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RESEARCH ARTICLE

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An evaluation model of water-saving reconstruction projects based on resource value flows

Abstract Due to uncertainties in water supply, there is growing demand for water resource management in enterprises. In this study, we evaluated the effects of companies' water-saving reconstruction projects. We used Hina Advanced Materials Company as a case to construct an investment decision model to (1) calculate the internal and external costs of water resources based on circular economic value analysis theory, and (2) locate the level of water resources circulation. We adopted gray situation decision analysis to identify the typical problems that occur in water resource utilization. Moreover, we demonstrated optimization plans for different potential improvements, thereby providing guidance and references for water resource cost management and the comprehensive optimization of environmental benefits. We concluded that the circulation economic value analysis model can effectively display the flow and amount of value derived from water resource flows, thereby providing guidance and suggestions for optimizing water resource flows.

Keywords value flow analysis, ternary materials enterprises, grey situation decision analysis, water resources

1 Introduction

Nearly half of China's water resources are substantially polluted as urbanization accelerates and industrial sewage is discharged irresponsibly. Some serious water pollution events, such as the contamination of Songhua River with benzene, algae water pollution in Taihu Lake, and Jingjiang water pollution, have caused adverse social impact and immense economic losses, which significantly threatens the sustainable development of society and the daily life of residents. The ternary materials industry has received widespread attention from the public due to the massive amount of wastewater discharged from its production processes which results in significant environmental pollution. This industry has a water consumption of 10 tons per ton of product and a low utilization rate of water recycling. Moreover, a large amount of wastewater containing heavy metals, salt, and ammonia is produced by this industry. The average emission of chemical oxygen, which is the most harmful indicator of environmental pollution in wastewater, is 150 mg/L. Evidently, the production and operation activities of the ternary materials industry cause severe environmental pollution and resource consumption, and its impact on the natural environment is similar to that of traditional high-pollution industries, such as iron and textiles. With the continuously increasing conflict between the supply and demand of water resources, this industry is facing several urgent problems: Poor water resource management; various threats, such as population growth, urbanization, climate change, and pollution; and aggravation of the disadvantages of the traditional water resource management system (Collet et al., 2015; Giuliani, 2016). Therefore, the demand for effective water management for the companies in this industry is increasing (Park et al., 2013; Signori and Bodino, 2013). However, extant studies disregard the

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important role of environmental management accounting in this field (Christ and Burritt, 2017). Research focusing on optimizing enterprise production from the aspects of theoretical construction and technological innovation to achieve energy conservation and emission reduction is thus required (Ding et al., 2018).

Environmental management accounting was developed in the 1990s. Managers began to realize the need to incorporate environmental impact into their economic decision-making processes. Many of them have successfully applied environmental management accounting to the low-carbon emissions research of enterprises (Burritt et al., 2011). However, water resources as an important component of natural resources have received little attention in environmental management research. Currently, the standard method widely recognized by the research community is material flow cost accounting (MFCA)1). In the current context of a circular economy, the application of MFCA has often led companies to experience a "circulatory diseconomy", and this method does not reflect "externalities" (Xiao and Jin, 2008). Resource value circulation accounting is a branch of accounting that considers the background of a circular economy. Through the accounting and diagnosis of the "material flow–value flow" of enterprises, the potential points for improvement are discovered, and an optimal decision-making scheme is analyzed to solve the problems in the circulation of enterprises. Material flow–value flow is a good complement to the existing cost accounting system; it helps overcome the difficulty of identifying the external damage value of waste discharge included in the product manufacturing cost figures, and track feedback to analyze the value flow information before and after the implementation of the circular economy (Zhou and Liu, 2017). Therefore, in this study we attempt to optimize the ternary materials industry using water resource value flow analysis to improve the economic benefits of water resources. This research bridges the application gap of resource value flow in the field of water resources management and provides suggestions for enterprises to open up the sources and regulate the flows with practical significance.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature on resource value circulation accounting, water resources accounting, and water disclosure. Section 3 applies cyclic economic value analysis method, analytic hierarchical process (AHP), and gray situation decision-making to construct the ternary materials industry water resources value circulation accounting model, evaluation, and decision system. Section 4 uses the Hina Advanced Materials Company as a case to calculate the water resource value flow, and uses the aforementioned evaluation and decision-making system to select the optimal program. Lastly, Section 5 summarizes the study.

2 Literature review

2.1 Resource value flow accounting

In recent years, many scholars have begun to use MFCA to analyze the relative costs of enterprises (Nakajima et al., 2015; Sulong et al., 2015). Specialized research has been conducted on eco-industrial parks and on the issue of material flow circulation in society from the recycling industry perspective (Prox, 2015; Wan et al., 2015; Xiao et al., 2017). At the corporate level, scholars have often used MFCA to calculate and analyze the relevant costs of companies to identify key improvements in their production processes and reduce their consumption of goods and production costs (Herzig et al., 2013).

Resource value flow accounting is an extension of MFCA in the context of a circular economy (Xiao and Liu, 2014; Xiong and Xiao, 2014; Xiong et al., 2015), forming a binary cost accounting system. The related research can be divided into three major categories. (1) System Construction. This category analyzes the material flow, element flow, and resulting value flow in the production processes in the context of a circular economy (Xiao and Liu, 2014). (2) Extended Research. These studies analyze the vertical expansion based on the calculation results of corporate resource value flow (e.g., Live Intrinsic Material Estimation (LIME) evaluation system of resource value circulation, evaluation systems based on AHP, and gray situation decision-making) (Xiao and Xiong, 2010; Zheng and Xiao, 2010). (3) Practical Application. This system standard is applied comprehensively across enterprises, enterprise groups, and industrial parks to test and improve theoretical systems in practice. Overall, the academic community has made immense progress studying heavy industries, such as coal and iron manufacturing, using cost accounting and environmental benefit assessment case studies that are based on resource value flow (Busch et al., 2005; Jasch, 2008). Water resources, as a special research object, can be regarded as a medium of energy, similar to such resources as coal and gas. However, extant literature has mainly evaluated the use of water resources based on MFCA evaluation models (Gao et al., 2016) and has not addressed water resources from the perspective of resource value flow accounting.

2.2 Water accounting

Water is a shared resource and its usage will impact all users. Therefore, governments, communities, and

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1) ISO 14051:2011. Environmental management: Material flow cost accounting—General framework. Available at: iso.org/standard/50986.html

companies must be responsible for their use of water resources (Chapagain and Tickner, 2012). Companies are the main consumers of fresh water resources (Jones et al., 2015), thereby necessitating that they assume water-related responsibilities and develop the related resource strategies (Hazelton, 2014; Martinez, 2015). Such strategies must consider various risks related to water usage, including financial, operational, product, reputation, and regulatory risks. The use of water accounting can effectively reduce these risks (Burritt et al., 2016; Cassimon et al., 2016). Accurate water accounting is an important component of cleaner corporate production. It can help companies determine the ecological impact of direct and indirect water emissions and assess corporate water risks, thereby allowing companies to properly report development trends and water usage impact to its stakeholders (Li et al., 2016). At present, water accounting is still evolving (Chapagain and Tickner, 2012). Some studies have analyzed the value accounting of water resources (Gao et al., 2016), but many companies continue to rely on incomplete data to make economic decisions on water resources. This situation is partially caused by lack of corporate water disclosure mechanisms. In response to this problem, empirical and case studies have been conducted on water information disclosure (Burritt et al., 2016; Qiu et al., 2016). However, understanding how to effectively use water information data for economic decision-making will become a concern, particularly with the deepening of the water disclosure research.

WBCSD-SIUCN proposed five stages of water resource management to enable managers understand the interaction of accounting tools in the analysis of water resources, and the corresponding steps they may follow (Christ and Burritt, 2017). Therefore, resource value transfer accounting can considerably meet the requirements of water resource management and help enterprises achieve circular economic management of water resource using resource value transfer accounting. Common methods that can be used for water resources efficiency evaluation and decision-making include fuzzy comprehensive evaluation, AHP, data envelopment analysis (DEA) efficiency evaluation analysis, and gray situation decision analysis. Among them, the membership function of each factor should be determined using fuzzy comprehensive evaluation, given that the practicality of applying this method is insufficient. The DEA efficiency evaluation analysis is based on relative efficiency and cannot directly reflect the objective level of decision-making units, which are subject to extreme values. However, the AHP is simple and easy to understand, and combines qualitative and quantitative analyses to enable systematic evaluation and decision-making. Accordingly, decision makers can easily master this process. The gray situation decision analysis mainly uses completely determined information to address incomplete information, and is suitable for the optimization problem of multi-objective projects (Pitchipoo et al., 2013). Water resource management needs to comprehensively consider various objectives, such as the economy, environment and resources. Meanwhile, the gray situation decision analysis uses deterministic information to address uncertain events and quantifies the incomparable indicators to choose between the optimal solutions. By contrast, other analysis methods cannot fully deal with various sudden uncertainties and generate major risks. The key of the gray situation decision analysis is to determine the target system and polarity of each target. A model should be introduced to determine the weight of each target owing to the inconsistency of each target. Furthermore, the characteristics of resource value flow and water information data limit the application of objective weighting methods, such as entropy weighting and coefficient of variation methods. By contrast, AHP is concise and practical, can deal with some data that cannot be measured quantitatively, and can reflect the real purpose of evaluation. Overall, the current study combines AHP with the gray situation decision-making method (Çelikbilek and Tüysüz, 2016; Bouzon et al., 2018).

In summary, many studies on water resource management have been conducted, but the research has generally remained at the theoretical framework and/or material circulation level. Research on water resource value flow has yet to be accomplished, and the application of environmental management accounting to water accounting has not been taken seriously. The current study used the calculation of the water resource value flow in the ternary materials industry as bases to propose a selection plan, and utilized AHP and gray situation decision-making to optimize the water resources of the case company.

3 Water resource value flow evaluation models

After water resources enter companies, their material forms gradually flow along with the production process. Except for an extremely small amount of water resources that reverts back to nature, other substances become new forms of water resources to be exported (i.e., products or wastes). This study combined the principle of vertical resource flow and the gradual carry-over processing method, and set the basic principle of the value flow analysis of water resources as a binary two-way structural model. The first element (i.e., fundamental element) refers to water resources material flow that corresponds with material flow analysis. The second element (i.e., derived element) refers to the value cycle of water resources and corresponds to the value flow analysis of water resources.

3.1 Water resource value flow calculation model

We used the internal resource value flow calculating model (1) to enable the positive product cost (i.e., effective use value of resource circulation) and negative product cost (i.e., the value of resource flow loss) of enterprises to be calculated to measure the internal loss of resources in their production processes. We used the external environmental damage value accounting model (i.e., LIME method) to statistically derive the external environmental cost of companies' resource consumption and pollutant emissions to provide a basis for production decision-making and environmental management.

$$\begin{aligned}&\text{The new investment cost of the volume center}\\&+\text{The transfer cost of the front volume}\\&=\text{Cumulative input cost,}\end{aligned}\tag{1}$$

$$\sum_{j=1}^{J}\sum_{i=1}^{I}s_i\times DF_{ij}\times WTP_j=\sum_{i=1}^{I}s_i\times\left(\sum_{j=1}^{J}DF_{ij}\times WTP_j\right),\tag{2}$$

where s_i indicates the life cycle list of substance i, DF_{ij} represents the damage coefficient of substance i to protective object j, and WTP_j represents the amount of damage avoidance that j is willing to pay for each i-metric unit.

To strengthen the management of corporate resource value flow and effectively reduce waste and the consumption of resources, internal losses should be assessed and the impact of production on the environment must be measured. This study combined the value of negative product loss with that of external environmental damage to form a complete two-dimensional accounting and diagnosis model for resource flow. This model constitutes a two-dimensional analysis framework and evaluation theory of "internal loss of resource–external environmental damage to waste".

3.2 Water resource value flow evaluation model

The analysis of water resource value flow evaluation is extremely important and has the function of linking with other types of analysis. The commonly used methods are AHP, eco-efficiency assessment method, and DEA efficiency evaluation analysis method. The current research analyzed the value flow of water resources comprehensively. Therefore, AHP was used (Khalil et al., 2016; Sindhu et al., 2017).

In the process of constructing our model, the current study referred to scholars' methods for constructing value flow indicators according to the basic characteristics of resource input, recycling and output links, and availability of enterprise data (Hu et al., 2014; Zhou et al., 2018). Moreover, the evaluation index system was divided into target, criterion, and index layers. Thereafter, we referred to scholars who have adopted expert consultation method to evaluate the comparative value of the importance of evaluation indicators at all levels (Yang, 2006; Song and Li, 2012). For example, the indicators of the criterion layer include water input (C1), water recycling (C2), and water output (C3). The criterion layer establishes the judgment matrix according to the professional:

$$A=\begin{bmatrix}1 & 2 & 1\\ 1/2 & 1 & 1\\ 1 & 1 & 1\end{bmatrix}.$$

First, we found the weight of the indicator system W_i = (0.413, 0.260, 0.327).

Second, we determined the largest eigenvalue of the judgment matrix as follows: $\lambda_{\max} = 3.0536$, $CI = (\lambda_{\max} - n)/(n-1) = (3.0536 - 3)/2 = 0.0268$.

If $n = 3$, then we checked the table to find that $RI = 0.52$. Thus, $CR = CI/RI = 0.0515 < 0.1$.

Note that the judgment matrix had relatively satisfactory consistency, and the distribution of weights was reasonable. We used the same method to judge other indicators, and we obtained the weight coefficient of the three indexes to the two indexes of the evaluation index system (Table 1). Furthermore, we referred to the Cleaner Production Guidelines of the ternary materials industry, and combined the brainstorming method thereafter with the expert scoring method to determine the resource flow efficiency evaluation level (see Table 2).

3.3 Control of water resource value flow

3.3.1 Model construction

The comprehensive evaluation and diagnosis of the cost analysis results of the enterprise value flow is the basis for decision-making optimization. This study integrated the existing literature (Çelikbilek and Tüysüz, 2016; Wei, 2017; Bouzon et al., 2018) with the industry characteristics, and used the gray relational method to build a circular economic optimization model and draw a complete evaluation index system according to the judgment score from the application level (Table 3). Table 3 further illustrates and progresses the indicator system shown in Table 1.

3.3.2 Decision optimization implementation

Combined with the extended optimization model that we constructed, the decision-making and optimal design of the circular economy value flow of the ternary materials industry could be made in accordance with the basic flow of the gray situation decision-making. The gray situation decision model has four basic elements: Situations, countermeasures, targets, and effects.

Table 1 Quantitative index system for water resource value flow evaluation in the ternary materials industry

Goal layer	Criterion layer	Weight	Index layers	Weight
Water resource value flow evaluation index (H)	Water input (C1)	0.413	Sales water cost rate	0.462
			Fresh water consumption per unit product	0.203
			Cycle water consumption per unit product	0.203
			Wastewater treatment cost per unit product	0.132
	Water recycling (C2)	0.260	Water resource cost loss rate	0.388
			Water recycling rate	0.214
			Ratio of internal resource value to external environmental damage	0.274
			Ammonia wastewater treatment rate	0.124
	Water output (C3)	0.327	Ammonia emissions per unit product	0.218
			Ammonia wastewater discharge per unit product	0.380
			Chemical oxygen demand emissions per unit product	0.152
			External damage value per unit product	0.175
			Total nitrogen emissions per unit product	0.075

Table 2 Ternary materials industry resource flow efficiency evaluation level

Resource flow efficiency level	Comprehensive evaluation score	Resource flow efficiency
I	0.80 to 1.00	Consistent with international advanced standards
II	0.60 to 0.80	Consistent with domestic advanced standards
III	0.40 to 0.60	Met the basic domestic standards
IV	Below 0.40	Failed to meet basic domestic standards

Table 3 Optimization of water resource value flow index and weight allocation in ternary materials industry

Validity index	Specific indicators	Weight	Extremum
Comprehensive economic utility indicators A	A1: Total investment	0.0893	Minimal
	A2: Economic benefits	0.0954	Maximal
	A3: Annual operating cost	0.0659	Minimal
	A4: Added value output efficiency	0.0686	Maximal
Resource flow indicators B	B1: Water resource cost loss rate	0.0995	Minimal
	B2: Water recycling rate	0.0680	Maximal
	B3: Change rate of wastewater treatment cost	0.0955	Minimal
	B4: Change rate of internal resource value flow	0.1246	Minimal
Social environmental benefit indicators C	C1: Change rate of ammonia nitride emissions	0.1182	Minimal
	C2: Change rate of exhaust gas damage value	0.0304	Minimal
	C3: Change rate of external damage per unit output	0.0593	Minimal
	C4: Change rate of wastewater discharge	0.0752	Minimal

(1) Build the situation

Only one event is involved in the decision-making process for water resource value flow in the ternary materials industry: Optimizing project investment marked as a_1, where b_j ($j = 1, 2, \ldots, n$) is the jth decision of the corresponding event a_1. The combination of b_j and a_1 is the situation $S_{1j} = (a_1, b_j)$ = (event, countermeasure), and the situations constitute a situation set $S = \{S_{1j} = (a_1, b_j)\}$.

(2) Provide targets and their polarity

The target is a measurement of how good the situation is, and the number of targets for multi-objective decision-making is generally above 1. The polarity of the target is a requirement for the magnitude of the sample effect, which is divided into three types: “maximal”, “minimal”, and “moderate”. The calculation method for measuring the effects of different polarity targets is also different from one another. Table 3 provides the details.

(3) Assign effect samples to different targets

The essence of the effect samples is to determine the effects of situations. The effect sample of the qualitative target is obtained by expert scoring or from the experience of the enterprise management. Moreover, the effect sample of the quantitative index can be obtained through the budget of the solution. In particular, E_{ij}^P is the effect sample of S_{ij} at target P and E is the effect sample matrix for all targets.

$$E = \begin{bmatrix} E_{11}^P & E_{12}^P & \cdots & E_{1n}^P \\ E_{21}^P & E_{22}^P & \cdots & E_{2n}^P \\ \vdots & \vdots & \vdots & \vdots \\ E_{m1}^P & E_{m2}^P & \cdots & E_{mn}^P \end{bmatrix}. \tag{3}$$

(4) Calculate the effect measure for targets of different polarities

The effect measure of the "maximal" target:

$$R_{ij}^P = \frac{E_{ij}^P}{\max E_{ij}^P} \ (0 \leqslant R_{ij}^P \leqslant 1). \tag{4}$$

The effect measure of the "minimal" target:

$$R_{ij}^P = \frac{\min E_{ij}^P}{E_{ij}^P} \ (0 \leqslant R_{ij}^P \leqslant 1). \tag{5}$$

The effect measure of the "moderate" target:

$$R_{ij}^P = \frac{\min E_{ij}^P}{\max E_{ij}^P} \ (0 \leqslant R_{ij}^P \leqslant 1). \tag{6}$$

(5) Calculate comprehensive performance measures and make optimal decisions

According to the weight of each target, a comprehensive measure of effectiveness can be obtained.

$$R_{ij}^{\Sigma} = \sum\nolimits_{P=1}^{k} W_P \times R_{ij}^P \quad (W_P \text{ is the weight of } P; \ k \text{ is the target number, } P = 1, 2, \ldots, k). \tag{7}$$

4 Case analysis: Hina Advanced Materials Co., Ltd.

4.1 Background

Hina Advanced Materials Co., Ltd. was established on September 10, 2003 in the Ningxiang Economic and Technological Development Zone, Hunan Province. This company is an integrated supplier of positive electrode precursor materials and related products for lithium ion batteries. It is a representative enterprise in ternary material industry. According to the characteristics of Hina shown in Fig. 1, the production process is divided into three stages: Synthesis reaction, water filtration, and dry sieving. Two types of wastewater are discharged during the production process: One is ammonia-containing wastewater, while the other is precipitated water that cannot be treated with ammonia during the precipitation process. The water resources cycle process in Hina is relatively complex. Accordingly, some data cannot be measured quantitatively and the target value of water resource transfer is difficult to define. Therefore, the model in this study is more suitable than the objective weighting model.

4.2 Calculation of Hina's water resource value flow

Hina converts resources into positive and negative

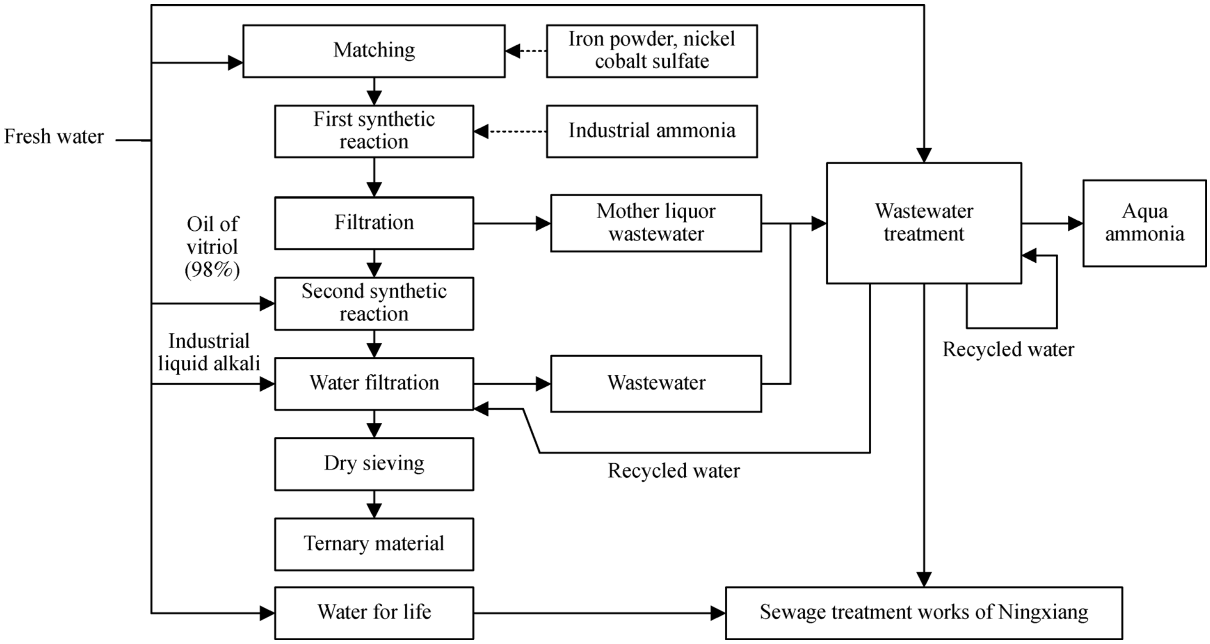

Fig. 1 Water resource transfer balance graph of Hina.

products through its production processes. Positive products are sold to form the total industrial output value of the company. By contrast, negative products, such as washing slag, are discharged into the environment. We can calculate the internal costs of positive and negative products based on the input and output data of the company's water resources. The various wastewater, exhaust gas, and waste residues generated by the company in the production process will inevitably produce a corresponding external effect on the natural environment. We combined the value of the negative product losses in the company's internal production with the value of its external environmental damage (Table 4).

Note that the internal resource flow and external damage costs of the water filtration stage are the highest. Hence, improving the link between these two factors will reduce the value of internal resource loss, create direct economic benefits, and reduce environmental pollution. Similarly, the costs of the internal resource flow in the synthesis reaction and dry screening stages are considerably high. If the enterprise improves these links, it can reduce its internal resource loss and generate direct economic benefits without increasing social cost. Therefore, companies should increase their recycling rate of water resources by investing in new sewage treatment equipment and the latest production processes. This method will increase costs and reduce profits in the short-term, but in the long-term, it could reduce resource waste and external damage costs. The reduced costs may be greater than the reduction in revenues, thereby resulting in a net increase in profits.

4.3 Evaluation of Hina's water resource value flow

According to the weights of the indexes in Table 1, the comprehensive evaluation value of the value flow efficiency of a circular economy resource in iron production enterprises is 0.695. This value was obtained by adding the weighted comprehensive scores combined with the actual index values of Hina in 2016, and the ideal values of the indicators in the ternary materials industry (we referred to the index values of advanced companies, industry averages).

Compared with the level evaluation criteria in Table 2, the comprehensive score is between 0.60 and 0.80. Therefore, the evaluation level of resource value flow efficiency of the circular economy should be level II, which is consistent with the domestic advanced standard. Compared with the ideal value, the input index of water resources is in a relatively long cycle, and the index of water circulation is also in a good level. Meanwhile, the output index of water resources is relatively low, thereby indicating that the water resource output performance is relatively poor.

4.4 Control of Hina's water resource value flow

(1) Optimize investment options

This study used the preceding comprehensive analysis and research on the circulation of Hina's circular economy as bases to propose four alternative water-saving reconstruction projects for the different production stages. These projects are denoted as b_1, b_2, b_3, and b_4. Table 5 shows the comprehensive cost-efficiency of the different options.

Table 5 Comprehensive cost-efficiency of different options (unit: yuan)

Project	b_1	b_2	b_3	b_4
Internal economic benefits	518946	–406956	558182	763166
External economic benefits	111339	475105	447321	–128362

b_1: The use of a new water-saving reaction vessel in the center of the synthesis reaction requires equipment investment of 5.46 million yuan, which would be amortized over the use life of 10 years. According to the data provided by the construction unit, the total water consumption of the synthetic reaction workshop would decrease to 176783 tons after the water-saving renovation. The rate of positive products remained unchanged, but the amount of mother liquor wastewater and ammonia-containing waste gas generated would decrease.

Table 4 Two-dimensional accounting summary of Hina's water resource internal and external cost

Stage	Internal water loss cost			External environmental damage cost	
	Item	Value flow cost (yuan)	Proportion	Value flow cost (yuan)	Proportion
Synthesis reaction	Positive products	3671931	77.90%	523865	32.92%
	Negative products	1041715	22.10%		
	Total	4713646	100%		
Water filtration	Positive products	4963938	57.07%	917713	57.66%
	Negative products	3734043	42.93%		
	Total	8697981	100%		
Dry sieving	Positive products	3409800	68.69%	149967	9.42%
	Negative products	1554241	31.31%%		
	Total	4964041	100%		

b_2: In water filtration, the use of new circulating water treatment technology would enable the company to use only recycled water in the production process. This technology would require an equipment investment of 3.9 million yuan, which would be amortized over the use life of 10 years. Moreover, the technology increases the cost of circulating water to 1.924 yuan/ton.

b_3: A new type of semi-enclosed water circulation process could be adopted in the center of the water filtration. After the process is adopted, fresh water in the water filtration system would be substantially reduced, and the amount of wastewater generated would also be considerably reduced. The technology requires an investment of 9.62 million yuan to implement the transformation, which would be amortized over the 10-year use period.

b_4: A high-pressure ammonia removal process could be used for Hina's wastewater treatment system. The data indicated that the cost of wastewater treatment would be reduced to 1.43 yuan/ton, and approximately 195 tons of ammonia water would also be recovered. However, the cost of the external environmental damage would be increased. Overall, this technology requires an investment of 1.56 million yuan to implement the transformation, which would be amortized over the use period of 10 years.

(2) Provide targets and its polarity

Table 3 shows that each target value and polarity can be determined, and the effectiveness of the aforementioned scheme can be analyzed accordingly.

(3) Assign effect samples to different targets

The various optimization projects established by Hina were brought into the target system of the optimization model, and the target effect sample data of different projects was obtained (Table 6).

(4) Calculate the effect measure for targets of different polarities

The polarity of each indicator indicated that the effect measurement formula can be used for calculation. However, a few special indicators will have negative values, thereby showing contrasts with the operating rules of the gray situation method. Therefore, this study uniformly set negative results to 0. Table 7 shows the effect measure of each target value.

(5) Calculate comprehensive performance measures and make optimal decisions

Lastly, we calculated the comprehensive effect measurement according to Eq. (7), where $R_{11}^{\Sigma} = 0.5771$, $R_{12}^{\Sigma} = 0.7056$, $R_{13}^{\Sigma} = 0.9083$, and $R_{14}^{\Sigma} = 0.7041$. In terms of the transformation effect, we found that the improvement project b_3 of the water filtration system using the new semi-enclosed water cycle process would have the best effect. First, the program would enable the internal water resource consumption of Hina to be effectively controlled. The amount of ammonia-nitrogen emissions into the external environment would be substantially reduced, and the overall utility would be effectively improved. Second, project b_3 requires relatively large input resources. Considering the cash flow and strategic development of the enterprise, project b_2 is also a good investment choice when combined with the actual situation of the company. The reason is that project b_2 requires the smallest amount of capital investment. Although it would increase the internal water resource costs of the enterprise to a certain extent, it has evident environmental protection effects, which would considerably enhance the sense of corporate social responsibility. The effects of project b_1 on reducing water resource consumption and external environmental damage are weaker than those of project b_3. Hence, this study excluded project b_1. Project b_4 focuses on the reduction of water resource consumption, which increases the damage to the external environment, and has the highest annual operating cost and high cash flow pressure. Thus, this project was also excluded.

The specific application of the aforementioned scheme can be implemented in combination with the PDCA (plan–do–check–action) cycle management. Doing so can form a

Table 6 Target effects of the different reconstruction projects in Hina

	Projects	b_1	b_2	b_3	b_4
Comprehensive economic utility indicators A	A1: Total investment (yuan)	5460000	3900000	9620000	1560000
	A2: Economic benefits (yuan)	518946	–406956	558182	763166
	A3: Annual operating cost (yuan)	273127	27307	1740172	280319
	A4: Added value output efficiency	0	0.24	0	1.56
Resource flow indicators B	B1: Water resource cost loss rate (%)	60.42	45.63	40.35	64.32
	B2: Water recycling rate (%)	72.64	84.62	88.65	67.52
	B3: Change rate of wastewater treatment cost (%)	–10.15	0	–48.75	–34.95
	B4: Change rate of internal resource value flow (%)	–7.60	6.59	–8.69	–9.53
Social environmental benefit indicators C	C1: Change rate of ammonia nitride emissions (%)	–16.50	–35.60	–58.69	–19.65
	C2: Change rate of exhaust gas damage value (%)	–0.94	–31.00	–1.96	45.63
	C3: Change rate of external damage per unit output (%)	–7.00	–29.85	–28.11	8.07
	C4: Change rate of wastewater discharge (%)	–39.15	–46.85	–55.63	0

Table 7 Performance measurement of the different reconstruction projects in Hina

	Projects	b_1	b_2	b_3	b_4
Comprehensive economic utility indicators A	A1: Total investment	0.71	1.00	0.41	0.25
	A2: Economic benefits	0.33	0	0.35	1.00
	A3: Annual operating cost	0.10	1.00	0.02	0.10
	A4: Added value output efficiency	0	0.15	0	1.00
Resource flow indicators B	B1: Water resource cost loss rate	0.67	0.88	1.00	0.63
	B2: Water recycling rate	0.82	0.95	1.00	0.76
	B3: Change rate of wastewater treatment cost	0.21	0	1.00	0.74
	B4: Change rate of internal resource value flow	0.80	0	0.91	1.00
Social environmental benefit indicators C	C1: Change rate of ammonia nitride emissions	0.28	0.61	1.00	0.33
	C2: Change rate of exhaust gas damage value	0.03	1.00	0.06	0
	C3: Change rate of external damage per unit output	0.23	1.00	0.94	0
	C4: Change rate of wastewater discharge	0.70	0.84	1.00	0

unique decision-making optimization application mode for Hina's resource value flow analysis.

1) Planning and arrangement. The circular economy development model indicated that Hina should adjust and optimize the industrial structure to establish a circular economy production system.

2) Doing and calculating. The costs are separately collected and distributed according to the three production stages of Hina. Thereafter, the cost of positive and negative products can be calculated from the loss and damage costs of each production stage.

3) Checking and decision-making. The previous analysis indicated that project b_3 is selected.

4) Action and continuous improvement. Hina's water resources value transfer efficiency has achieved substantial results after the improvement, and the negative environmental impact has been significantly reduced. Therefore, Hina can summarize its experience to develop standards, thereby enabling it to solve emerging problems through the PDCA cycle management.

5 Conclusions

Theoretically, this study used the structural characteristics and trends of the analysis of a circular economy resource flow in the ternary materials industry as bases to construct an intrinsic coupling mechanism of "resource flow–value flow". Through the combination of the external environmental damage value and the internal resource value flow of waste, the value of the effective use of resources and discarded losses can be determined to diagnose the potential for improvement. In the concrete construction of the optimization model of circular economy value flow, the gray situation decision model is adopted and the weight is determined by AHP, thereby enriching the research in the field of value flow.

In practice, this research proposed optimization ideas for water resource flow against the background of a circular economy using the production characteristics of the Hina company. The circulation economic value analysis method can effectively display the value flow and amount in the process of water resource flow, thereby providing guidance and suggestions to enterprises for optimizing the flow of water resources. The entire optimization system is based on the 3R principle of "reduction, reuse, and recycling", and is characterized by "low consumption, low emission and high efficiency". This system focuses on the efficient use and recycling of resources, and the improvement of social and environmental benefits. The application of the entire optimization system satisfied Hina's requirements for an economic growth model and its goal of sustainable development. Our findings have guiding significance for the water-saving and consumption reduction decision of the ternary materials industry. In addition, these results are beneficial in promoting the green transformation and upgrading of the industry. However, the specific input value of cost should be changed according to the actual situation of enterprises under the condition that the overall scale is fixed.

This study has certain shortcomings that may be addressed in future research. It fails to provide an in-depth analysis of the related derivative issues in the follow-up study of Hina's optimization, and it does not further expand the group level to industrial parks to discuss the development model of a circular economy. For example, we should consider the possibility of designing a circular economic value flow decision-making optimization system that is applicable to Hina's upstream and downstream activities at the park level. Accordingly, this possible system can be used to meet the integration needs of practical applications. Lastly, research on the optimization system of circular economic value flow needs further evolution and innovation.

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