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Research on the Performance Evaluation of Green Supply Chain of Papermaking Enterprises based on AHP

Yuxi Wu*

Business School, Shandong University of Technology, Zibo 255000, China

***Corresponding author:** Yuxi Wu, wuyuxi97@126.com

Abstract: In the context of increasingly stringent global environmental regulations, paper enterprises need to optimize supply chain management and improve green supply chain performance to achieve a balance between economic benefits and environmental sustainability. This paper builds a green supply chain performance evaluation system based on the analytic hierarchy process (AHP), selects three dimensions of economic performance, environmental performance, and social performance, and calculates the index weight through expert scoring and consistency tests. The results show that economic performance (0.56) is the dominant factor in enterprise decision-making, and the energy consumption reduction rate (0.45) and production cost reduction rate (0.30) are the core factors. The environmental performance (0.29) is followed by the carbon emission reduction rate (0.50), which indicates that enterprises have invested in energy conservation and emission reduction but still need to optimize; Social performance (0.15) has the lowest weight, and supply chain transparency and social responsibility implementation still need to be strengthened. The final performance score of 76.9 indicates that the enterprise has achieved some results in green supply chain management, but there is still room for improvement in green product promotion, carbon footprint optimization, social responsibility fulfillment, and other aspects. In this paper, short-term optimization strategies (energy saving, consumption reduction, recycling efficiency improvement) and long-term optimization strategies (intelligent green supply chain, carbon neutral supply chain construction) are proposed to provide decision support for the green transformation of paper enterprises.

Keywords: Paper enterprise; Green supply chain; Performance evaluation; Analytic hierarchy process (AHP); Carbon emission

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1. Introduction

1.1. Research background

In recent years, global environmental issues have become increasingly severe, and carbon neutrality, circular economy,

and sustainable supply chain management have become important expressions of enterprise competitiveness [1]. As a key industry in resource consumption and pollution emissions, the paper industry faces increasingly stringent environmental regulations and market pressure [2]. For example, the Chinese government has proposed a "dual carbon" goal (carbon peak, carbon neutrality), requiring high-energy industries to accelerate green transformation; EU REACH regulations and global supply chain ESG (Environmental, Social, Governance) requirements have also prompted paper companies to increase investment in green supply chain management [3].

The supply chain model of traditional paper enterprises takes cost and efficiency as the core, often ignoring environmental and social factors, resulting in resource waste, excessive carbon emissions, improper waste treatment, and other problems. With the strengthening of policy supervision and the enhancement of consumers' awareness of environmental protection, paper enterprises not only need to control production costs but also must pay attention to the green development of the supply chain to improve market competitiveness and promote sustainable development [4].

1.2. Necessity of green supply chain performance evaluation

Green supply chain management covers raw material procurement, production, logistics, recycling, and other links, and its performance not only affects the economic benefits of enterprises but also directly relates to environmental protection and social responsibility. Therefore, the construction of a scientific and reasonable green supply chain performance evaluation system is crucial for enterprises to optimize supply chain strategy and enhance green competitiveness [5].

At present, the research on green supply chain performance evaluation mainly focuses on the following aspects:

Qualitative research: Many scholars use case analysis or theoretical modeling to discuss the impact of GSCM on enterprises, but lack quantitative analysis to guide the actual decision-making of enterprises [6].

Evaluation of a single index: Some studies only focus on a single index (such as carbon emission and energy consumption reduction), and fail to comprehensively measure multiple dimensions such as economy, environment, and society [7].

Imperfect evaluation system: The existing research index system is often not comprehensive enough and lacks consideration of supply chain transparency, social responsibility, and other factors.

To make up for the above shortcomings, this paper adopted the analytic hierarchy process (AHP) to build a green supply chain performance evaluation system, evaluated the actual performance of paper enterprises in green supply chain management by quantifying the weights of different performance indicators, and proposed targeted optimization strategies [8].

1.3. Research objectives and methods

1.3.1. Research purpose

Construct a green supply chain performance evaluation system for paper enterprises, comprehensively considering the three dimensions of economy, environment, and society to ensure scientific and comprehensive evaluation.

Use AHP to calculate the weight of indicators, quantitatively analyze the impact of various performance factors on the green supply chain, and provide a quantifiable decision-making basis.

Verify the feasibility of the evaluation system through case analysis, and put forward optimization suggestions based on the calculation results to help enterprises improve the management level of the green supply chain.

1.3.2. Research methods

This paper adopts the analytic hierarchy process, the specific steps are as follows.

Construction of evaluation index system: Based on literature research and expert interviews, a green supply chain performance evaluation index system covering three dimensions: economy, environment, and society is established.

Establish a judgment matrix: Invite industry experts to score the importance of each indicator, and build a pair of comparison matrices.

Calculation weight and consistency test: The AHP method is used to calculate index weight to ensure that the judgment matrix meets the consistency requirements.

Case analysis: Select a paper-making enterprise as the research object, apply AHP to calculate the performance score, and analyze the advantages and disadvantages of the enterprise in green supply chain management.

1.4. Research contribution and innovation

The contribution of this research is mainly reflected in the following three aspects.

Build a systematic performance evaluation system: integrate the three dimensions of economy, environment, and society to make up for the one-sidedness of the traditional performance evaluation system.

AHP is adopted for quantitative analysis: the weight of performance indicators is scientifically calculated through expert scoring and consistency tests to improve the objectivity and operability of evaluation.

Put forward optimization strategy based on case analysis: Based on actual data analysis, provide feasible green supply chain optimization path for papermaking enterprises and improve practical guidance value.

2. Construction of green supply chain performance evaluation index system

2.1. Principles of green supply chain performance evaluation system construction

To ensure the scientificity, rationality, and operability of the green supply chain performance evaluation system, this study follows the following principles when constructing the index system [9].

Comprehensive principle: The index system should cover the three dimensions of economy, environment, and society to comprehensively measure the actual performance of enterprise green supply chain management.

Scientific principle: The selected indicators should be based on supply chain management theory, green development policy, and industry standards, and meet the requirements of the AHP analysis method.

Quantification principle: Quantitative indicators (such as carbon emission reduction rate and energy consumption reduction rate) should be adopted as far as possible. For indicators that are difficult to quantify (such as supply chain transparency), an expert scoring method can be adopted.

The principle of comparability: The selection of indicators should consider the general applicability of the industry, to conduct a comparative analysis between different enterprises.

Operability principle: The calculation method of indicators should be clear and clear, which is convenient for enterprises to collect and apply data in actual management.

2.2. Construction of evaluation system

Based on relevant literature, policies and regulations, and interviews with experts in the paper industry, this study established a green supply chain performance evaluation system consisting of 3 first-level indicators and 9 second-level indicators, as shown in the following **Table 1**.

2.3. Weight setting of performance indicators

In this study, AHP is used to calculate the weight of each index. Through the expert interview, the pair comparison

matrix is constructed, the consistency test is carried out, and the weight distribution is finally obtained as shown in **Table 2**.

Table 1. Construction of evaluation system

Primary indicator	Secondary indicator	Description	Index type
Economic performance (C1)	Production cost reduction rate (C11)	Proportion of cost reduction resulting from green supply chain measures	quantify
	Energy consumption decline rate (C12)	The proportion of energy consumption reduction per unit product by optimizing the supply chain	quantify
	Green product sales growth rate (C13)	Growth in sales of green products	quantify
Environmental performance (C2)	Carbon emission reduction rate (C21)	The contribution of green supply chain measures to carbon emission reduction	quantify
	Waste recovery rate (C22)	The proportion of waste recovered and reused within the supply chain system	quantify
	Supply chain environmental certification rate (C23)	The proportion of supply chain enterprises with environmental certification	quantify
Social performance (C3)	Supply chain transparency (C31)	Supply chain information disclosure degree	Qualitative (expert rating)
	Employee health and safety index (C32)	The impact of supply chain improvement on employee working environment and occupational safety	Qualitative (expert rating)
	Social responsibility performance index (C33)	The impact of supply chain optimization on social responsibility	Qualitative (expert rating)

Table 2. Weight setting of performance indicators

Performance dimension	Weight	Secondary index	Weight
Economic performance (C1)	0.56	Production cost reduction rate (C11)	0.3
		Energy consumption decline rate (C12)	0.45
		Green product sales growth rate (C13)	0.25
Environmental performance (C2)	0.29	Carbon emission reduction rate (C21)	0.5
		Waste recovery rate (C22)	0.35
		Supply chain environmental certification rate (C23)	0.15
Social performance (C3)	0.15	Supply chain transparency (C31)	0.4
		Employee health and safety index (C32)	0.35
		Social responsibility performance index (C33)	0.25

As can be seen from the above table, the economic performance dimension has the highest weight (0.56), indicating that papermaking enterprises still take cost control and energy efficiency optimization as the core goals in green supply chain management. The second is environmental performance (0.29), in which the highest weight of carbon emission reduction rate (0.50), indicates that enterprises pay more attention to carbon footprint management in the green supply chain. The weight of social performance (0.15) is the lowest, reflecting that the investment of paper enterprises in social responsibility, employee health, and supply chain transparency still needs to be strengthened.

2.4. Calculation method of green supply chain performance

To calculate the green supply chain performance score of enterprises, the following calculation formula is adopted in this study:

$$GSP = W1 \times S_{\text{Economic}} + W2 \times S_{\text{Environmental}} + W3 \times S_{\text{Socialc}}$$

Where, W1, W2, and W3 are the weights of economic, environmental, and social performance respectively, while $S_{Economy}$, $S_{Environmental}$, and S_{Social} are the performance scores of each dimension.

The performance scores of paper enterprises are as follows.

Economic performance score: 85

Environmental performance score: 70

Social performance score: 60

GSP=0.56×85+0.29×70+0.15×60=47.6+20.3+9=76.9

According to the calculation results, the enterprise's green supply chain performance score is 76.9, indicating that it has achieved certain results in green supply chain management, but there is still room for optimization.

3. Evaluation process of AHP

3.1. Overview of analytic hierarchy process (AHP)

The analytic hierarchy process (AHP) is a multi-criteria decision-making method proposed by Saaty in the 1970s, which is suitable for weight calculation and priority ranking of complex decision problems. AHP makes decision-making more scientific and reasonable by constructing a hierarchical structure model, combining expert judgment, pair comparison, and consistency tests [10].

In this study, the AHP method is used to calculate the weight of each index of the green supply chain performance evaluation system to ensure a scientific and practical evaluation system.

3.2. AHP evaluation process

The AHP evaluation process usually consists of the following five steps: Construct a hierarchical structure model; Construct a pair comparison matrix; Calculate the weight vector; Consistency check; Calculate green supply chain performance.

3.3. Detailed steps of the evaluation process

3.3.1. Step 1: Build a hierarchical model

The core of the analytic hierarchy process is hierarchical structure modeling, which usually includes a target layer, criterion layer, and index layer. The AHP model of this study is shown in the figure below **Figure 1**.

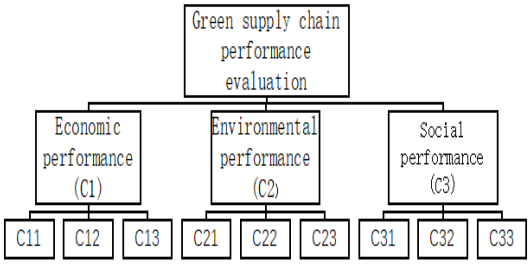

Figure 1. Hierarchical model

Target layer (first layer): Green supply chain performance

Criterion layer (second layer): Economic performance, environmental performance, social performance

Index layer (third layer): 9 specific indicators, such as energy consumption reduction rate, carbon emission reduction rate, supply chain transparency, and so on.

3.3.2. Step 2: Build a pair comparison matrix

A pairwise comparison matrix is used to reflect the important relationship between indicators. Experts use a 9-level scale (**Table 3**) to determine the importance of each indicator.

Table 3. AHP 9 scale method

Scoring value	Implication
1	Both factors are equally important
3	One factor is slightly more important than another
5	One factor is obviously more important than another
7	One factor is strongly more important than another
9	One factor is extremely more important than another
2, 4, 6, 8	An intermediate value between the above judgments

3.3.3. Step 3: Calculate the weight vector

For pairwise comparison matrices, the steps for weight calculation are as follows.

Normalized matrix: Calculate the normalized value of each column (each element divided by the sum of the columns in which it is located), and then average to get the weight.

Eigenvector method to calculate the weight: Calculate the maximum eigenvalue of the matrix λmax and its corresponding eigenvector, and normalize the eigenvector to obtain the final weight of each index.

After calculation, the following is obtained:

$$W = (0.56,0.29,0.15)$$

Economic performance weight: 0.56

Environmental performance weight: 0.29

Social performance weight: 0.15

Step 4: Consistency check

The AHP method requires a consistency check to ensure the consistency of expert scores and avoid logical conflicts. Common testing methods include calculating the consistency ratio (CR value):

$$CI = \frac{\lambda max\ - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

Among them:

λmax: Maximum eigenvalue

n is the order of the matrix

RI is the random consistency index (**Table 4**)

Table 4. Random consistency index (RI)

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

4. Result analysis

In this study, AHP was used to quantitatively evaluate the green supply chain performance of a paper enterprise. By constructing the judgment matrix, calculating the weight, and combining it with the actual data of the enterprise, the influence weight of each index on the overall performance is obtained. The calculation results are as follows:

4.1. Weight calculation results

According to AHP calculation, the weight distribution of each dimension is as follows:

Performance dimension weight

Economic performance (C1) 0.56

Environmental performance (C2) 0.29

Social performance (C3) 0.15

In addition, the weights of each sub-indicator are calculated in **Table 5**.

Table 5. The weights of each sub-indicator

Performance dimension	weight	Secondary index	weight
Economic performance (C1)	0.56	Production cost reduction rate (C11)	0.3
		Energy consumption decline rate (C12)	0.45
		Green product sales growth rate (C13)	0.25
Environmental performance (C2)	0.29	Carbon emission reduction rate (C21)	0.5
		Waste recovery rate (C22)	0.35
		Supply chain environmental certification rate (C23)	0.15
Social performance (C3)	0.15	Supply chain transparency (C31)	0.4
		Employee health and safety index (C32)	0.35
		Social responsibility Performance Index (C33)	0.25

4.2. Key Findings

Economic performance has the highest weight (0.56), which is the focus of enterprises. The weight of economic performance reached 0.56, much higher than environmental and social performance, indicating that enterprises still take economic benefits as the core goal when promoting green supply chain management.

The weight of energy consumption reduction rate (C12, 0.45) is the highest, indicating that enterprises are most concerned about reducing energy consumption when optimizing the supply chain, which may be due to the high energy

cost of paper enterprises, energy saving, and energy consumption reduction can directly improve corporate profits. The production cost reduction rate (C11, 0.30) is second, indicating that enterprises want to reduce overall operating costs through a green supply chain, such as optimizing procurement, reducing raw material waste, and improving production efficiency. The sales growth rate of green products (C13, 0.25) is relatively low, indicating that the promotion of green products by enterprises may still need to be strengthened, and the market demand has not been fully stimulated. Enterprises should further optimize the supply chain energy structure, such as the use of energy-saving equipment, green energy supply chain, and improve energy efficiency. Reduce the production cost of green products and improve market competitiveness through scale effect.

The weight of environmental performance is medium (0.29), and carbon emission control is the key. The weight of environmental performance is 0.29, reflecting that enterprises have attached importance to environmental factors in supply chain management, but there is still a certain gap compared with economic performance. The emission reduction rate (C21, 0.50) has the highest weight, indicating that the environmental issue that enterprises are most concerned about in green supply chain optimization is reducing carbon footprint, which may be related to the government's "two-carbon" policy and international environmental regulations. The waste recycling rate (C22, 0.35) followed, indicating that enterprises have made progress in solid waste management and resource recycling, but still need to strengthen. The lowest weight of the supply chain environmental certification rate (C23, 0.15) indicates that the enterprise has less investment in green certification, which may be due to the high cost of environmental certification or the imperfect certification system. Enterprises should adopt low-carbon raw materials, optimize production processes, increase the proportion of clean energy use, and further reduce carbon emissions. Improve waste management capabilities, such as the establishment of closed-loop recycling systems to improve the reuse of industrial by-products. Apply for international environmental certification such as ISO 14001 to improve the credibility of the enterprise's green supply chain.

Social performance has the lowest weight (0.15), and transparency and employee health and safety need to be improved. The weight of social performance is the lowest, only 0.15, reflecting that enterprises still pay little attention to social responsibility when promoting green supply chain management. Supply chain transparency (C31, 0.40) has the highest weight, indicating that the market has increased requirements for supply chain information disclosure, such as green product certification, supply chain carbon emission information, etc., and enterprises need to further enhance transparency. The employee health and safety index (C32, 0.35) is high, indicating that the enterprise has a certain investment in occupational health and safety management, but it still needs to improve the papermaking environment. The social responsibility fulfillment index (C33, 0.25) is the lowest, indicating that enterprises invest less in social welfare, community environmental protection, and other aspects, which may affect brand image.

Enterprises should promote the construction of supply chain traceability, such as the use of blockchain, big data, and other technologies, to improve the transparency of green supply chains. Strengthen occupational health management, such as improving production protection measures, providing health training, and improving the papermaking environment. Enhance the image of social responsibility, such as participating in environmental protection public welfare projects, strengthening community cooperation, and enhancing the influence of green brands of enterprises.

4.3. Conclusion summary

Economic performance is the most important factor for enterprises (weight 0.56), but energy conservation and consumption reduction still need to be continuously optimized, and at the same time, the promotion of green products

should be strengthened.

Environmental performance comes in second (0.29), and carbon emission management is particularly important. Enterprises should strengthen carbon footprint control, improve waste recovery rates, and increase environmental certification.

The weight of social performance is the lowest (0.15), and it is necessary to improve the transparency of the supply chain, employee health and safety management, and social responsibility fulfillment.

5. Conclusion and optimization suggestions

5.1. Research conclusions

Based on the analytic hierarchy process (AHP), the paper constructs a green supply chain performance evaluation system for paper enterprises and quantitatively evaluates the green supply chain performance of a paper enterprise through case analysis. The main conclusions of the study are as follows.

5.1.1. Green supply chain performance can be evaluated quantitatively

Through the AHP method, the green supply chain performance is divided into three key dimensions: economic performance, environmental performance, and social performance, and further refined into nine specific indicators to make performance evaluation more scientific, systematic, and operable.

5.1.2. Economic performance has the highest weight, while social performance is relatively low

The results show that the weight of economic performance (0.56) is the highest in green supply chain management, indicating that papermaking enterprises are still highly concerned about economic benefits in supply chain management, such as production cost control, energy efficiency management, and green product sales.

The environmental performance (0.29) is at the medium level, indicating that enterprises have paid some attention to environmentally sustainable development, but there is still much room for improvement, such as carbon emission control, waste recycling, and so on.

Social performance (0.15) has the lowest weight, reflecting that enterprises pay less attention to supply chain transparency, employee health, and safety, social responsibility fulfillment, etc., which needs to be further optimized in the future.

Through AHP calculation, the green supply chain performance score of a paper enterprise is 76.9, indicating that it has achieved certain results in green supply chain management, but there is still room for optimization. In particular, the low social performance indicates that enterprises need to be strengthened in fulfilling their social responsibilities and improving the transparency of the supply chain.

5.2. Suggestions for green supply chain optimization

Based on the research conclusions, this paper proposes the following short-term (1–2 years) and long-term (3–5 years) optimization strategies to help paper enterprises further improve green supply chain performance.

5.3. Short-term optimization strategy (1–2 years)

5.3.1. Improve energy efficiency and optimize economic performance

Optimize the production process and adopt advanced energy-saving equipment to reduce the energy consumption per unit product. Promote digital management, use smart manufacturing and big data analytics to improve the precision of

production planning, and reduce resource waste. Optimize supply chain logistics, reduce energy consumption during transportation, and improve overall supply chain efficiency.

5.3.2. Strengthen environmental management and reduce pollution emissions

Reduce carbon emissions: increase the proportion of new energy utilization, such as the use of clean energy, and improve the utilization rate of waste heat recovery. Improve waste recovery rate: Optimize solid waste and wastewater treatment technology, promote waste reuse, and improve green production levels. Supply chain green certification: Suppliers are encouraged to pass environmental certifications such as ISO 14001, build a green procurement system, and improve the environmental standards of the overall supply chain.

5.3.3. Enhance social responsibility awareness and supply chain transparency

Optimize the information-sharing mechanism of the supply chain, strengthen the data transparency management of all links of the supply chain, and enhance the credibility of enterprises. Improve employee health and safety management, strictly implement the occupational health and safety management system, and improve the safety of the working environment. Strengthen supplier supervision, establish a green supply chain cooperation mechanism, and require suppliers to fulfill environmental protection and social responsibilities.

5.4. Long-term optimization strategy (3–5 years)

5.4.1. Build an intelligent green supply chain to improve economic and environmental performance

Promote smart manufacturing: Use the Internet of Things, artificial intelligence, blockchain, and other technologies to achieve intelligent supply chain management and improve resource utilization. Building a low-carbon supply chain: Phasing out high-energy equipment, introducing renewable energy, and improving the low-carbon level of the overall industrial chain. Optimize the green supply chain finance mechanism: promote the "green finance" policy, cooperate with banks to provide low-interest loans, and encourage upstream and downstream enterprises in the supply chain to invest in environmental protection projects.

5.4.2. Improve corporate social responsibility strategy and build sustainable supply chain ecology

Build green sourcing alliances: Build partnerships with green suppliers and environmental agencies to improve supply chain sustainability.

Enhance corporate Social Responsibility brand influence: Regularly publish corporate social responsibility (CSR) reports to increase consumer awareness of green supply chain management. Promote fair trade and sustainable development of the supply chain: Encourage green supply chain enterprises to participate in international environmental certification, such as the SA8000 social responsibility standard, ISO 26000 social responsibility guide, etc., to enhance global competitiveness.

Disclosure statement

The author declares no conflict of interest.

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