

Study on Eco-Efficiency Optimization Based on LCA-MFCA Integration Method: A Case Study on the Cement Industry

Abstract

Cement production in China suffers from low eco-efficiency due to high coal and electricity consumption and substantial emissions. This study proposes a novel approach integrating Life Cycle Assessment (LCA) and Material Flow Cost Accounting (MFCA) to improve both economic and environmental performance. The method includes: (1) quantifying material, economic, and environmental losses using LCA and MFCA; (2) identifying improvement strategies through Pareto analysis, hypothesis testing, and expert input; and (3) validating results using an empirical case study. Applied to a cement company in Xinjiang, the approach increased eco-efficiency from 0.8737 to 1.0519, demonstrating synchronous economic and environmental gains. This is one of the first studies to apply LCA–MFCA integration in China’s cement sector.

Keywords: eco-efficiency; MFCA; LCA; Circular economy

Paper type: Research paper

1 Introduction

China has always adopted an extensive mode of economic growth, which is accompanied by huge resources consumption and great destruction of the environment, especially in heavily polluting industries such as cement. According to the statistics released by the Ministry of Environmental Protection of China, in 2022, the emissions of NO_x, SO₂ and particulate matter/smoke dust in China's cement industry were 875kt, 167kt and 254kt respectively, accounting for 17.1%, 5.6% and 19.3% of the total industrial emissions in China(MEP, n.d.), which seriously damaged the ecological environment in China. On the other hand, although the cement industry is one of the basic industries in China's national economic construction and occupies an important position in China's economy, it has also made substantial progress in energy efficiency and cleaner production since the 13th Five-Year Plan, but it still has the characteristics of serious pollution and low efficiency.. According to the data of China Statistics Bureau, the total profit of the cement industry in China in 2023 accounted for less than 5% of the profits of industrial enterprises above designated size in China(National Bureau of Statistics of China, 2023). At the same time, it is the only way for the future development of cement industry to improve economic and environmental benefits and achieve a substantial increase in eco-efficiency.

1 In order to improve the eco-efficiency, extensive exploratory research has been carried out
2 from both theoretical and practice perspectives. For example, Lamas *et al.* (2013) proposed to
3 improve the eco-efficiency through rational utilization of waste from cement production, and
4 Mikulčić *et al.* (2016) conducted environmental assessment on different cement manufacturing
5 processes through emergy and ecological footprint analysis, with a view to finding ways to improve
6 the environmental benefits of cement production. Coccozza *et al.* (2024) evaluates the human impact
7 of cement plants through comprehensive biological monitoring of three different biological
8 indicators in central Italy, Chen *et al.* (2016) adopted the Emergy Analysis method based on Life
9 Cycle Inventory (LCI) to analyze the cement industry in China, and concluded that the cement
10 industry in China has brought higher environmental burden and is unsustainable, so it is necessary
11 to improve energy efficiency and adopt substitutes to replace raw materials to improve the
12 sustainability of the cement industry. However, improving eco-efficiency is a complex problem,
13 especially for China cement production, which is a heavily polluted and inefficient industry.
14 Research progress to date is not sufficient to clearly identify the improvement points of low eco-
15 efficiency, leading to inadequate eco-efficiency optimization.

16 Accounting has long been a significant tool in environmental research, providing essential data
17 to effectively address numerous environmental challenges(Wang et al., 2019). MFCA is a vital
18 method that enables the identification of potential points for economic and environmental
19 improvement in the production process. By connecting the material flow and value flow of resources,
20 MFCA helps reduce resource waste and environmental pollution (Ling Zheng and Zhifang Zhou,
21 2010). By utilizing MFCA, it becomes possible to simultaneously enhance economic and
22 environmental benefits, ultimately optimizing eco-efficiency. Since the publication of ISO14051,
23 the fundamental concept of MFCA has garnered considerable attention from scholars. Many
24 enterprises, particularly in Japan, have implemented this method in their production practices and
25 achieved significant results(Sudha, 2020). Heavily polluting enterprises in China, such as steel and
26 chemical enterprises, have also adopted MFCA, which has improved their economic
27 performances(Xu et al., 2017). However, during the implementation process of MFCA, it has been
28 observed that the quantification and visualization of material loss limited to material flow, energy
29 flow, and enterprise boundaries can hinder efforts to improve eco-efficiency(Doorasamy, 2016;
30 Götze et al., 2014; Higashida, 2020). By integrating MFCA with LCA, the limitations of
31 standalone MFCA analysis can be addressed, enabling a more comprehensive improvement of
32 ecological efficiency. This combined approach extends the focus from internal production processes
33 and the industrial chain to encompass the impact on external resources and the environment.(Zeng
34 et al., 2021).

35 This paper analyzes the principle of combining MFCA with LCA and proposes specific
36 questions to be considered when implementing it in enterprises: (1) How to achieve the Integration

of internal economic efficiency of MFCA with the external environmental impact of LCA; (2) How to utilizing MFCA to support decision-making regarding environmental impact from a life cycle perspective; (3) How to harness the synergy between LCA and MFCA to improve eco-efficiency. This method is applied to Cement Company A in western China to verify the effectiveness of this method. While there have been existing studies on the combination of MFCA and LCA methods, the extension of MFCA from a life cycle perspective is currently limited to a theoretical framework, lacking concrete methodologies (Zeng et al., 2021). In this paper, we propose a combination of LCA and MFCA to evaluate the eco-efficiency of the manufacturing process. By employing MFCA, we can identify waste losses in the production process and utilize the LCA method to guide and optimize these processes, ultimately leading to improved eco-efficiency.

2 Literature Review

2.1 Eco-efficiency

Since Schaltegger and Sturm (1990). put forward the concept of "eco-efficiency" in 1990 and used it to measure the environmental performance of economic activities, scholars and organizations have done a lot of research on this indicator In 1992, WBCSD (2000) defined and popularized the concept of eco-efficiency, which was defined as "gradually reducing the ecological pressure and resource consumption to the recoverable environmental capacity while meeting the needs of human life and social progress and development" The United Nations Conference on Development and Trade (UNCTAD, 2003) takes the maintenance of ecological quality as the starting point, and holds that eco-efficiency is to reduce the negative impact on the natural environment on the premise of maintaining or increasing the economic value (United Nations Conference on Trade and Development. In 1998, the OECD defined eco-efficiency as the efficiency of ecological resources to meet the survival and development of human beings, and the specific form is the ratio of output to input. Input refers to the ecological load or environmental pollution generated by enterprises, departments or an economy in the process of ecological management, and output refers to the increase in the economic value of products and services (Organisation for Economic Co-operation and Development., 1998).

At present, scholars mainly adopt many methods to measure eco-efficiency, such as ratio method, index system method, mathematical model method and so on. Ratio method is the simplest and most direct method to measure eco-efficiency with a single index, which can flexibly determine input and output indexes according to the purpose of research. Bribian based on the life cycle theory, used the ratio method to analyze the eco-efficiency of the construction industry, and analyzed how to improve the eco-efficiency of building materials (Zabalza Bribián et al., 2011). Aldieri *et al.* (2019) adopted the proportion of renewable energy in the total energy as a measurement index when measuring the eco-efficiency of ten European countries. Index system method is an evaluation

system based on various characteristics of eco-efficiency and interrelated indicators. Dahlstroem and Ekins (2005) proposed that the set of eco-efficiency indicators includes the ratio of input to output and the ratio of economic and pollution output. Guenster *et al.* (2011) used indicators such as water eutrophication and volatile acid content when studying the eco-efficiency of iron and steel enterprises. Ghimire and Johnston (2017) selects 11 indicators such as acid rain, ecotoxicity, energy consumption level and ozone consumption as environmental indicators, and GDP as economic indicators to calculate eco-efficiency. Mathematical model method is the most widely used method in the study of eco-efficiency at present, which mainly includes data envelopment analysis (DEA), LCA, material flow analysis (MFA), MFCA, Ecological footprint method and so on. DEA mainly evaluates the comprehensive efficiency of resource utilization and environmental impact by constructing multi-dimensional index system and combining input-output model, and provides quantitative basis for the optimization path of ecological efficiency(Dong and Wu, 2020); MFA can improve the efficiency of resource utilization by quantifying the process of material flow and identifying the bottleneck of resource utilization, but the research perspective is limited to the technical level of material and lacks consideration of economic indicators(Fujii *et al.*, 2017); Ecological footprint method provides a targeted basis for efficiency optimization by identifying key resource consumption areas (such as energy and land), but there are some problems such as data limitations and static model defects(Lin, 2021). Ewertowska *et al.* (2017) used DEA model method, life cycle assessment method and Monte Carlo simulation method to quantitatively study the eco-efficiency under uncertain environment. Juana *et al.* (2013) adopted the SBM model based on unexpected output when measuring eco-efficiency together with the World Economic Cooperation Organization. (Sadorsky, 2021) used data envelopment analysis (DEA) to measure the energy eco-efficiency of the main 18 countries in G18. (He *et al.*, 2023; Zhou *et al.*, 2020) used Slack-Based Measure (SBM) model considering unexpected output to measure provincial energy eco-efficiency.

The single ratio method is simple to operate, but it is difficult to consider other influencing factors, and it is also impossible to calculate the best comparison set(Zabalza Bribián *et al.*, 2011). Although the index system method can integrate more environmental or economic indicators, there are subjective factors in the selection of indicators(Ghimire and Johnston, 2017); Among the mathematical model methods, LCA and MFCA have their own advantages, but they can only take into account one aspect of eco-efficiency, and cannot comprehensively measure eco-efficiency(Doorasamy, 2016).

In this paper, we draw upon the concepts of eco-efficiency index introduced by the WBCSD, and related of MFCA and LCA(Huppes and Ishikawa, 2005). We propose that eco-efficiency should not only measure output value and waste discharge levels but also consider the quantitative relationship between resource output value and resource input. Therefore, we define that:

$$1 \quad \text{ecological efficiency} = \frac{\text{the effective added value of resources/}}{\text{the external environmental damage value}} \quad (1)$$

2 Among these, the effective added value of resources measures the difference between the actual
3 output and the input resources in the resource circulation, serving as an economic indicator. Unlike
4 traditional metrics such as gross output value, the economic value added indicator incorporates
5 social benefits and places greater emphasis on the effectiveness of value creation. Furthermore,
6 since this study evaluates the ecological efficiency of each cost center individually, using output
7 value as a metric would fail to account for the interdependencies between centers—specifically, it
8 would not eliminate the influence of upstream processes on downstream evaluations. Conversely,
9 the external environmental damage value quantifies the environmental harm caused by waste
10 discharged during the product life cycle, providing insights into the environmental benefits of the
11 product or production process. The combination of these two indicators effectively measures the
12 implementation efficiency of a circular economy, ultimately enabling the reduction, recycling, and
13 reuse of resources.

14 ***2.2 Optimization Methods for Eco-efficiency***

15 Scholars have conducted extensive studies to enhance eco-efficiency, utilizing various
16 optimization measures including LCA, MFCA, and DEA. As key tools in environmental
17 management, MFCA and LCA play irreplaceable roles in optimizing eco-efficiency.

18 LCA, originated from the energy crisis in the 1960s, is an important tool for product
19 environmental management. It enables effective quantitative analysis and evaluation of current
20 environmental conflicts, tracking the complete life cycle of products from production to disposal,
21 and evaluating environmental issues arising throughout this process (Walz and Guenther, 2021).
22 LCA is a comprehensive method that encompasses the environmental impact of the entire product
23 life cycle, extending beyond the manufacturing phase. LCA focuses on identifying and quantifying
24 environmental burdens and their potential implications, providing suggestions to mitigate
25 environmental impacts (Torregrossa et al., 2018; Vinci et al., 2019). It can be used for enterprise
26 product development and design, effectively support government environmental management
27 departments to formulate relevant environmental policies, and also provide clear product
28 environmental signs to guide consumers' consumption behavior of environmental products(Canaj et
29 al., 2021). Therefore, since LCA considers not only resource consumption but also broader external
30 impacts, including environmental load, ecological damage, and health effects. Given the wide range
31 of factors involved, a key challenge lies in developing a unified measurement framework that allows
32 for comprehensive analysis and meaningful comparison across impact categories. (Ben-Alon et al.,
33 2019; Comanita et al., 2018).

34 MFCA originated in Germany in the second half of 1990s and has become an important method

of circular economy and environmental management. By tracking and quantifying the material path and quantity of material and energy flow in the production system, and calculating the value information it represents, we can find out the resource improvement potential(Xu et al., 2017). Compared to industrial metabolic MFA, MFCA goes beyond tracking the inflow, outflow, and inventory changes of specific materials. MFCA also accounts for inputs such as energy, labor, and depreciation. By integrating material quantities with monetary values, MFCA enables the quantification of both the economic and environmental costs associated with material losses. Compared with traditional cost accounting, MFCA not only allocates the cost in the production process to the expected qualified products (so-called positive products), but also to the waste loss (so-called negative products) (“BS EN ISO 14051,” 2011). Therefore, the cost of resource loss includes not only the disposal cost of waste, but also the hidden and indirect costs from upstream processes, such as the cost of semi-finished products put into production or the system cost of labor and manufacturing expenses. Through the monetization measurement of the resource value and resource flow cost contained in the waste, we can find the potential point for enterprises to improve the circular economy and provide support for making relevant improvement decisions, thus generating economic and ecological benefits and enhancing eco-efficiency (Weyand et al., 2021). MFCA can be used to reduce waste, thus improving resource efficiency and environmental performance (Wang et al., 2017). Its advantage lies in that MFCA method conveys the information of value loss in different process steps and makes it transparent t(Schmidt and Nakajima, 2013). The resulting information can be used as the driving force of industrial planning, seeking opportunities and simultaneously generating economic benefits and reducing adverse environmental impacts.

However, these methods have certain limitations when it comes to optimizing eco-efficiency. Traditional MFCA, for instance, the principle of "system boundary" leads to the neglect of the influence of industrial systems on the external environment.. Additionally, MFCA lacks detailed cost analysis and fails to consider alternative energy flows and energy loss flows(Weyand et al., 2021). On the other hand, LCA examines the environmental impact of the entire life cycle of a product and identifies potential issues qualitatively. However, it lacks monetary value data and often requires other analytical techniques for more comprehensive evaluation and problem-solving(Walz and Guenther, 2021). Life cycle cost analysis (LCCA) can also evaluate the cost information of products in monetary terms, however, its focus is on long-term decision-making and life cycle costs, including usage, maintenance and end of life disposal. (Nyakuwanika et al., 2021).

To address these limitations, this paper proposes an optimization method to improve eco-efficiency of manufacturing process. This is achieved by integrating MFCA and LCA into a unified LCA-MFCA mechanism.

3 A new mechanism combining LCA and MFCA

In this section, the design of a new mechanism, namely unified LCA-MFCA mechanism, will be introduced. This new mechanism considers the material and value information of resource loss throughout the entire supply chain, covering the entire product life cycle. It provides an effective

and easy-to-use measurement standard for optimizing the eco-efficiency of the entire process. By integrating MFCA and LCA, this approach can overcome the limitations of each individual tool and enhance their application in practice.

3.1 Comparison between MFCA and LCA

In this section, we will examine the distinct advantages of MFCA by analyzing its differences with LCA. The comparison will be based on their respective standards, ISO1404011-2009 for LCA and ISO1405112-2011 for MFCA. Table 1 provides an overview of the key differences between LCA and MFCA.

Table 1 Main differences between LCA and MFCA

standard	LCA	MFCA
focal point	environmental effect	Resource and energy efficiency
System boundary	Whole life cycle	enterprise
main body	Suppliers, manufacturers, consumers	manufacturer
Impact category	Resources, climate change, atmospheric environment, water and soil toxicity	Resource consumption, cost and global greenhouse effect
Target group	Public and internal	internal
Accounting object	Quantity center	product
Accounting content	Ecological information or environmental impact	Value information

LCA primarily focuses on assessing the environmental impact, with the system boundary encompassing the entire life cycle of products, processes, or services from their inception to disposal. MFCA centers around the material and energy consumption within a company, specifically targeting the efficiency of resource utilization within specific manufacturing links(Zeng et al., 2021) . Specific to the subject of accounting, MFCA emphasizes the economic interests of a specific entity, taking a production stage or link as the focal point and considering resource cost-related information within that specific process. In contrast, LCA not only considers value information such as a producer's cost but also pays attention to the ecological and environmental impacts throughout the entire life cycle of the product, including both internal and external impacts within the production system (Weyand et al., 2021).Both methodologies compile product life cycle inventories of input and output flows. However, they differ in terms of methods and scope. LCA generates life cycle inventories based on specific functional units, while MFCA considers input and output flows within a fixed observation period. Additionally, in MFCA, results are not only related to the product but also take into account material loss, enabling the identification of inefficiencies and the discovery of optimization potential (Pauliuk, 2018).LCA encompasses numerous impact categories to assess the

environmental impact of product systems. On the other hand, MFCA places greater emphasis on cost considerations, determining environmental impact based on the amount of resources consumed. Although there is currently no definitive and authoritative method to quantify the ecological effects of resources, ongoing research in MFCA is expected to make monetizing environmental benefits, such as global warming, feasible in the near future. The application goals of the two methods also differ. LCA can be used for external communication as well as identifying optimization potential, while MFCA is primarily employed for internal purposes. Through the comparison between LCA and MFCA, it is evident that MFCA is more suitable for improving resource efficiency by optimizing processes within an enterprise or industrial chain. The double measurement of physical quantities and monetization of resource loss and environmental impact in MFCA also makes it more suitable for optimization decision-making within enterprises(Wang et al., 2017).

Indeed, despite their differences, MFCA and LCA are interoperable and complementary. They share similarities in terms of system modeling, method (flow network), and data (flow). Both methodologies emphasize the material flow throughout the entire life cycle of product production and embody the concept of product life cycle. The analysis of material flow in the production process serves as the foundation for both MFCA and LCA. The modeling methods employed are quite similar, utilizing elements such as “inventory” and “flow.” Therefore, it can be said that material flow analysis in MFCA provides a solid basis for the smooth implementation of LCA (Dunuwila et al., 2018).Moreover, MFCA and LCA each have their own limitations when used independently. MFCA does not include an explicit consideration of environmental impact, while LCA can assess the external environmental damage of enterprises. However, determining the output of the input-output list in LCA can often be challenging. To accurately assess the environmental impact of an enterprise, obtaining a precise output list is necessary(Nakajima, 2016).By combining MFCA and LCA, their respective shortcomings can be addressed. MFCA focuses on reducing costs by minimizing waste, thus enhancing enterprise productivity. With MFCA, for a material center, both input and output adhere to the principle of material flow balance. By understanding the input of materials and energy, it becomes possible to accurately calculate the output list and material qualities for a material center. This helps in identifying and quantifying the reduction of waste, leading to cost reductions and improved efficiency within the enterprise.

3.2 The Basic Principle of the LCA-MFCA Method

The MFCA method serves as a means to initiate waste reduction and support decision-making by assessing costs. However, excessively focusing on economic benefits and costs can lead enterprises to overlook other important factors such as the environment. Furthermore, short-term cost increases may not align with long-term comprehensive development interests. To overcome this limitation, integrating environmental impact into MFCA and adopting a holistic approach that incorporates the entire life cycle of products - including material production, product manufacturing, and product consumption - can offer a solution to address the short-term constraints of MFCA(Kokubu et al.,

2023). Therefore, enhancing MFCA by incorporating environmental impact data can help address the issue of information silos. This is achieved by expanding the system boundary—shifting the focus from solely internal enterprise production processes to also include the external environment, such as emissions and waste discharge. . When implementing MFCA in the supply chain, enterprises may be hesitant to share cost-related information. However, sharing physical quantity information is relatively less challenging. Additionally, employing specific evaluation methods, such as utilizing CO₂ as a comprehensive coefficient in LCA, allows for the assessment of material and energy flows and losses with a focus on specific environmental considerations, such as e.g., reducing greenhouse gases. This, in turn, aids in minimizing material losses. Over time, focusing on environmental protection by reducing greenhouse gases throughout the supply chain has garnered attention. Such behavior may be recognized by investors and consumers, ultimately leading to improved economic benefits. In practical decision-making endeavors aimed at reducing material losses, enterprises within the supply chain can determine priorities and estimate the reduction effects based on greenhouse gas information while also conducting cost evaluations.

As depicted in Figure 1, both MFCA and LCA rely on material flow analysis, which examines the flow of materials throughout the entire product life cycle. On one hand, MFCA is utilized to calculate material flow costs, assess the effective utilization value, and identify resource loss within the industrial chain. It highlights the value loss of resources and identifies potential areas for optimization. On the other hand, the LCA method calculates the external environmental damage cost resulting from waste during the production process. It evaluates the environmental damage points within the production process, pinpoints key areas for environmental protection, and utilizes the MFCA method to estimate the costs and economic benefits of various optimization measures. The combination of these two methodologies forms the fundamental framework of the resource flow LCA-MFCA method. Based on this framework, the eco-efficiency of the industrial chain, enterprises, and processes can be evaluated, leading to corresponding optimization decisions.

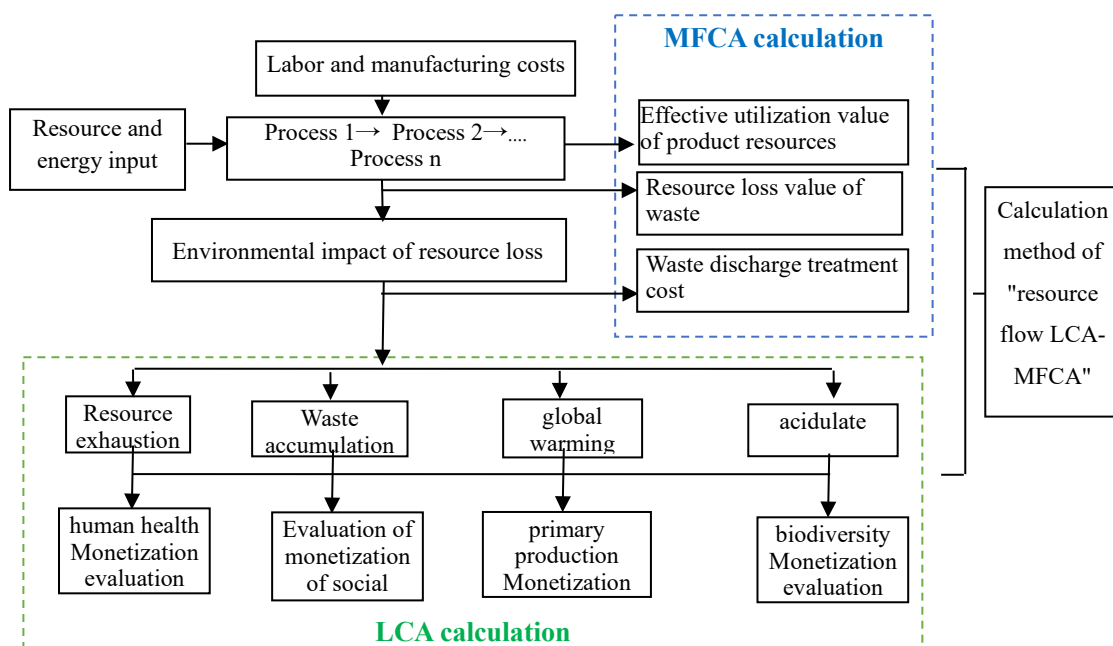


Fig. 1 schematic diagram of the integrated framework method

Assessing the external environmental damage requires an input-output data list, which cannot be accurately obtained solely through the LCA method. MFCA tracks and controls various substances and energy, allowing for the acquisition of output lists and material qualities for each process or material center. These enable the evaluation of environmental damage resulting from various activities within an enterprise's economic process. By analyzing treatment methods, these external environmental damages are then aggregated into measurable components, and ultimately monetized using established accounting methods. Several methods can be employed to evaluate external environmental damage in practice, including Japan's LIME (Life-cycle Impact Assessment Model Based on Endpoint), Sweden's EPS, the Netherlands' Eco-indicator95 and 99, and the European Union's ExternE identification coefficient (Doorasamy, 2016). The Japanese version of LIME, for example, quantifies human health damage caused by various environmental substances. It aggregates these damages considering the significance of each endpoint, and subsequently converts them into monetary value for evaluation. LIME, as a comprehensive evaluation tool, offers unique advantages (Ariefiara et al., 2021).

3.3 Steps to Implement LCA-MFCA Eco-efficiency Optimization

To achieve the objective, this study follows a three-step approach: (1) Tracking the material flow path, quantifying material flow data, analyzing material balance, and calculating MFCA and LCA results to obtain eco-efficiency data. (2) Identifying key factors of cost loss and environmental impact through two-dimensions analysis and hypothesis testing, identifying problems, and proposing feasible improvement schemes. (3) Verifying the potential for improvement. The specific tools and integration methods of data technology used in each step can be seen in Figure 2.

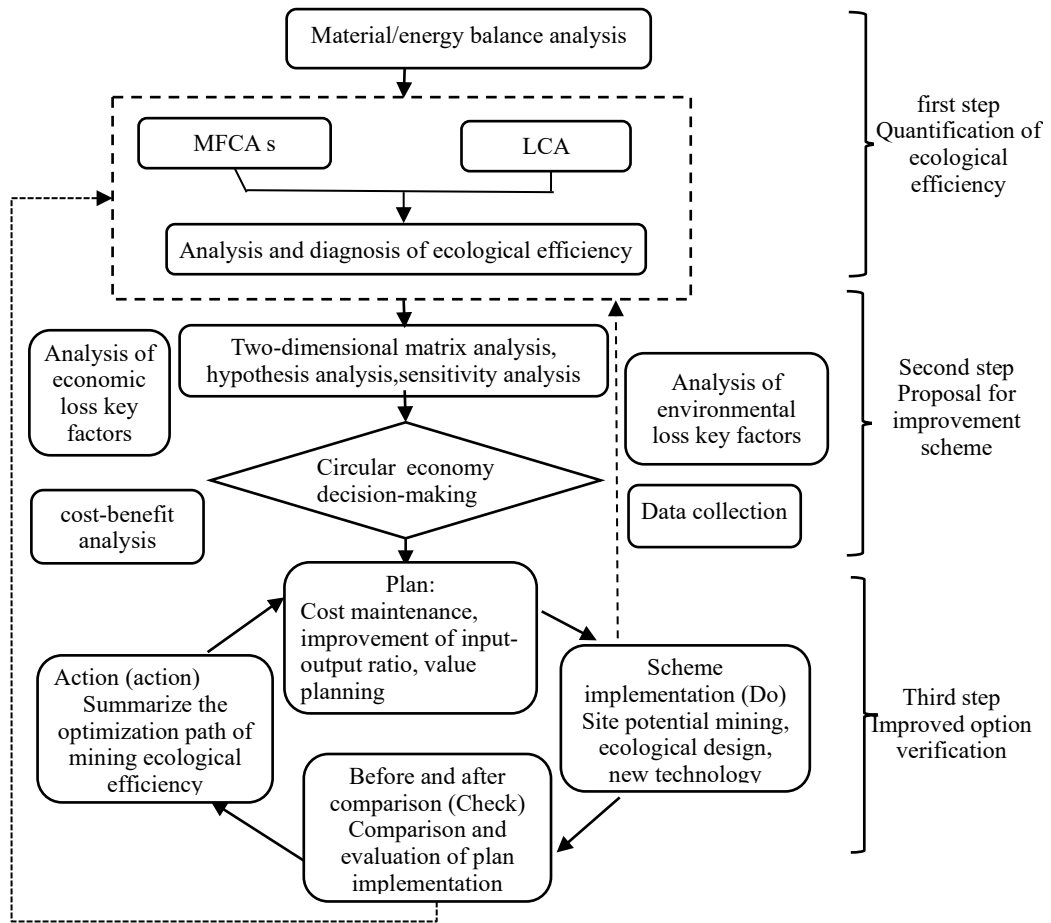


Fig. 2 eco-efficiency optimization steps based on LCA-MFCA

(1) Quantification of Eco-efficiency

In this step, relevant data for the LCA-MFCA method is collected based on the defined system boundary. The system boundary can be determined according to the actual circumstances and may be limited to the entire life cycle from cradle to grave. By referring to enterprise practices, literature, and databases, the most influential parts of the product life cycle can be identified. It is essential to consider the willingness of companies in the upstream and downstream life cycles of the industrial chain to participate, as well as the impact of the use and disposal processes of various intermediate products on eco-efficiency.

The studied system can be further divided into several material circulation centers based on the path of material flow. Material flow within the system can be examined, and a material balance table or diagram can be established to elucidate the circulation path and quantity of resources. Utilizing this quantitative data, the corresponding material flow cost data and life cycle data are allocated. It is important to note that the principle of comprehensive life cycle assessment allocation requires careful consideration. Commonly used allocation criteria include material quantity, weight, working

hours, and economic assessment. However, it is generally not recommended to use economic indicators as allocation criteria in LCA because economic data may come from MFCA. The specific approach can be based on the quantity, volume, and area of element flow instead. It is insufficient to rely solely on economic standards as treatment capacity and cost vary significantly among different materials.

(2) Proposals for Improvement Scheme

The main objective of this step is to identify the links and factors that have the greatest potential for resource loss and environmental damage in the product life cycle and identify possible improvement options. In the implementation process, the loss of each process can be selected to be placed in the same two-dimensional table, and the improvement potential of each center can be visualized according to the location of each volume center in the two-dimensional table. Through what-if analysis, sensitivity analysis, Pareto analysis and other tools, the most influential factors contributing to environmental damage in each process (or volume center) are identified by evaluating how changes in key environmental factors affect the environmental damage of individual processes or the overall system. In order to make up for the lack of researchers, after determining the key influencing factors, professionals can be consulted and literature can be consulted to find available improvement programs.

(3) Verification of Improvement Options

The purpose of this step is to verify the effectiveness of the improvement plan. After selecting the scheme, the enterprise adopts the LCA-MFCA integration method to verify the implementation effect of the scheme by means of actual implementation or data simulation. The optimization scheme may contain multiple projects, so it is best to verify the single scheme in the project separately, and then adopt the integrated method to simulate and verify the effect of the scheme that applies all options, that is, the "combination scheme", and carry out the relevant cost-benefit analysis.

4 A case study of implementing the unified LCA-MFCA mechanism

Company A, a limited liability company established in 1984, located in the western part of China, focuses on the production of 32.5 and 42.5 cements. Over the years, the company has faced various challenges, including outdated equipment, a small production scale, high operating costs, and an inability to undergo technical transformations, resulting in continuous losses.

As a major cement production enterprise with significant environmental impact, Company A has made the decision to respond to the call for “energy-saving and emission reduction” and the development of the circular economy. To achieve energy efficiency, reduce resource consumption, improve production efficiency, enhance environmental conditions, and reduce pollutant emissions,

the company has opted to implement the LCA-MFCA method for transformation, ultimately aiming to enhance eco-efficiency.

4.1 Quantification of Eco-efficiency

(1) Definition of Quantity Centers

Based on Company A's production status and the production process flowchart, and considering the moderate setting of quantity centers, the division of quantity centers in the LCA-MFCA analysis, as well as information from production process investigations and cost reports, the production organization is subdivided into quantity centers. The specific quantity centers are illustrated in Figure 3:

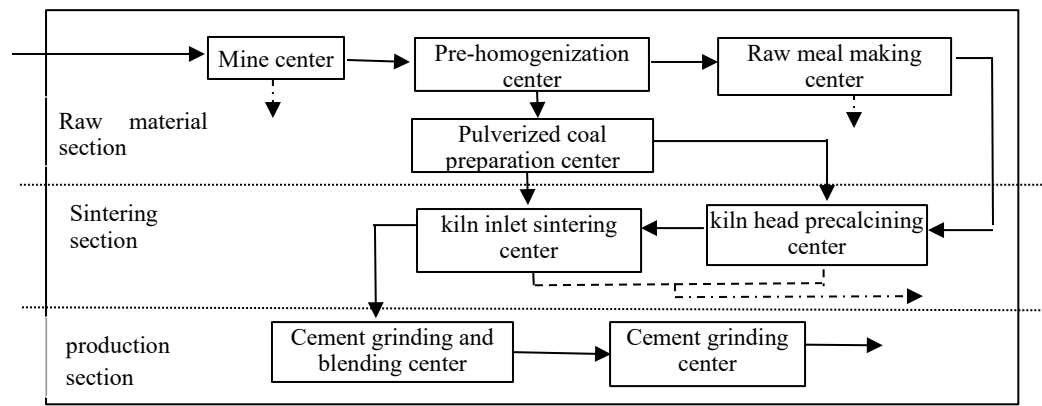


Fig. 3 Company A's production technology and division of quantity centers

Finally, Company A's production management will consist of eight quantity centers: the Mine Center, Pre-Homogenization Center, Raw Meal Preparation Center, Pulverized Coal Preparation Center, Kiln inlet sintering center, Kiln head precalcining center, Cement grinding and blending Center, and Cement Grinding Center. This forms the basic framework for the production management analysis of Cement Company A. The production process involves stacking, reclaiming, blending, and grinding of raw materials. During the transportation, conveying, and grinding of raw materials, dust discharge occurs. The homogenized raw meal is mixed with 60% pulverized coal and burned in a preheater. It is then dried, preheated, and pre-decomposed before undergoing high-temperature sintering and cooling in a rotary kiln with the remaining pulverized coal to form clinker. This process results in the emission of a significant amount of greenhouse gas CO₂ due to the decomposition of raw carbonate and fuel combustion. It also generates a small amount of harmful gases such as NO_x and SO₂, as well as dust particles due to the closed environment and the presence of SO₃ components in raw materials under high-temperature combustion conditions. The clinker, after cooling with a grate cooler, is stored in a warehouse and transported to the cement grinding and blending station to be further ground with crushed gypsum and mixed materials, resulting in the production of cement products. Some dust is generated during the grinding process(Saleh, 2021).

(2) Cost Definition

LCA-MFCA analysis is based on the flow of elements in the production process and dynamically describes the changes in value during production and operation. At the resource input stage, the cost value is divided into four parts: materials, systems, energy, and waste treatment costs. The main costs of Company A are outlined in Table 2.

Table 2 Definition of Cost Content of LCA-MFCA Analysis of Company A

Cost item	Cost content
cost of material	main material Limestone, shale, clay, iron ore, etc
	Secondary material Gypsum and coal gangue
	supplementary materials Mixed wood
Energy cost	Electricity, water, coal, oil, gas, etc.
System cost	direct labor Wages and welfare expenses of production workers
	Other direct costs Processing fee, etc.
	overhead expenses Salary and welfare expenses of management personnel, depreciation expenses, consumable materials expenses, repair expenses, etc.
Waste disposal cost	Labor costs, maintenance costs, etc. incurred in treating the three wastes.

Dividing the cost items based on the flow of resources, as described above, is convenient for LCA-MFCA to allocate material costs and also for allocating energy and system costs based on working hours and manual labor. This approach allows for a detailed understanding of the composition of costs and identifies key areas with potential for improvement, facilitating decision-making in circular economy optimization.

(3) Data Collection and Compilation

Following the principle of including all important inputs and outputs, this study encompasses the entire production and operation process of Company A for LCA-MFCA data collection. The main financial data is obtained from the company's financial management department, while technical data is sourced from relevant production management, energy management, and environmental management departments. Additionally, certain data is derived from cleaner production standards and specifications formulated by the National Development and Reform Commission and the steel industry. These data include conversion standards, process material consumption, energy consumption, standard energy consumption, and other relevant information. According to the production data of Company A in September 2022, the data of inflow and outflow can be sorted out as shown in Table 3:

Table 3 Material Balance Sheet of Company A

Last quantity center input	New input	output
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	Material type	Quantity (t)	Material type	Quantity (t)	Material type	Quantity (t)
Mine center			Calcareous resources	14,605,450	limestone	14,604,720
					dust	730.21
Pre-homogenization center	limestone	14,604,720	shale	3,119,935	raw material	18,255,900
			iron ore	303,043	raw coal	1,426,620
			coal gangue	228,202		
			raw coal	1,426,620		
Pulverized coal preparation center	raw coal	1,426,620			gum	1,416,360
					dust	10260.20
Raw meal making center	raw material	18,255,900			raw material	18,196,707
					dust	59193.47
					fired	
kiln inlet sintering and kiln head precalcining center	raw material	18,196,707	Pulverized coal (kiln tail)	849,816	refractory material	12,090,000
			Pulverized coal (kiln head)	566,544	dust	9470.83
					CO2	9,573,590
					NOx	16200.6
	fired				fired	
Cement grinding and blending center	refractory material	12,090,000	plaster	715,000	refractory material	12,090,000
			Mixed material	1,495,000	plaster	715,000
					Mixed material	1,495,000
					cement	14,284,215
Cement grinding center	Clinker	14,300,000				
	gypsum					
	mixed material				dust	15,784,925

1 Data source: According to the actual data of Company A in September 2022.

2 (4) Cost Distribution Method

3 The input of each quantity center can be categorized into material, energy, system, and
4 treatment costs, and each type of cost has a different distribution principle.

5 ① Material Cost: This includes various expenses related to raw materials in cement
6 production, including main materials and auxiliary materials. Main materials consist of limestone,
7 clay, and iron powder used in the initial quantity center, as well as materials added in subsequent
8 quantity centers and semi-finished products carried forward from previous quantity centers.

Auxiliary materials are less commonly used than the main materials. Material costs are typically allocated among quantity centers based on product output or the content of key elements.

② Energy Costs: This encompasses expenses for electricity, water, and steam. Cement enterprises utilize coal and electricity as energy sources, and energy costs are distributed among quantity centers based on power consumption, coal consumption, and corresponding unit prices.

③ System Costs: This includes wages, depreciation, and other manufacturing expenses consumed during the production process. System costs are calculated based on loss rates or activity rates and are then allocated between positive products and negative products according to criteria such as calorific value or materials.

④ Waste disposal costs are not directly tied to the production of positive products, and therefore, their costs do not need to be proportionally distributed. Instead, they are directly included in the cost value of negative products.

(5) Summary of MFCA Calculation Results

By calculating the distribution method as above, the MFCA results of each volume center in the cement production process of Company A can be calculated.

In this volume center, material cost and energy input are calculated by multiplying the quantity of materials used by the corresponding unit price. System cost is derived from salary, depreciation and other manufacturing expenses presented in the cost calculation sheet of Company A. The costs transferred from the previous volume center reflects the cost of semi-finished products consumed by the current volume center. Since Company A does not store semi-finished products in warehouses, this data directly represents the cost of qualified products from the previous volume center. The total input cost of this volume center is the sum of its own input costs and the transfer costs from the prior volume center. This cost is then allocated to positive and negative products based on their respective distribution ratios. To simplify the calculation, all costs are allocated using the same ratio.

$$RUV_i = \frac{RUV_{i-1} + Cm_i + Ce_i + Cs_i}{Qp_i + Qw_i} \times Qp_i \quad (2)$$

RUV :the Positive products cost; i -process i ; Cm :materials cost; Ce :Energy cost; Cs :system cost;
 Qp :Quantity of distribution standard for positive products; Qw :Quantity of distribution standard for negative products.

From this, the effective added value of each quantity center can be calculated as:

$$EAV_i = OV_i - RUV_i \quad (3)$$

EAV_i :effective added value; OV_i :output value

The calculation results are shown in Table 4:

Table 4 Company A's cement production material flow cost accounting table (unit: 10⁴CNY)

Project	Cost item	Mine center	Pre-homogenization center	Raw meal making center	Pulverized coal preparation center	Kiln inlet sintering center	Kiln head precalcining center	Grinding and blending center	Cement grinding center
New input	mc	45904.93	12270.18	0.00	0.00	0.00	0.00	17321.46	0.00
	ec	1053.00	826.80	18798.00	44150.73	4056.00	16302.00	429.00	27534.00
	sc	1785.20	4374.04	5767.38	2732.20	1869.92	4946.24	1023.36	7704.84
	TC	48743.13	17471.02	24565.38	46882.93	5925.92	21248.24	18773.82	35238.84
Transfer from upper quantity center	mc	0.00	38101.09	30043.44	16177.24	42473.62	34678.04	33184.11	46859.06
	ec	0.00	873.99	1014.42	546.23	54361.18	52598.20	65931.98	61569.71
	sc	0.00	1481.72	3492.61	1880.63	12802.13	11766.10	15992.37	15787.19
	TC	0.00	40456.80	34550.47	18604.10	109636.93	99042.33	115108.45	124215.97
Total input	mc	45904.93	50371.27	30043.44	16177.24	42473.62	34678.04	50505.57	46859.06
	ec	1053.00	1700.79	19812.42	44696.96	58417.18	68900.20	66360.98	89103.71
	sc	1785.20	5855.76	9259.99	4612.83	14672.05	16712.34	17015.73	23492.03
	TC	48743.13	57927.82	59115.85	65487.03	115562.85	120290.57	133882.27	159454.81
Positive product distribution ratio		83.00	83.00	91.76	99.68	99.28	73.33	95.69	92.78
Negative product distribution ratio		17.00	17.00	8.24	0.32	0.72	26.67	4.31	7.22
RUV _i (qualified)	mc	38101.09	46220.68	29946.10	16060.92	31144.63	33184.11	46859.06	46807.52
	ec	873.99	1560.64	19748.23	44375.58	42835.57	65931.98	61569.71	89005.70
	sc	1481.72	5373.24	9229.98	4579.67	10758.57	15992.37	15787.19	23466.19
	TC	40456.80	53154.57	58924.31	65016.18	84738.77	115108.45	124215.97	159279.41
Negative products (losses)	mc	7803.84	4150.59	97.34	116.31	11328.99	1493.93	3646.50	51.54
	ec	179.01	140.15	64.19	321.37	15581.62	2968.22	4791.26	98.01
	sc	303.48	482.51	30.00	33.17	3913.47	719.97	1228.54	25.84
	TC	8286.33	4773.25	191.54	470.85	30824.08	5182.12	9666.30	175.40
Output Value		89197.43	208005.89	263924.15	316579.74	415122.32	541242.05	665402.62	850169.92
effective added value of resources		48740.63	65653.89	90605.31	46563.73	78819.98	95750.05	115053.05	149703.86

(6) Calculation of External Environmental Damage in LCA

In LCA calculations, the environmental impact factors such as resource loss, energy consumption, waste disposal, and emission of waste gases are further analyzed. The impact of waste loss on the environment is considered as the medium, and environmental assessment methods related to resource depletion, energy depletion, and environmental damage caused by waste disposal are combined to calculate the external environmental damage value. Currently, there are no specific regulations or guidelines for calculating the external damage cost of waste in the cement industry in China. As a result, the calculation is based on the LIME comprehensive coefficient calculation table from Japan.

$$EDC_i = \sum_{j=1}^n DF_{ij} \times WTP_j \quad (4)$$

EDC_i : external damage cost of process I; DF_{ij} : The quantity of the J-type waste in I process,

WTP_j : external damage cost of J-type waste in LIME. The calculation results of the external damage cost for the main wastes of Company A are presented in Table 5.

Table 5 LCA calculation table of each quantity center of Company A (unit: 10^4 CNY)

waste	WTP	Mine center	Raw meal making center	Pulverized coal preparation center	Kiln head precalcining center	Kiln inlet sintering center	Cement grinding center
dust	70.8	5174	419081	72631	60346	6656	111761
CO2	0.1044	-	-	-	85618	14079	-
SO2	4.308	-	-	-	1027	689	-
NOX	8.46	-	-	-	2743	10959	-
total	-	5174	419081	72631	149734	32383	111761

(7) Calculation of eco-efficiency

Through the above data calculation, we can get the eco-efficiency indicators of each quantity center and general factory of Company A.

$$Ec_i = \frac{EAV_i}{EDC_i} \quad (5)$$

The calculation results is shown in Table 6:

Table 6 Company A's eco-efficiency calculation index

Quantity center	Mine center	Raw meal making center	Pulverized coal preparation center	Kiln head precalcining center	Kiln inlet sintering center	Cement grinding center	company
eco-efficiency	9.4203	0.2162	0.6411	0.5264	2.9568	1.3395	0.8737

4.2 Optimal Diagnosis of Eco-efficiency

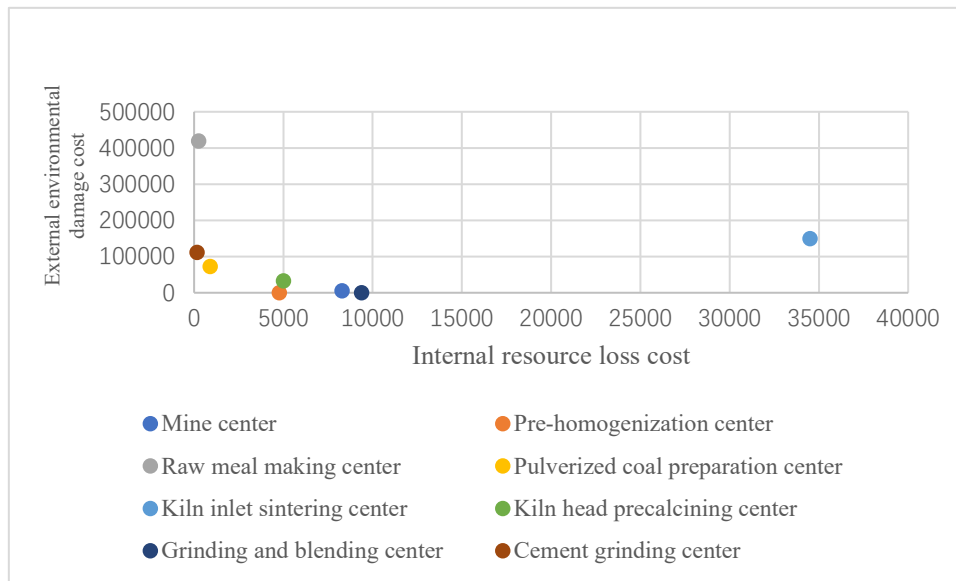
4.2.1 Ranking Quantity Centers for eco-efficiency improvement

Based on the results from the summary table and summary chart, the key quantity centers for LCA-MFCA transformation in Company A can be ranked as follows: the raw meal preparation center is the highest priority, followed by the kiln head precalcining center and the pulverized coal preparation center. The kiln inlet sintering center and the mine center have relatively high eco-efficiency values, indicating that they do not require immediate attention for circular economy improvement. The pre-homogenization center and the grinding and blending center generate minimal waste, meaning they not only utilize resources more efficiently but also cause minimal pollution to the external environment. Therefore, the improvement and optimization of circular

1 economy in these centers can be temporarily suspended.

2 Furthermore, when considering circular economy optimization, the impact of mandatory
3 indicators such as national standards and regulations should not be overlooked. The external
4 environmental damage in Company A primarily stems from the consumption of raw material
5 resources like limestone or iron powder, as well as industrial dust generated during the raw material
6 crushing process. Currently, there are no specific regulations in China regarding environmental
7 compensation for resource consumption. However, the cement industry must adhere to mandatory
8 standards for controlling industrial dust emissions. According to national environmental standards,
9 the dust emissions from the preheating decomposition center exceed 10% of the standard. Therefore,
10 when optimizing circular economy practices, compliance with this mandatory standard must be
11 considered in the decision-making process.

12 The negative product cost and external environmental damage cost of each property center of
13 Company A are analyzed in two dimensions, and the matrix diagram can be obtained as shown in
14 Figure 4:



15
16 Fig. 4 A Two-dimensional matrix diagram of negative products and waste damage in each quantity center of
17 company.

18 In the two-dimensional matrix of each material center of Company A, the abscissa is the loss
19 of internal resources and the ordinate is the damage of external environment. The farther away from
20 the origin, the higher the improvement potential. As can be seen from Figure 4, the Kiln head
21 precalcining center is the biggest loss of internal resources. Undoubtedly, this center is the key factor
22 of monetization loss of circular economy, and company A should take it as the focus of design when
23 implementing circular economy optimization. Among the external environmental damages, the Raw
24 meal making center and Kiln head precalcining center in Company A have great improvement

potential. Through accounting, diagnosis, evaluation, and analysis of resource flow in cement Company A, the priority order for improvement decision-making of each quantity center can be determined. The selection criteria include low eco-efficiency, high cost of internal resource loss, and significant external environmental damage. Accordingly, Kiln head precalcining center, with the greatest potential for improvement and the most noticeable effect, is identified as the primary focus for optimization. The secondary focus is on the Raw meal making center, characterized by low internal resource loss cost but high external environmental damage cost. Compliance with national environmental protection policies is crucial, as exceeding the critical points specified by the government could lead to penalties such as fines. Therefore, the external environmental damage caused by the secondary improvement points must be controlled within the environmental standards. Improvements in material centers with high external environmental damage values and low internal resource loss should be approached optimally, taking care not to breach environmental standards. Quantity centers with low internal resource loss and external environmental damage costs present limited potential for benefit improvement, making them a lower priority. However, continuous monitoring of these quantity centers is important.

4.2.2 Optimization scheme design

Consequently, it is proposed that Company A adopts the following optimization scheme:

(1) Reconstruction Scheme 1: Replacing the Electrostatic Precipitator with a Bag Dust Collector in the Kiln head precalcining center

Due to process inefficiencies, the electrostatic precipitator used in Cement Company A lacked proper water spraying in the humidifying tower, resulting in insufficient dust collection and exceeding the national standards for dust emissions. A bag filter is proposed as a replacement for the electrostatic precipitator due to its superiority in reducing industrial dust emissions. Unlike the electrostatic precipitator, the bag filter is less affected by factors such as particle size, concentration, and specific resistance. It delivers consistently stable dust removal efficiency of approximately 99.784% and emission concentrations below 30 mg/m, fully complying with the current GB4915-2013 standard. Additionally, the bag dust collector offers advantages such as high temperature resistance (180°C ~ 260°C), corrosion resistance, oil repellency, waterproofing, flame resistance, explosion prevention, and the ability to undergo maintenance without stopping operations. In contrast, the electrostatic precipitator requires downtime for maintenance (Martínez-Martínez et al., 2020).

While the replacement of the electrostatic precipitator with a bag dust collector may increase the initial installation cost, annual energy consumption, energy consumption for overcoming resistance, and maintenance costs, it can reduce input power. More importantly, the bag dust collector effectively decreases dust emissions, achieves compliance with mandatory national

environmental emission standards, and minimizes environmental pollution losses.

(2) Transformation Scheme 2: Substituting Limestone with Carbide Slag as Raw Material for Cement Enterprises

The environmental damage cost incurred by the Raw meal making center is a significant concern for the entire company and a crucial area for transformation. Through a thorough analysis of pollution sources, it is evident that limestone, the primary raw material used by Company A, releases substantial amounts of carbon dioxide, resulting in severe environmental pollution. To address this, Transformation Scheme 2 is proposed: utilizing calcium carbide slag as a replacement for limestone as the raw material in cement production.

Currently, the use of calcium carbide slag as a replacement for limestone has been successfully implemented in cement enterprises such as Yibin in Sichuan Province and Shihezi in Xinjiang. This substitution not only reduces carbon dioxide emissions from cement production but also conserves non-renewable limestone resources. Carbide slag, a chemical waste from chemical enterprises, contains sulfides and phosphides, posing environmental risks. Unfortunately, there is currently no effective treatment method for calcium carbide slag, resulting in its disposal in landfills, which wastes valuable land resources and can lead to secondary pollution. Thus, using carbide slag instead of limestone is technically feasible and contributes to resource conservation while reducing environmental damage(Martínez-Martínez et al., 2020).

(3) Reconstruction Scheme 3: Implementation of a Low-Temperature Waste Heat System in Cement Enterprises

Although Company A has adopted advanced new dry cement production technology and preheating decomposition technology in China, it has not effectively utilized the waste heat generated by the clinker cooler at the Kiln inlet sintering center and the Kiln head precalcining center, resulting in energy wastage. The low-temperature preheating technology in cement enterprises has matured, with many new cement enterprises successfully implementing it(Martínez-Martínez et al., 2023).

Implementing a waste heat recovery system that captures the waste gas below 350 degrees Celsius released by the Kiln inlet sintering center and the Kiln head precalcining center at Company A can significantly save energy and contribute to ecological protection.

4.3 Verification of Improved Options (Step 3)

To ascertain the effectiveness of the selected improvement schemes determined in Step 2, the LCA-MFCA method initially conducts hypothetical analysis on each scheme's independent adoption to simulate and verify their implementation effects. Subsequently, assuming the implementation of all the schemes, a "combination scheme" is established to simulate the combined

1 effect of the individual schemes. Additionally, this study includes a simple cost-benefit analysis.

2 **5 Results and Discussion**

3 **5.1 Results(1) Impact of Bag Filter in Replacement of Electrostatic Precipitator**

4 After analyzing the current situation of Cement Company A and collecting market data, the
5 replacement of the electrostatic precipitator with a bag filter has two significant effects:

6 Internal Resource Loss Impact: According to the current market quotation,the one-time
7 installation cost of the bag filter is estimated to be around 33 million CNY, with a service life of 16
8 years(LIU Luoqian et al., 2024). Calculated at an interest rate of 8%, the annualized cost amounts
9 to 3,728,200 CNY. The yearly costs for energy consumption during installation, overcoming
10 resistance, and maintenance amount to approximately 2.7 million CNY. By utilizing the bag dust
11 collector, it is estimated that 462.5 kW of electricity can be saved annually(LIU Luoqian et al., 2024),
12 equivalent to a value of 2.775 million CNY.

13 External Environmental Cost Impact: The implementation of the bag dust removal system
14 reduces the dust emission concentration to below 30 mg/m(LIU Luoqian et al., 2024), resulting in
15 only 0.09 kg of industrial dust emitted per ton of clinker produced by the Kiln head precalcining
16 center. Currently, Company A emits 0.165 kg of industrial dust per ton of clinker. Therefore, by
17 installing the bag filter in the Kiln head precalcining center, the industrial dust emission can be
18 reduced to 0.075 kg per ton of clinker. With an annual clinker output of 12.09 million tons from the
19 Kiln head precalcining center, it can be calculated that the installation of the bag filter will reduce
20 industrial dust emissions by 906,750 kilograms per year. Each kilogram of industrial dust has a
21 LIME value of 67.26 CNY. Therefore, the installation of the bag filter can reduce the external
22 environmental cost by $906,750 \times 67.26 = 60,988,000$ CNY.

23 The table 7 below presents the cost-benefit analysis before and after the improvement:

24 Table 7 Cost-benefit Analysis Table of Bag Filter Replacing Electrostatic Precipitator

project	New input cost of process (10 ⁴ CNY)	External damage cost (10 ⁴ CNY)
Before improvement	124453.98	149734
One-time investment	3300	
Annualized initial cost	372.82	
Annual operating cost	270.00	
Annual energy saving	277.50	
After improvement	124819.30	143635.20
Cost saving (or benefit) (10 ⁴ CNY)	-365.32	6098.80

25 The reconstruction scheme of replacing the electrostatic precipitator with a bag dust collector

1 in the Kiln head precalcining center incurs an additional investment of 3,653,200 CNY per year.
2 However, it results in a reduction of 60,988,800 CNY in the cost of external environmental damage.
3 Overall, the scheme is considered feasible.

4 ***(2) Impact of Replacing Limestone with Carbide Slag***

5 It has been verified that using 1 ton of carbide slag as a raw material for cement production can
6 save 1.28 tons of limestone and reduce carbon dioxide emissions by 0.56 tons(Liao Xueyan et al.,
7 2024). Company A typically employ limestone as the raw material, consuming 146,047.2 million
8 tons per year. Based on the ratio of using calcium carbide slag as a substitute for limestone, it is
9 determined that only 114,099.375 million tons of calcium carbide slag can replace the annual
10 limestone consumption of these enterprises, resulting in a reduction of 8,178,600 tons in carbon
11 dioxide emissions. Utilizing carbide slag not only conserves resources but also mitigates
12 environmental pollution. Nonetheless, the substitution of limestone with carbide slag necessitates
13 investment and the transformation of the current production line. In the case of dry cement
14 production enterprises, according to the current market quotation and legal service life, the initial
15 investment amounts to 220 million CNY, with a service life of 10 years. Employing carbide slag
16 instead of limestone can lead to savings of 44.75 million CNY in raw material costs.

17 By adopting carbide slag as a replacement for limestone in cement production, Cement
18 Company A can not only reduce annual carbon dioxide emissions by 8.1786 million tons but also
19 minimize the environmental damage caused by carbide slag. Calculations based on a LIME value
20 of 0.

21 Table 8 Cost-benefit analysis table of carbide slag replacing limestone before and after improvement

Internal resource cost		External damage cost	
project	Amount (10 ⁴ CNY)	project	Amount (10 ⁴ CNY)
Before improvement	58172.81	Before improvement	790764
Annualized initial cost	3278.65	Carbon dioxide emission reduction	85385
Material saving	4475	Recovery of carbide slag	43652
After improvement	56976.46	After improvement	661727
Cost saving (or benefit) (10 ⁴ CNY)	1196.35	Cost saving (or benefit) (10 ⁴ CNY)	129037

22 ***(3) Impact of Low-Temperature Waste Heat Recovery***

23 The low-temperature waste heat system will be installed in the existing new dry-process
24 cement production line of Company A. This installation requires a total initial investment of 31
25 million CNY and is expected to have a service life of 10 years, providing the enterprise with an

1 annual electricity output of 25.2 million kWh(YI Wenjie et al., 2022).

2 Internal Economic Benefits: The annual electricity generated by the low-temperature waste
3 heat power generation system multiplied by the difference between the electricity price per kilowatt-
4 hour and the electricity generation cost per kilowatt-hour results in a benefit of 12.6 million CNY.

5 External Environmental Benefits: The installation of the low-temperature waste heat system
6 on a 2500t/d cement production line in Cement Company A can reduce CO2 emissions by
7 approximately 20,000 tons annually(YI Wenjie et al., 2022). With a LIME value of 0.1044 CNY/kg
8 for each kilogram of CO2, this reduction in emissions contributes to a decrease in external
9 environmental damage of 2.088 million CNY each year.The waste heat boiler itself also aids in
10 reducing industrial dust. Additionally, a pre-dust removal device is installed before the waste heat
11 boiler, further reducing the industrial dust emissions from Cement Company A. The 2500t/d waste
12 heat boiler is capable of reducing 25.03 tons of industrial dust annually, while the pre-dust removal
13 device further reduces 5.72 tons each year. In total, these measures reduce dust emissions by 30.75
14 tons annually. With a LIME value of 67.26 CNY/kg for each kilogram of industrial dust, the
15 reduction in dust emissions contributes to a decrease in external environmental damage of
16 approximately 2,068,200 CNY.

17 Table 9 Cost-benefit analysis table before and after improvement of low-temperature waste heat

Internal resource cost		External damage cost	
project	Amount (10 ⁴ CNY)	project	Amount (10 ⁴ CNY)
Annualized initial cost	461.99	Carbon dioxide emission reduction	208.80
energy saving	1260	Dust emission reduction	168.35
Cost saving (or benefit) (10 ⁴ CNY)	798.01	Cost saving (or benefit) (10 ⁴ CNY)	377.15

18 ***(4) Analysis of the Effects of Combination Mechanism***

19 Based on the analysis conducted above, it is necessary to reallocate the internal resource cost
20 accounting and allocation for each process. By performing a cost-benefit analysis of the previous
21 transformation decision, the following results can be obtained: Replacing the original electrostatic
22 precipitator with a bag dust collector will increase the internal cost by 3,653,200 CNY per year.
23 However, it will reduce the external damage cost by 60,988,000 CNY. The quantity centers that
24 benefit from this change include the raw meal making center, pulverized coal preparation center,
25 kiln head precalcining center, and cement grinding center. Substituting limestone with carbide slag
26 can save an internal resource loss of 11,963,500 CNY and reduce the external damage cost by
27 1,290,370 CNY. This change benefits the raw meal making center, pulverized coal preparation
28 center, kiln head precalcining center, and kiln inlet sintering center. Implementing the low-
29 temperature waste heat power generation system can reduce the total cost of electric energy by
30 7,980,100 CNY per year and the external environmental damage by 3,771,500 CNY. This change

involves the mine center, pre-homogenization center, raw meal making center, pulverized coal preparation center, kiln head pre-decomposition center, and Kiln inlet sintering center.

After the redistribution in each quantity center, the cost benefit can be determined after the transformation. Due to the replacement of limestone with calcium carbide slag, the mine center can be eliminated. Materials are now inputted from the pre-homogenization center, resulting in zero input resources and external environmental damage cost for the mine center. The input resources for the pre-homogenization center increase by 492.54 million CNY, while the resource cost for the raw meal making center decreases by 4.2823 million CNY. The external environmental damage cost is reduced by 665.49 million CNY for the pre-homogenization center, 6.4565 million CNY for the pulverized coal preparation center, 131.65 million CNY for the Kiln head precalcining center, 275.77 million CNY for the Kiln inlet sintering center, and 2.5956 million CNY for the cement grinding center.

Based on this, we can construct an improved internal resource cost accounting table. Additionally, a comparative analysis of the external environmental damage cost before and after the improvement can be performed, enabling the calculation of eco-efficiency.

Table 10 Summary of Eco-efficiency Optimization of A Cement Enterprises

Project classification		Mine center	Pre-homogenization center	Raw meal making center	Pulverized coal preparation center	Kiln head precalcining center	Kiln inlet sintering center	Grinding and blending center	Cement grinding center	company
Invest resources	Before improvement	48743.13	17471.02	24565.38	46882.93	5925.92	21248.24	18773.82	35238.84	218849.3
	After improvement	0	66725.22	24137.15	46237.28	5560.58	20806.91	18773.82	34979.28	217220.2
	benefit	48743.13	-49254.2	428.23	645.65	365.34	441.33	0	259.56	1629.041
External damage	Before improvement	5174	0	419081	72631	149734	32383	0	111761	790764
	After improvement	0	0	352532	59466	122157	21407	0	99689.05	655251.1
	benefit	5174	0	66549	13165	27577	10976	0	12071.95	135513
eco-efficiency	Before improvement	9.4203	-	0.2162	0.6411	0.5264	2.9568	-	1.3395	0.8737
	After improvement	-	-	0.2582	0.7939	0.6482	4.4935	-	1.5043	1.0519

5.2 Discussion

From the case of Company A, it is evident that implementing the LCA-MFCA integration method can significantly enhance eco-efficiency, improve both economic and environmental benefits, and alleviate resource and environmental constraints. However, there are still some

challenges in this study:

1. **Balancing Environmental and Economic Goals:** When enterprises work toward circular economy improvements, there is often a conflict between environmental and economic objectives. Enhancing environmental benefits typically requires investments, which can impose additional economic costs, leaving enterprises with little incentive to prioritize environmental improvements. This is especially true in developing countries like China, where environmental benefits are often undervalued. As a result, businesses may struggle to spontaneously improve environmental outcomes and might even sacrifice them for economic gains. Coordinating these goals requires government intervention. In this research, external environmental damage was measured using Japan's LIME method, but further study is needed to find ways to internalize these environmental costs and encourage businesses to independently pursue circular economy improvements.
2. **Short-Term vs. Long-Term Goals:** Many businesses focus on short-term profits and survival, often overlooking long-term objectives such as the development of a circular economy. The benefits of the LCA-MFCA integration method may take time to manifest, which can deter businesses from making short-term investments in these areas. Promoting and fostering the concept of sustainable development is essential to overcoming this challenge. Additionally, establishing mandatory environmental standards can help shift long-term goals into short-term priorities by forcing companies to meet these benchmarks.
3. **Technical Implementation Challenges:** Implementing the LCA-MFCA method requires extensive environmental and economic data, which can be difficult to obtain. For example, when calculating LCA data, the cost of external environmental damage from waste emissions is needed. This study utilized Japan's LIME based on an endpoint model, but the coefficients used may not align perfectly with China's context, potentially affecting the accuracy of results. Additionally, obtaining accurate industrial chain-related data can be challenging, which further affects the reliability of the research findings.⁴ The application of the LCA-MFCA method across different industries presents several challenges, primarily due to variations in core parameters such as production processes and industry-specific resource consumption standards. Issues such as defining material centers, selecting appropriate cost allocation methods, and determining core process parameters can complicate the calculation of MFCA and LCA. These challenges are particularly pronounced in small and medium-sized enterprises (SMEs), where environmental data may be limited or lack sufficient granularity, further hindering the effective application of this method.

4.

Despite these limitations, the LCA-MFCA method remains a highly effective tool for optimizing the eco-efficiency of the circular economy. It provides a clear foundation for

visualizing eco-efficiency improvements and identifying areas that require further enhancement.

6 Conclusion and Future Prospects

This study proposes a comprehensive method to improve eco-efficiency by combining the advantages of LCA and MFCA. By using MFCA to measure resource costs in the production process and LCA to measure external environmental damage in the product life cycle, the aim is to enhance the ratio between the two, which aligns with the goal of circular economy development. Through analyzing the similarities and differences between LCA and MFCA, this study identifies a coupling mode and procedure for integrating the two methods. The unified LCA-MFCA mechanism is then proposed and implemented in a real case study of cement enterprise. The results from the case study demonstrate that the unified LCA-MFCA mechanism effectively improves eco-efficiency from 0.8737 to 1.0519. By identifying the limitations in eco-efficiency, various circular economy optimization schemes are proposed, including Bag Filter in Replacement of Electrostatic Precipitator, Replacing Limestone with Carbide Slag, Low-Temperature Waste Heat Recovery and Combination Mechanism. These schemes not only generate additional profits but also reduce the consumption of non-renewable resources and environmental waste discharge, thereby relieving the dual pressure of resources and the environment. Consequently, the eco-efficiency of each material center is significantly enhanced.

However, it should be noted that the research conclusions of this paper are partly based on simulated verification of actual cases, which may limit its persuasiveness. The most significant achievement lies in the reduction of external environmental damage costs. However, the data source for these costs relies on the LIME coefficient, which may not align with China's specific national conditions. It remains challenging to internalize the costs of external environmental damage into the economic benefits of enterprises. As a result, many enterprises lack the intrinsic motivation to actively promote this optimization process during implementation. Further research is needed to investigate how enterprises, as key economic actors, can actively drive this optimization process and how to effectively internalize the external environmental damage costs.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Study on eco-efficiency optimization based on LCA-MFCA integration method: a case study on the cement industry

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