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OPTIMIZATION OF MANUFACTURING STRUCTURE CONSIDERING ECOLOGICAL CONSTRAINTS

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Abstract. *We show that ecological goals should be taken into account in the optimization of industrial structure, and the impact of the change of ecological efficiency in sub sectors on the optimization of industrial structure is considered as well. Specially, it is meaningful to analyze the total effect of structural optimization considering that the ecologicalization of manufacturing industry has become more and more important. Therefore, two models are constructed: one is the optimization of manufacturing structure keeping the ecological efficiency of sub sectors unchanged, and the other is the optimization under the assumption that the ecological efficiency of sub sectors will increase over time. Taking Anhui province of central China as an example, we obtain the empirical results of the optimization through the program planning, and explore the effects and their differences of structural optimization ways for the two hypothetical scenarios.*

Keywords: Industrial structure, Optimization model, Ecological efficiency, Ecologicalization

1. **Introduction.** As an important 'resource converter' and 'pollution controller', the adjustment of industrial structure plays a key role in ecological protection [1]. Existing literature has put forward many optimization models for structure considering ecological constraints [2]. However, most of these models ignored the changes in the ecological efficiency of sub sectors within the industry.

The effect resulted from the ecologicalization and upgrading of industrial structure is called 'the total ecological effect of industrial structure' (abbreviated as TEEIS, the same below). This effect can be decomposed into two components: the structural effect produced by structural change, and the ecological effect caused by the increasing ecological efficiency of sub sectors. Currently, there is less literature focusing on the latter.

Meanwhile, both the structural change and ecological efficiency are influenced by many factors [3-6]. Consequently, it is necessary to study the optimization of industrial structure based on the hypotheses of unchanged and variable ecological efficiency for sub sectors. Nevertheless, this will bring about three challenges.

The first is the construction of the optimization model. Particularly, the setting of objective function is very important, which should reflect the comprehensive benefits of environment and economy.

The second is the prediction of parameters. In order to scientifically evaluate the total effect of structural optimization in the target year, the crucial step is to forecast the evolution of parameters, including environmental efficiency, ecological efficiency for sub sectors, structural thresholds, etc. This principally depends on estimates of future environmental regulations and industrial development patterns.

The third is the stress on structural optimization for manufacturing industry, because the high emissions and pollutions industries mainly come from this industry. It is substantial for industrial upgrading to present a reasonable classification of manufacturing sectors and to analyze possible changes in its composition.

Anhui province is located in the central part of China. In recent years, the local manufacturing industry has been growing rapidly, but the total amount of value-added is relatively low; meanwhile the structure is unsatisfactory. Based on the data from Anhui manufacturing industry and ecological environment during 2000-2015, we firstly assume that the ecological efficiency for sub sectors within manufacturing industry remains unchanged, and discuss the total effect of the structural optimization for the year 2025; and then, we explore the change in the total effect based on the predicted variations of ecological efficiency for sub sectors.

The current study is expected to make two innovations. First of all, we solve the problem of structural optimization in manufacturing industry considering ecological goals. More importantly, the impact of the change in sub sectors' ecological efficiency on the structural optimization is presented. To the best of our knowledge, these contributions are groundbreaking.

2. **Methodologies.**

2.1. **The total ecological efficiency of industrial structure.**

The total ecological efficiency of industrial structure E (also known as TEEIS) can be divided into two components: energy efficiency of industrial structure E_{ene}, and environmental efficiency of industrial structure E_{env}, which can be expressed as follows.

$$E = [E_{ene} \times E_{env}]^{(1/2)} \tag{1}$$

$$E_{ene} = \sum_{i=1}^{n} \varphi_i \times \frac{Y_i}{C_i} \tag{2}$$

$$E_{env} = \left[\prod_{j=w,g,s} \left(\sum_{k=1}^{2} \lambda_k \times \frac{Y_k}{P_{j,k}} \right) \right]^{(1/3)} \tag{3}$$

where $i = 1, 2, \ldots, n$ indicates different sub sectors of manufacturing industry. As shown in Table 1, this industry is divided into three sub sectors, i.e., $i = 1, 2, 3$, representing textile manufacturing sector (also known as labor-intensive sector), resource processing sector (also known as energy-intensive sector), and machinery and electronics manufacturing sector (also known as technology-intensive sector), respectively. Y_i, φ_i and C_i denote the value-added, the proportion of value-added, and the energy consumption for sector i respectively. φ_i meets the condition that $\sum_{i=1}^{3} \varphi_i = 1$. The subscript $j = w, g, s$ stands for the amount of industrial waste water, waste gas and solid waste, and $k = 1, 2$ delegates industrial and non-industrial sectors. Y_k is the value-added for sector k, while $P_{j,k}$ is the emissions of pollutant j by sector k. λ_k is the proportion of value-added for sector k to the manufacturing industry.

Focusing on industrial pollution, we suppose $k = 1$. Formula (3) can be simplified as

$$E_{env} = \left[\prod_{j=w,g,s} \frac{Y}{P_j} \right]^{(1/3)} \tag{4}$$

where Y is industrial value-added; P_j is the emissions of pollutant j by industrial sector. As can be seen, the environmental efficiency of three sub sectors is the same. For simplicity, suppose $E_{env} = A$.

Table 1. The division of the manufacturing sector

Industry	Category	Sub sector
Manufacturing	Textile manufacturing	Agricultural food processing industry Food industry Wine, beverage and refined tea industry Tobacco products industry Textile industry Textile and dress industry Leather fur feather and its products and footwear industry Wood processing, bamboo and rattan, and brown grass products industry Furniture industry Paper and its products industry Printing and recording media reproduction industry Activities of sports and entertainment supplies manufacturing industry
	Resource processing	Petroleum processing, coking and nuclear fuel processing industry Chemical raw materials and chemical products manufacturing industry Pharmaceutical manufacturing industry Chemical fiber manufacturing industry Rubber and plastic products industry Non-metallic mineral products industry Ferrous metal smelting and rolling processing industry Non-ferrous metal smelting and rolling processing industry Metal products industry
	Machinery and electronic manufacturing	General equipment manufacturing industry Special equipment manufacturing industry Automobile manufacturing industry Rail, vessel, aerospace and other transport equipment manufacturing industry Electrical machinery and equipment manufacturing industry Computer communications and other electronic equipment manufacturing industry Instruments manufacturing industry Other manufacturing industry Comprehensive utilization of waste resources industry Metal products, machinery and equipment repair industry

Further, the ecological efficiency of sub sectors E_i $(i = 1, 2, 3)$, can be calculated according to Formulae (1) to (4) as

$$E_i = \left[A \times \frac{Y_i}{C_i}\right]^{(1/2)} \tag{5}$$

Let E^0, E^t denote the TEEIS for year 2015 and year 2025 respectively.

Noting that the TEEIS in 2015 may also be expressed as follows

$$\begin{aligned} E^0 &= \left[A \times \frac{Y_m}{C_1 + C_2 + C_3}\right]^{1/2} = \left[A \times \frac{Y_m}{\frac{C_1}{Y_1}Y_1 + \frac{C_2}{Y_2}Y_2 + \frac{C_3}{Y_3}Y_3}\right]^{1/2} \\ &= \left[\frac{1}{\frac{1}{A}\frac{C_1}{Y_1}\frac{Y_1}{Y_m} + \frac{1}{A}\frac{C_2}{Y_2}\frac{Y_2}{Y_m} + \frac{1}{A}\frac{C_3}{Y_3}\frac{Y_3}{Y_m}}\right]^{1/2} = \left[1 \bigg/ \left(\frac{\varphi_1^0}{e_1^0} + \frac{\varphi_2^0}{e_2^0} + \frac{\varphi_3^0}{e_3^0}\right)\right]^{1/2} \end{aligned} \tag{6}$$

where Y_m is the value-added of manufacturing industry, and e_i^0 $(i = 1, 2, 3)$ is the ecological efficiency of sub sectors for 2015.

Similarly, we can obtain the TEEIS in 2025 as

$$E^t = \left[1 \bigg/ \left(\frac{\varphi_1^t}{e_1^t} + \frac{\varphi_2^t}{e_2^t} + \frac{\varphi_3^t}{e_3^t}\right)\right]^{1/2} \tag{7}$$

where e_i^t $(i = 1, 2, 3)$ is the ecological efficiency of sub sectors in 2025.

2.2. **The optimization model of manufacturing structure.** The change rate δ of TEEIS from 2015 to 2025 can be described as

$$\delta = \frac{E^t - E^0}{E^0} = \frac{E^t}{E^0} - 1 \tag{8}$$

As the ecological efficiency is the reciprocal of ecological intensity, Formula (8) can be transformed into

$$\begin{aligned} \mu &= \frac{1}{E^t} \bigg/ \frac{1}{E^0} - 1 = E^0 \left(\frac{\varphi_1^t}{e_1^t} + \frac{\varphi_2^t}{e_2^t} + \frac{\varphi_3^t}{e_3^t}\right)^{1/2} - 1 \\ &= E^0 \left[\left(\frac{1}{e_2^t} - \frac{1}{e_1^t}\right)\varphi_2^t + \left(\frac{1}{e_3^t} - \frac{1}{e_1^t}\right)\varphi_3^t + \frac{1}{e_1^t}\right]^{1/2} - 1 \end{aligned} \tag{9}$$

The objective function is to determine the manufacturing structure for 2025 φ_i^t, which can make μ minimum and δ maximum simultaneously. In this case, the objective function is as

$$\text{Min } \mu = E^0 \left[\left(\frac{1}{e_2^t} - \frac{1}{e_1^t}\right)\varphi_2^t + \left(\frac{1}{e_3^t} - \frac{1}{e_1^t}\right)\varphi_3^t + \frac{1}{e_1^t}\right]^{1/2} - 1 \tag{10}$$

Now, there are two possible scenarios as follows.

(1) The ecological efficiency of sub sectors for target year e_i^t has the following relationship: $e_3^t > e_2^t > e_1^t$. It can be inferred that $\frac{1}{e_2^t} - \frac{1}{e_1^t} < 0$, and $\frac{1}{e_3^t} - \frac{1}{e_1^t} < 0$. In order to minimize μ, φ_2^t and φ_3^t should be as large as possible. However, the two parameters are constrained by their upper thresholds $\varphi_2^{\max}$ and $\varphi_3^{\max}$ respectively, so

$$\varphi_2^t \le \varphi_2^{\max} \tag{11}$$

$$\varphi_3^t \le \varphi_3^{\max} \tag{12}$$

Meanwhile, the proportion for the first sub sector is also restricted to its upper and lower bounds $\varphi_1^{\max}$ and $\varphi_1^{\min}$. By combining with the relationship $\sum_{i=1}^{3}\varphi_i = 1$, we obtain

$$\varphi_2^t + \varphi_3^t \leq 1 - \varphi_1^{\min} \tag{13}$$

$$\varphi_2^t + \varphi_3^t \geq 1 - \varphi_1^{\max} \tag{14}$$

Then the optimization problem of manufacturing structure can be presented as

$$\begin{aligned} &\text{Min } \mu = E^0\left[\left(\frac{1}{e_2^t} - \frac{1}{e_1^t}\right)\varphi_2^t + \left(\frac{1}{e_3^t} - \frac{1}{e_1^t}\right)\varphi_3^t + \frac{1}{e_1^t}\right]^{1/2} - 1 \\ &\text{s.t. } \varphi_2^t \leq \varphi_2^{\max} \\ &\qquad \varphi_3^t \leq \varphi_3^{\max} \\ &\qquad \varphi_2^t + \varphi_3^t \leq 1 - \varphi_1^{\min} \\ &\qquad \varphi_2^t + \varphi_3^t \geq 1 - \varphi_1^{\max} \end{aligned} \tag{15}$$

(2) The ecological efficiency of sub sectors for target year e_i^t has the following relationship: $e_3^t > e_1^t > e_2^t$. Hence, $\frac{1}{e_2^t} - \frac{1}{e_1^t} > 0$ and $\frac{1}{e_3^t} - \frac{1}{e_1^t} < 0$. In order to minimize μ, φ_2^t should be as small and φ_3^t as large as possible. Similarly, φ_2^t should not be less than its lower limit $\varphi_2^{\min}$.

Then the optimization problem of manufacturing structure can be described as

$$\begin{aligned} &\text{Min } \mu = E^0\left[\left(\frac{1}{e_2^t} - \frac{1}{e_1^t}\right)\varphi_2^t + \left(\frac{1}{e_3^t} - \frac{1}{e_1^t}\right)\varphi_3^t + \frac{1}{e_1^t}\right]^{1/2} - 1 \\ &\text{s.t. } \varphi_2^t \geq \varphi_2^{\max} \\ &\qquad \varphi_3^t \leq \varphi_3^{\max} \\ &\qquad \varphi_2^t + \varphi_3^t \leq 1 - \varphi_1^{\min} \\ &\qquad \varphi_2^t + \varphi_3^t \geq 1 - \varphi_1^{\max} \end{aligned} \tag{16}$$

3. **Data.**

The data on value-added of sub sectors, consumption of main energies, and industrial waste emissions are from Statistical Yearbook of Anhui during 2006-2015. Among them, the value-added was converted to 2005 constant price. Using the above data, we can get the proportion of value-added and energy efficiency of sub sectors, and then estimate the environmental efficiency by combining Formula (4).

In order to determine the reasonable thresholds for sub sectors' proportions, the manufacturing structure for years 2016-2025 is predicted by regression analysis based on the historical data of manufacturing structure for years 2006-2015 (see Figure 1).

As can be seen from Figure 1, the proportion of the resource processing and the machinery and electronics manufacturing sectors varies in exponent and in power function over time, and the fitting degree R^2 is 0.95 and 0.90, respectively. The proportion of the textile manufacturing sector equals the difference between 1 and the sum of the other two sub sectors' proportions. The prediction of manufacturing structure for 2016-2025 is given in Table 2.

Table 2. The predicted proportion of value-added for sub sectors during 2016-2025

Sub sectors	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
textile manufacturing	0.271	0.275	0.280	0.285	0.289	0.294	0.298	0.302	0.307	0.312
resource processing	0.345	0.338	0.331	0.324	0.317	0.310	0.304	0.298	0.291	0.285
machinery and electronics manufacturing	0.384	0.387	0.389	0.391	0.394	0.396	0.398	0.400	0.402	0.403

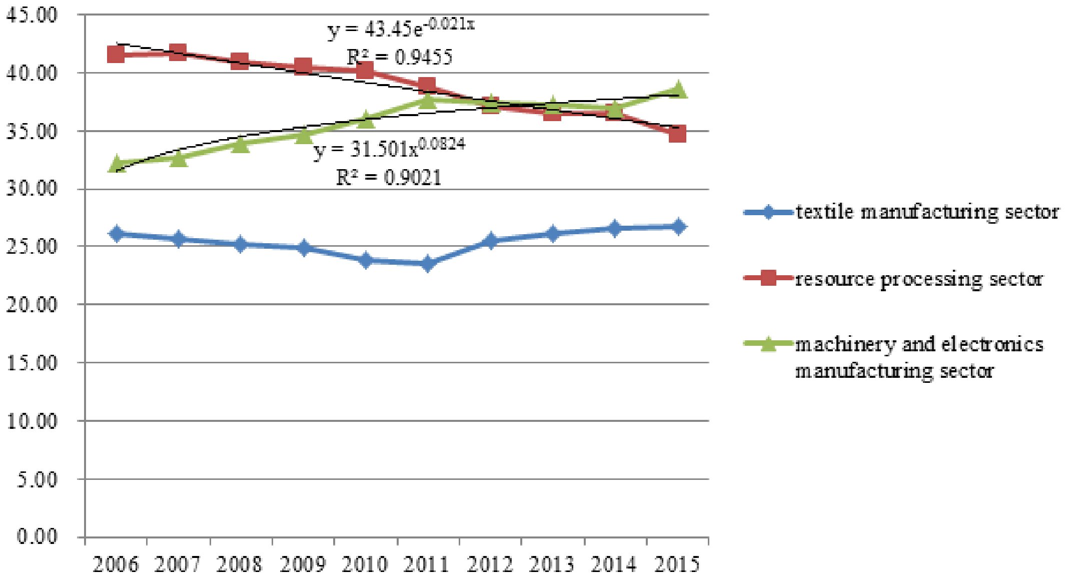

FIGURE 1. The fitting curves of manufacturing structure

TABLE 3. The predicted environmental efficiency of manufacturing structure (2016-2025)

Manufacturing industry	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
environmental efficiency	0.234	0.244	0.252	0.260	0.267	0.274	0.280	0.286	0.291	0.297

TABLE 4. The calculation process of ecological efficiency for sub sectors in 2025

Sub sectors	Energy consumption per value-added in 2015 ①	Energy consumption per value-added in 2025 ② = ① $\times(1-0.34)$	Energy efficiency in 2025 ③ = 1/②	Ecological efficiency in 2025 ④ = ③ $\times E_{env}$
textile manufacturing	0.31	0.20	4.90	1.21
resource processing	2.96	1.95	0.51	0.39
machinery and electronics manufacturing	0.17	0.11	9.07	1.64

The thresholds of φ_i^t are calculated based on Table 2 as follows: $\varphi_1^{\min} = 0.271$, $\varphi_1^{\max} = 0.312$, $\varphi_2^{\min} = 0.285$, $\varphi_2^{\max} = 0.345$, $\varphi_3^{\max} = 0.403$.

Similarly, the environmental efficiency for years 2016-2025 is estimated by regression analysis based on the historical data for years 2006-2015 (see Table 3).

Further, according to the binding target for Anhui, the energy consumption per industrial value-added in above-scale units by 2025 should be lowered by 34% on the level of 2015. Meanwhile, supposing that the energy consumption keeps the same rate of decrease, then the energy consumption for sub sectors in 2025 can be obtained through the data on energy consumption in 2015. According to the fact that the energy consumption per value-added is the reciprocal of energy efficiency, combined with the predictions of environmental efficiency in Table 3, we can acquire the ecological efficiency for sub sectors (see Table 4).

4. **Results.** Firstly, by using the value-added, energy consumption and environmental efficiency for manufacturing industry and three sub sectors in 2015, the total ecological

efficiency for the industry and sub sectors can be produced, i.e., $E^0 = 0.724$, and $e_1^0 = 0.85$, $e_2^0 = 0.28$, $e_3^0 = 1.16$.

(1) Structural optimization of manufacturing industry under the assumption of unchanged ecological efficiency for sub sectors. If the ecological efficiency for sub sectors remains constant during 2015-2025, in conjunction with the thresholds of value-added for sub sectors, the model (16) can be transformed as

$$\begin{aligned}
&\text{Min } \mu = 0.724\left[\left(\frac{1}{0.28}-\frac{1}{0.85}\right)\varphi_2^t+\left(\frac{1}{1.16}-\frac{1}{0.85}\right)\varphi_3^t+\frac{1}{0.85}\right]^{1/2}-1\\
&\text{s.t. } \varphi_2^t \geq 0.285\\
&\qquad \varphi_3^t \leq 0.403\\
&\qquad \varphi_2^t+\varphi_3^t \leq 1-0.271\\
&\qquad \varphi_2^t+\varphi_3^t \geq 1-0.312
\end{aligned} \tag{17}$$

Based on the programming solution by software Matlab 2010, the best structure of manufacturing industry in 2025 is estimated as: 31.1% for textile manufacturing sector, 28.5% for resource processing sector, and 40.3% for machinery and electronics sector. Results of the total ecological efficiency in 2025 are shown in Table 3 and Table 4. The total ecological efficiency increases by 4.36% caused by structural optimization effect.

(2) Structural optimization of manufacturing industry under the assumption of variable ecological efficiency for sub sectors. By combining the thresholds of φ_i^t with the ecological efficiency for sub sectors in 2025 (see Table 4), the model (16) can be transformed into as follows

$$\begin{aligned}
&\text{Min } \mu = 0.724\left[\left(\frac{1}{0.39}-\frac{1}{1.21}\right)\varphi_2^t+\left(\frac{1}{1.64}-\frac{1}{1.21}\right)\varphi_3^t+\frac{1}{1.21}\right]^{1/2}-1\\
&\text{s.t. } \varphi_2^t \geq 0.285\\
&\qquad \varphi_3^t \leq 0.403\\
&\qquad \varphi_2^t+\varphi_3^t \leq 1-0.271\\
&\qquad \varphi_2^t+\varphi_3^t \geq 1-0.312
\end{aligned} \tag{18}$$

Once again, the best structure of manufacturing industry in 2025 is produced as: 31.1% for textile manufacturing sector, 28.5% for resource processing sector, and 40.3% for machinery and electronics manufacturing sector. This indicates that the optimal structure keeps the same whether the ecological efficiency for sub sectors changes or not during 2015-2025. However, the total ecological efficiency of manufacturing industry in 2025 (E^t) rises to 0.897, and its growth rate climbs up to 23.92% resulted from both the structural optimization effect and the ecological improvement effect in sub sectors.

5. **Conclusions.** In this paper, the manufacturing industry of Anhui province is divided into three categories: textile manufacturing sector, resource processing sector, and machinery and electronics manufacturing sector. The structural optimization model of manufacturing industry is constructed. Results show that, among the three sub sectors, the ecological efficiency in machinery and electronics manufacturing sector is the highest, followed by textile manufacturing and resource processing sectors.

In addition, the structure of this industry should be as follows whether the ecological efficiency for sub sectors changes or not by 2025: the proportion for textile manufacturing sector increases to the expected 31.1%; the proportion for resource processing sector declines to 28.5%; and the proportion for machinery and electronics manufacturing sector rises to 40.3%. When the ecological efficiency for sub sectors is kept unchanged, the structural effect can make the total ecological efficiency of manufacturing industry increase by 4.36%; while if the ecological efficiency for sub sectors is assumed to improve with time, then the structural effect and the ecological effect will make the total ecological efficiency increase by 23.92%. Therefore, it is necessary to promote the structural adjustment and upgrading of the manufacturing industry, and strive to enhance the energy efficiency and environmental efficiency for sub sectors, so as to heighten the ecological efficiency of sub sectors at the same time.

Further, more reasonable predictions of ecological efficiency in manufacturing industry and in sub sectors can be produced if the changes of indicators including value-added growth rate, labor productivity, urbanization rate, and industrial pollution intensity are taken into account. However, this will not change the overall conclusions about the structural optimization of manufacturing industry in this paper.

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