emissions of the unit added value with waste recovery, which indicates the principle of "recycling."

The above method has a solid foundation in 2D analysis, and it is an important tool for 3D analysis, which is an important way to account for, evaluate and control the circular economic activities of organizations. Organizations are social entities that exist in close contact with the external environment, and the relationship between/among two or more organizations is generally held together through resource transport and material flow (Daft, 2011). Especially in the current business environment, organizational activities have an increasing influence on the ecological environment. Accordingly, understanding how to control and reduce the costs of environmental damage is important, as this comprehension allows an enterprise to make accurate decisions regarding environmental cost servicing to reduce organizational waste, and it helps the enterprise to ultimately reduce the environmental impact of the overall value network. Such evaluation and decision-making requires the help of environmental management accounting tools that enable a more accurate assessment.

As the results shown in Fig. 2 demonstrate, with the extension of organizational boundaries, applying RVFA in enterprises, industrial parks and at the country level has enjoyed a trend of gradual superposition. Enterprise-level resource value flow analysis regards the workshop as the basic business unit; the industrial park regards the enterprise as the basic business unit; and the country level regards all organizations or subsystems (including enterprises and industrial parks) within a certain geographical area as an economic system. For any organization, each sector of internal resource circulation involved in the life cycle will create positive products (final products to the consumer or semi-finished products to the next process); negative products (waste); system costs; the environmental damage costs of waste; and added-value. The identity of each will be determined by different organizational levels that cause differences in accounting boundaries. Traditional MFCA (one-dimensional analysis) commits to achieving the visualization of material flow within the physical plant of enterprises, with the purpose of reducing economic loss. 2D analysis, which establishes the link between economic benefit and environmental damage by considering the economic value added, can be applied both to the enterprise level and to material integration at the industrial park level. However, 3D analysis expands the system boundaries based on the cross-organizational flow of material; thus, it can be used to analyze the resource value flow of multi-species materials, with the organization (enterprise or industrial park) as the center, and it can also be used to analyze the material metabolism from micro to macro of a single substance (e.g., *Al* or *Cu*).

4.2. RVFA at the organizational level

The 3D model promotes RVFA from the organizational perspective, extending the organizational boundaries from the enterprise level to the industrial park and country levels. System optimization is the core of RVFA at the organizational level, and there is a strong correlation between the different organizational levels, with a substance and/or specific product as the link. RVFA may be practices at the enterprise-level relies on a closed-loop flow of material, energy and value within a single firm; such an application of RVFA requires the enterprise to implement cleaner production and follow the "3R" principles of a circular economy throughout the process. However, the environmental investment of a single enterprise may result in "resource circulation without economic effect." At this point, the industrial park, which is committed to centralized waste disposal and comprehensive waste utilization, can scale the effect and cost-effectiveness by means of system optimization. Meso-scale industrial parks are business groups that have mutually symbiotic relationships. These relationships require material flow, energy flow, information flow and value flow among enterprises or industries. These flows are accomplished by means of industrial metabolism and symbiotic relationships, and they will eventually create closed-loop flows and reduce resource consumption and waste emission. System optimization at the industrial park level supports the material flow of the country and prevents the stagnation of material circulation that may occur when a single enterprise prioritizes its own economic benefits. For material flows at the macro-scale, the benefits of "3R" vary according to different links, and they require the country to regulate cost-benefit relationships to achieve overall optimization of material flows. RVFA implemented at the country level emphasizes the comprehensive utilization of a certain material, such as Aluminum (*Al*). The material flow of the economic system may be divided into input, inventory and output. At the same time, an effective integration of resource elements (resources, environment and economy) among different sectors and industrial communities must be achieved. Specific ideas for implementing RVFA at the organizational level are listed in Table 1.

The overall implementation of the ideas of RVFA as applied at the enterprise, industrial park and country levels is described in Table 1. We can abstract the flow of resource value into a function with 3 variables—material flow (X), value flow (Y) and organizations (Z), as denoted by $f(X, Y, Z)$. Then, by the random combination of these three variables, we can satisfy the different demands of resource value flow analysis. As can be seen in Fig. 4, modular combinations among different dimensions represent the different functional positioning of the 3D model. Moreover, the value flow of different materials in the life cycle, considered from the perspective of organizations and the value flow of one material across the entire life cycle, can be calculated separately, and the value flow of direct costs and indirect costs across the entire life cycle can be tracked. The value flow of resources accounted for in terms of material varieties, life cycle and cost project is refined as the value structure of positive products and negative products, and this lays the foundation for accounting for the value flow of resources at the organizational level. RVFA at the organizational level can measure the value attribution of the material transfer process from the angles of positive and negative products, and it can also account for the value of environmental damage through categorizing the types and attributes of negative products. In

Table 1
Resource value flow analysis at the organizational level.

Organization	Enterprise	Industrial park	Country
Material quantity	Workshop	Enterprise	Economic subsystem (Region, sector)
Basic theories	Flows management theory, material flow cost accounting, etc.	Industrial symbiosis theory, life cycle theory, etc.	Input-output theory, frame analysis, etc.
Accounting object	Material flow, value flow	A variety of substances	Specific element
Accounting Methods	$C_p^{k,j} = \sum_{j=1}^{l}(1-r_{k,j})(C_p^{k-1,j}+C_{k,j})$ $C_n^{k,j} = \sum_{j=1}^{l} r_{k,j}\times(C_p^{k-1,j}+C_{k,j})$ $r_{k,j} = w_{k,j}/(\sum_{j=1}^{l}(\sum_{i=1}^{k} m_{i,j} - \sum_{i=1}^{k} w_{i,j}))$		$C_p^k = (1-r_k)(C_p^{k-1}+C_k)$ $C_n^k = r_k\times(C_p^{k-1}+C_k)$ $r_k = w_k/(\sum_{i=1}^{k} m_i - \sum_{i=1}^{k} w_i)$
Purpose	1) To optimize material circulation path, strengthen the ability of recycling the material; 2) To decrease environmental costs of production and achieve cleaner production.	Make the material or energy to flow in a closed loop by industrial metabolism and symbiotic relationship among enterprises, and achieve horizontal or vertical integration of the material.	1) Studying the specific element's transfer process, and transform the quantity information into value information; 2) To assess environmental damage information that serves in the economic decision-making.

Note: C_p represents positive product cost, C_n represents negative product cost, and C_k is new input cost (including material costs, system costs, energy costs); r is the loss rate; m is the weight of material inputs; w is the weight of waste; j is the type of material or substance; k is the production process; and i represents the working procedure.

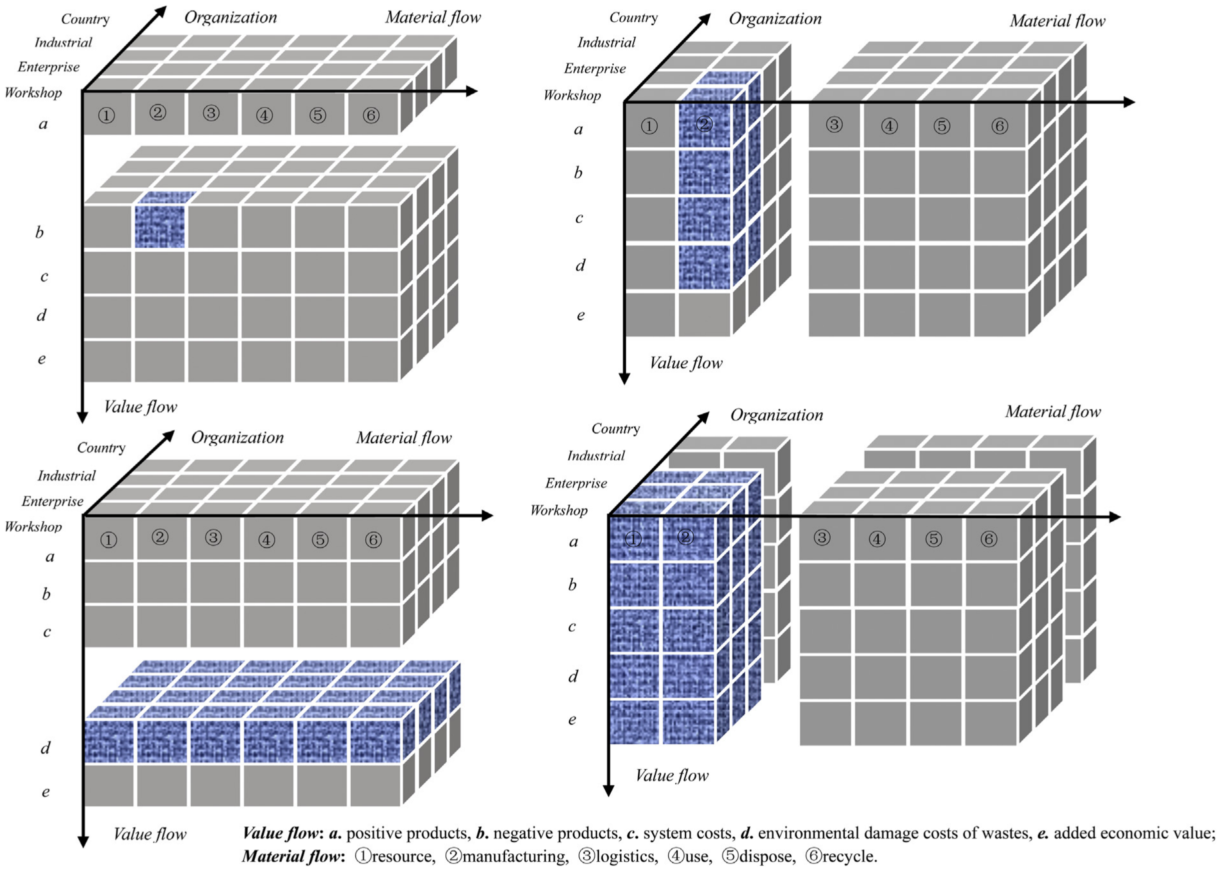


Fig. 4. Structural decomposition of the 3D model.

short, regardless of the level of the resource value flow, its logical starting point is the flow of material resources, and the gradual carry-over cost method of accounting is an essential tool for resource value flow accounting.

4.3. *Case application*

To further explore the inherent logic of the inter-organizational flow of materials, this paper takes aluminum (*Al*) as an example and further illustrates the resource value flow analysis at the enterprise, industrial park and national levels. Fig. 5 outlines the circular logic of aluminum usage at the enterprise, industrial park and national levels.

For cross-organizational resource value flow analysis, the whole life cycle metabolic process and industrial symbiosis of materials (or elements) are the important criteria for dividing the

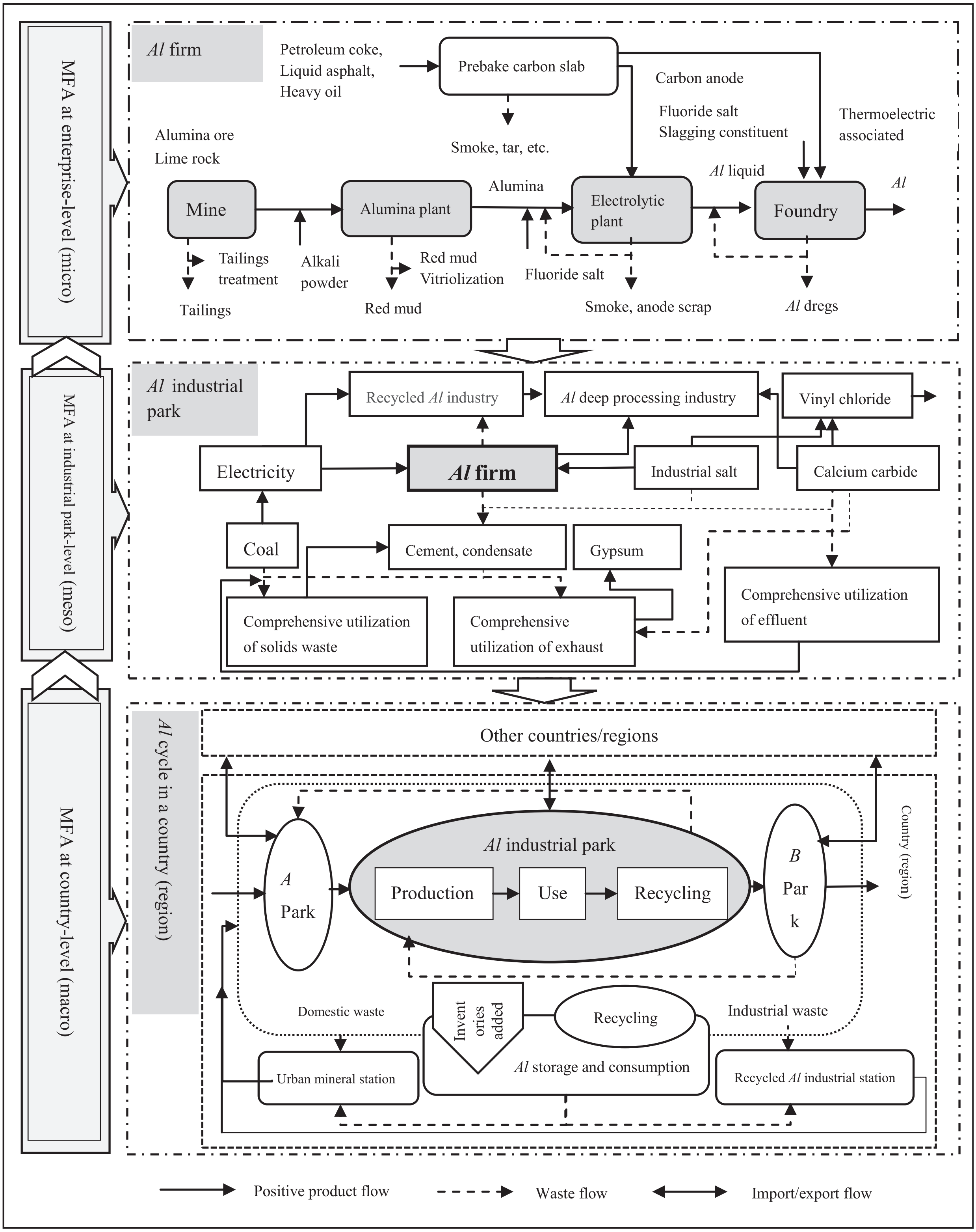


Fig. 5. Logic of MFA at the inter-organizational level.

organizational hierarchy. The “flux-path-performance” material metabolism analysis framework provides a basis for the integration of cross-organizational resource value flow analysis. “Flux” is a flow concept that includes flow scale and flow process. The cross-organizational material metabolic flux analysis is the material flow analysis and life cycle analysis of an input-output system, and value flow is the amount of value that the material adds to the economic system. The metabolic pathway of resource value flow reflects the direction of the material economy metabolism among subsystems, and the various substances entering the economic system cause the metabolic pathway to form an intricate network. The purpose of metabolic performance analysis is to guide the flow of material in the economic system, optimize the material circulation model and improve resource utilization efficiency and value output. In order to evaluate the material circulation effect of the whole life cycle, it is necessary to introduce a unified indicator to achieve the effective integration of the cross-organizational resource value flow analysis. The eco-efficiency index is the ratio of the value quantity to the physical quantity, while the resource value flow analysis results meet the needs of the measurement process of material flow and value flow information. The three cases in this paper illustrate the application principle of the resource value flow analysis tool at, respectively, the enterprise, industrial park and national levels.

4.3.1. *Aluminum Element's RVFA at the national level*

As mentioned above, a particular element, such as Aluminum (*Al*), may be the object of a national resource value flow analysis. The large cycle of aluminum at the national level is essentially a cycle of production and consumption; that is, the entire life cycle metabolic relationship (natural resources, production, consumption and secondary resources) is formed in society. Correspondingly, the RVFA of aluminum recycling must be divided into four stages: "production, processing and manufacturing, metal product consumption and waste recovery," according to the life cycle. Fig. 5 shows that in addition to the industrial park, the large base of renewable resources (for industrial waste) and the footprint of an urban mineral base (for domestic waste generated by community residents) are important parts of the subsystem of the national metabolism of aluminum. During the value flow calculation of the aluminum element cycle, each element that makes up the aluminum product is a carrier of the product's value. So, it is necessary to apportion the aluminum product value among the corresponding aluminum elements, and then the value flow corresponding to the aluminum element flow can be obtained.

This paper takes China aluminum industry's data from 2015 as an example for a case analysis. During the four stages of aluminum's industrial metabolism, the production stage covers the mining and electrolysis subsystems.

The processing and manufacturing stage involves the processing of the aluminum alloy to render the raw aluminum that was produced in the previous stage and form the aluminum alloy products. The wide use of aluminum makes the variety of aluminized products difficult to classify. Seven industries, including construction, transportation, machinery, consumer durables, packaging, power electronics and other industries make up the current divisions of aluminum use. Aluminum products entering the consumption system will be withdrawn from the economic system after they have reached the age of abandonment. According to their location, they may be divided into: entering the waste landfill, entering the natural environment system, or being recycling into renewable processing after recovery. Based on aluminum's four stages of social mobility, as well as the input-output measurement for all phases of aluminum products, China's aluminum social circulation flow in 2015 can be drawn as shown in Fig. 6. On this basis, value flow can be calculated according to the flow of aluminum elements, and the results are shown in Table 2 (the calculation process is omitted). The results objectively reveal the negative product costs and external environmental damage value of each section of aluminum flow, and this is also the breakthrough point at which a nation may strengthen its circular economic reforms and establish its "urban mineral base" and "aluminum regeneration base."

4.3.2. *RVFA of aluminum industrial park*

The further decomposition of the national aluminum cycle system reveals that the aluminum industrial park is the quintessential mesoscopic organization. The material flow path inside the aluminum industrial park is mainly based on the symbiotic material network that exists among enterprises, and the division of the quantity center is based on each enterprise. In this paper, the *Baotou Aluminum Industrial Park* (Located in the Inner Mongolia region of China) is taken as an example; it comprises an aluminum deep processing sector, an aluminum alloy castings sector and a building materials sector, and its power generation system includes two industrial sectors that involve the power generation and aluminum industries. Generally, material integration, water integration and energy integration constitute the complete system of the industrial park's RVFA. This paper gives an introduction only of the material integration, and the *Baotou Aluminum Industrial Park*'s material flow network is shown in Fig. 7.

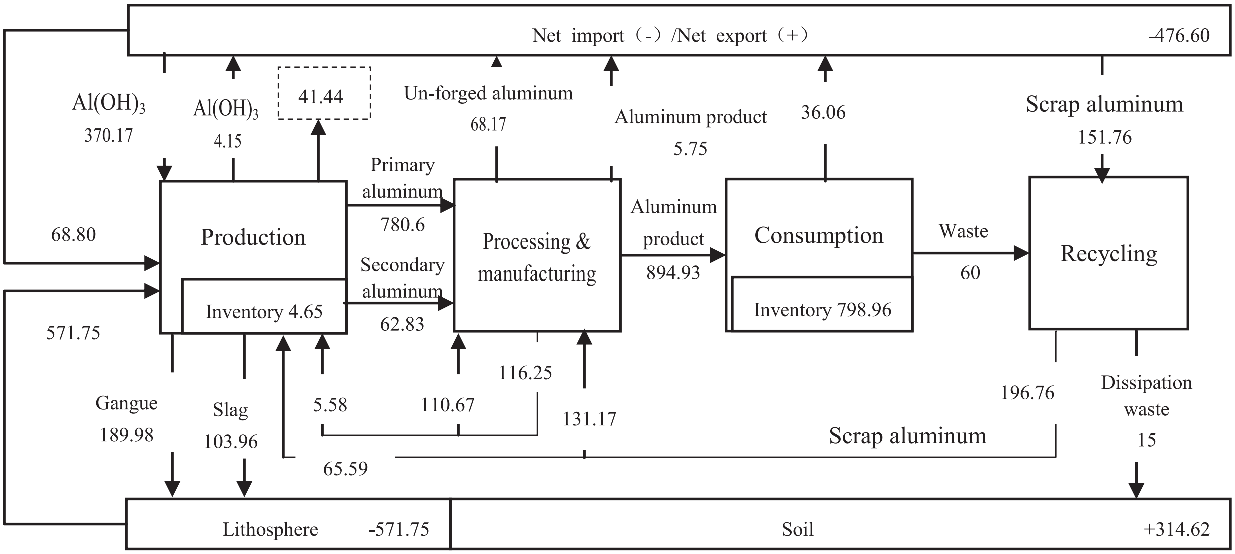


Fig. 6. The social mobility of aluminum in China in 2015 (unit: 10 thousand ton)
Note: *Al* element flow data is calculated according to "*Almanac of nonferrous metallurgical industry*" (2015).

Table 2
The value flow of aluminum in China in 2015 (unit: 10 thousand yuan).

Input		Output									
		Production sector	Processing and manufacturing sector	Consumption sector	Waste recycling sector	Final use					Total output
						Positive products		Negative products			
						Products output	Inventory change	Reuse	Regeneration	Waste	
Intermediate input	Production sector	0	10928400	0	0	10928400	65100	0	0	881.82	21922781.82
	Processing and manufacturing sector	18972	0	14318880	0	15545280	0	348.75	0	0	29883480.75
	Consumption sector	0	0	0	20400	576960	12783360	0	20400	0	13401120
	Waste recycling sector	22300.6	44597.8	0	0	66898.4	0	0	0	5100	138896.8
Initial input	Competitive input	2290076	0	0	0						
	Noncompetitive input	30616	43680	0	51598.4						
	Local mining	194395	628300	0	0						
	Initial input value	2515087	671980	0	51598.4						
Additive terms	External environmental damage value	10585.98	98115	50640	12660						
	Added economic value	4384556	5976696	2680224	27779						

Taking the transfer of electrolytic aluminum in the park as the mainline, we find that bauxite is used as the main raw material input in the aluminum production enterprise. After the aluminum production enterprise's processing and output, the process is left with a positive product—aluminum oxide—and a negative product—red mud. After the aluminum oxide is electrolyzed, the electrolytic aluminum, a raw material, is imported into the aluminum processing enterprise, the aluminum casting enterprise and the aluminum deep processing enterprise. The aluminum waste, aluminum slag and aluminum solid waste that are produced during this process are recycled by means of the renewable aluminum enterprise, and then the output of the regenerated aluminum is reused by the aluminum processing enterprise and the aluminum casting enterprise. The results of the resource value flow of the major enterprises in the *Baotou Aluminum Industrial Park* are shown in Table 3. The results show that this process is an effective way to reduce environmental pollution and improve economic efficiency by strengthening the recycling and utilization of the aluminum casting enterprise and managing the aluminum processing enterprise's negative products. Meanwhile, this analysis also points out directions for the further strengthening of the integration of the aluminum industry's venous and arterial industry chains.

4.3.3. RVFA of the primary aluminum enterprise

The enterprise is the principal part of an industrial park, and enterprise RVFA focuses on resource input, use, circulation and output at the enterprise level. The workshop is the basic unit of enterprise resource value flow accounting, and material flow optimization for the enterprise is based on minor-cycle applications with cleaner production. The key is to reduce resource consumption and pollutant emissions in the manufacturing process and improve ecological efficiency.

This paper takes the "*Guizhou Aluminum Plant*" (*GZAl*) as an example to analyze resource value flow at the enterprise level. As a primary aluminum enterprise, *GZAl*'s basic material flow path can be determined as "bauxite → aluminum oxide → carbon anode → carbon cathode→ electrolytic aluminum liquid". During the process of material flow, the input raw materials include bauxite, limestone, alkali powder, petroleum coke and bituminous coke. Major energy inputs include electricity, heavy oil, coal, water and steam. *GZAl*'s output of negative products includes red mud, dust and smoke; the final output of the positive product is electrolytic aluminum liquid. *GZAl*'s resource value flow accounting results are shown in Fig. 8. As compared to other aluminum workshops, it is found that the cost of negative product loss in this aluminum oxide workshop is the largest, and the reason for this lies in *GZAl*'s low utilization of raw materials. The cost of negative product loss in the electrolytic aluminum workshop is high, because electrolytic aluminum production is accompanied by a large amount of energy input, and energy efficiency is low. This further clarifies the key point of *GZAl*'s circular economy transformation.

5. Conclusions

With the gradual centralization of sustainability in industrial production processes, concern about material flow cost and waste cost is no longer confined within a single organization, but rather has gradually extended to the inter-organizational level, and it is relevant across the entire life cycle of the materials. This study, based on the material flow cost accounting and life-cycle theories, constructed a 3D model and its theoretical framework and analyzed the application of the model at the enterprise, industrial park and country levels, taking aluminum production and processing as a case study. Our novel 3D model, which is proposed for this first

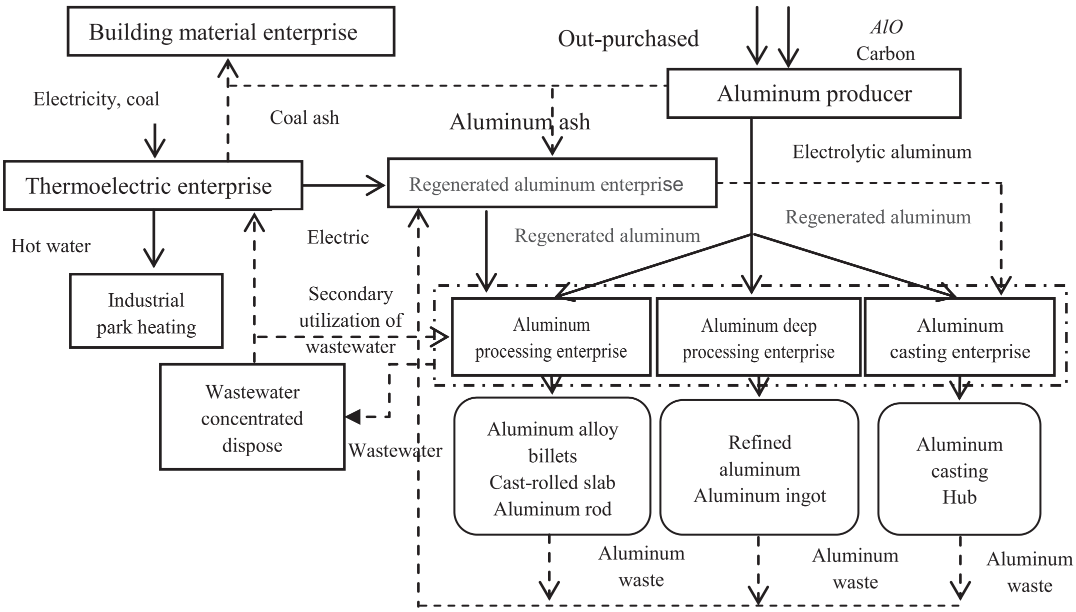


Fig. 7. Material flow model of the *Baotou Aluminum Industrial ParkNote*: The solid line represents the positive products' value flow, while the dotted line represents the negative products' value flow.

time in this paper, is a comprehensive integration model for the high-level abstraction of multidisciplinary approaches, such as industrial ecology, a circular economy, environmental accounting and organizational theories.

Specifically, the contributions of this paper are as follows:

1) The 3D model combines value flow with material circulation under the full life-cycle angle, so that the value flow analysis runs throughout the various stages of resource processing (extraction, raw material processing, manufacturing, transportation, consumption, product waste, product recycling, etc.). Further, we expanded the analytic angle of the 2D analysis. In this paper, MFA draws lessons from the principles of industrial metabolism in industrial ecology, and it assimilates these lessons into a full life cycle of environmental management. We believe that MFA should adhere to the “from the earth, to the earth” principle. Previous studies about RVFA mostly take the manufacturing process of products as the main object of study, and they do not emphasize logistics, consumption, recycling or remanufacturing. The 3D model provides guidance for the full life cycle of RVFA.
2) This paper proposes the concept of RVFA within a multi-level organization and expands the organization's boundary beyond 2D analysis. Resource value flow analysis, based on material circulation, pursues the continuous optimization of the material flow path. The division of the organizational level in this paper follows the classification standards of organizations that is used in MFA. The 3D model establishes a practical guide about industrial symbiosis and information integration for the industrial park and for coordination among natural systems, including industrial systems and economic systems for a country (or region). Simultaneously, this study also provides an important reference for the standard construction of resource value flow analysis at the organizational level.
3) According to the classification of material input and product output of ISO14051, the model decomposes the material costs or resource costs that are input into the economic system as positive and negative product values, system costs, environmental damage costs and economic value-added values, in accordance with the flow of output products. To some extent, this study makes up for the problem that traditional accounting cannot calculate the value of the effective utilization of resources and waste. Additionally, the paper proposes an accounting method of resource value flow in different organizations. The study addresses resource value flow accounting at an organizational level. It also considers the structural decomposition of resource value flow, and it tracks the contribution of material life cycle costs to the “visualization” of resource value flows in terms of quantity, value, structure and other aspects.

However, this study establishes only a preliminary 3D model, without elaborating on each dimension in depth. As with any research, this study has certain limitations. For example: *a*. the RVFA of the entire life cycle relies on mapping the entire life cycle of the material flow model; however, this kind of mapping presents certain difficulties; *b*. establishing a standard of resource value flow analysis of a circular economy as technical support for a quantitative assessment at the enterprise, industrial park and country levels is a goal; however, currently, we lack guidelines that can establish the harmony and authority of such a set of standards. These challenges provide opportunities and direction for further research.

Future research could explore the following aspects: 1) The framework of a 3D model remains to be further refined, and future studies might construct a more detailed 3D analysis framework from the park (or industry) and country (or region) level. Also, we may put forward a detailed analysis system that includes diagnosis, decision-making, control and evaluation, and carry out the corresponding case studies. 2) With the introduction of the full life cycle concept, the difficulty of acquiring material flow information has increased, especially in the phases of logistics and consumption. Thus, a significant difficulty remains in obtaining original data. Follow-up studies may attempt to combine life cycle assessment (economic and environmental assessment) with a life cycle model of material flow. 3) Although existing studies have tried to establish circular economy value flow analysis guidelines, which focus on energy or material integration for a typical industry (or enterprise)

Table 3
Value flow accounting results of the *Baotou Aluminum Industrial Park*.

Quantity center			Material category	Material (ton)	Positive products (ton)	Negative products (ton)	Input cost (10 thousand yuan)	Cost of positive products (10 thousand yuan)	Cost of negative products (10 thousand yuan)	External environmental damage value (10 thousand yuan)
Aluminum processing enterprise	Input		Electrolytic aluminum	12917.00			854.32			
	Output	Positive products	Aluminum alloy billets		3317.00			219.38		
			Cast-rolled slab		4267.00			282.22		
			Aluminum rod		4633.00			306.42		
			Subtotal		12217.00			808.03		
		Negative products	Aluminum solid waste			700			46.29	0.89
Aluminum deep processing enterprise	Input		Electrolytic aluminum	7356.93			486.58			
	Output	Positive products	Refined aluminum		2963.23			195.99		
			Aluminum ingot		2610.46			172.65		
			Pure aluminum alloy		1481.61			97.99		
			Subtotal		7055.30			466.63		
		Negative products	Aluminum scrap			301.63			19.95	4.81
Aluminum casting enterprise	Input		Electrolytic aluminum	9363.37			619.29			
	Output	Positive products	Aluminum casting		1726.61			114.20		
			Aluminum alloy ingot		1899.27			125.62		
			Hub		5007.16			331.17		
			Subtotal		8633.03			570.98		
		Negative products	Aluminum scrap			730.34			48.30	24.96
Regenerated aluminum enterprise	Input		Aluminum solid waste	700.00			46.29			
			Aluminum scrap	1031.98			68.25			
			Subtotal	1731.98			114.55			
	Output	Positive products	Regenerated aluminum		1541.46			101.95		
		Negative products	Aluminum slag			190.52			12.60	–

Sources: Calculated according to data obtained from a field survey of *Baotou Aluminum Industrial Park* conducted in July 2015.

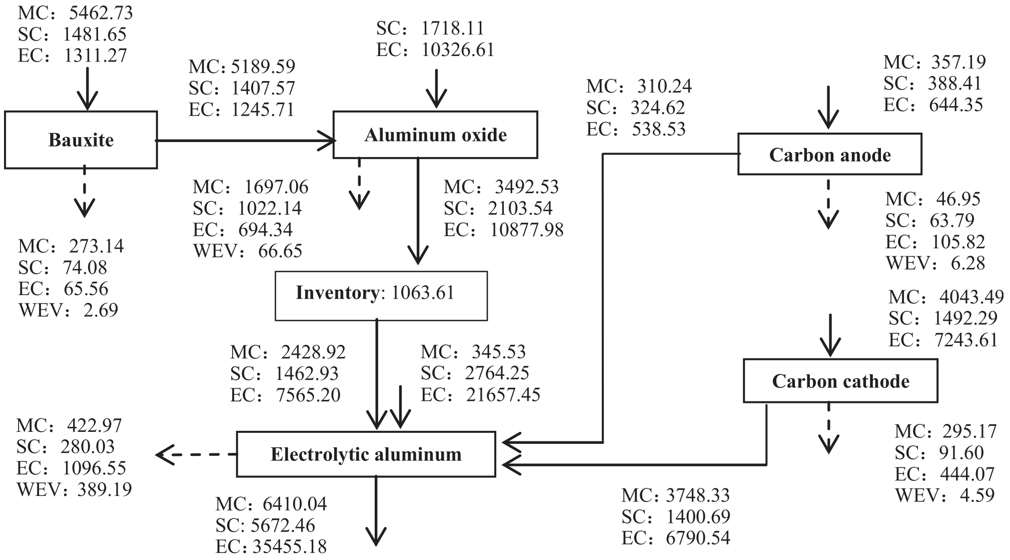


Fig. 8. *GZAl*'s resource value flow model (unit:10 thousand yuan)
Note: *GZAl*'s material flow data was obtained from field research conducted in May 2015; the solid line represents the positive products' value flow, while the dotted line represents the negative products' value flow.

and an industrial park, these remain at the theoretical level, and they lack the promotion of specific and uniform standards put forward by the government. As a result, there is no policy guarantee that we may conduct a quantitative assessment that incorporates a circular economy value flow analysis. Therefore, further studies are needed to strengthen the transformation from theory to practice.

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