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The measurement of sustainable regional manufacturing industry: The case of China

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Abstract: Since the introduction of Made in China 2025 and its focus on sustainable development and manufacturing industry transformation, appropriate evaluation methods to accurately assess the development of China's manufacturing industry have become essential. Therefore, this research constructed an innovative evaluation index system for manufacturing development based on seven dimensions: innovation, structural optimization, economic benefits, efficiency enhancements, green development, international competition, and social benefits. An objective combination weighted-gray correlation-TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) evaluation model was applied to the Sichuan Province manufacturing industry data from 2009 to 2018 to create a representative sample, in which the overall development level from 2009 to 2016 took on an inverted U-shaped curve that reached its maximum in 2013, fell to its lowest point in 2016, and then began a steady upward trend marked by innovation and efficiency improvements; however, sustainability fell. Based on these results, this research provides a scientific reference for policy-makers with recommendations for innovation-driven development strategies, green development promotion, and social benefit improvements with the aim of promoting more sustainable development of China's manufacturing industry.

Keywords: manufacturing industry; sustainable development; combination weighting; gray correlation-TOPSIS

1. Introduction

The 19th National Congress of the Communist Party of China recognized that as China's economy shifted from rapid growth to high-quality development, economic development needed to be focused on sustainability, and advanced manufacturing needed to be accelerated. In 2017, the development of high-quality manufacturing resulted in the following characteristics: low production factor inputs, high resource allocation efficiency, and low resource and environmental costs, and positive economic and social benefits (Xi, 2017). Manufacturing, an important pillar of China's national economy, has been the driving force for China's rapid industrialization and modernization (Deng, Jin, Ye, & Zheng, 2019). With the recent "Made in China 2025" campaign, China aims to bring its manufacturing in line with the that of the most advanced countries in the world. China's manufacturing industry is far behind in terms of independent innovation, efficient resource utilization, industrial structure, informatization, and quality. Therefore, as part of China's effort to optimize economic structure, supply-side reform, and industrial upgrading, it has become increasingly important to accurately assess sustainable developments in the country's manufacturing industry from a regional perspective to inform the transformation of high-quality manufacturing in the Industry 4.0 era.

Researchers have reviewed sustainable manufacturing development strategies from four main perspectives: implications, influencing factors, evaluation systems, and path countermeasures (Han & Zhu, 2018; J. Zhang, Hou, Liu, He, & Zhuo, 2019). The establishment of a sustainable development evaluation index and associated quantitative measurements could aid in identifying the strengths and weaknesses of

regional economic developments and provide valuable guidance. As innovation, coordination, greenness, openness, and sharing are the guiding ideologies for China's sustainable development, these ideologies also tend to be the main dimensions in the construction of sustainable development evaluation indicators (B. Li, Tian, Shi, & Han, 2020) along with economic growth, public welfare, effectiveness, comprehensiveness, and income and labor output levels. For example, C. Li (2019) used eight evaluation dimensions—corporate quality, product quality, growth, efficiency, innovation, external dependence, social contribution, and the environment—and found that China's manufacturing development was relatively poor. Jiang, He, and Fang (2019) used six dimensions—quality brand, economic benefits, high-end development, integration of the two, green development and technological innovation—to assess the manufacturing quality in China's provinces and found that overall, sustainable regional manufacturing developments trended upward but were uneven.

While research into sustainable development index systems has enriched theories, the indicators still need improvement. First, insufficient attention has been given to the relevant microenterprise indicators. As manufacturing is a key part of China's economy, it is necessary to construct world-class manufacturing companies and brands to improve competitiveness. However, no relevant indicators reflecting China's international competitiveness have been suggested. Second, few indicators have been developed to reflect the quality of the human environment; however, social and cultural environments are important factors in judging regional economic development. Therefore, to fill these research gaps, this research constructed an innovative evaluation index system for sustainable Industry 4.0 manufacturing development in China and an objective combination weighting-gray correlation-TOPSIS evaluation model with seven dimensions: innovation, structural optimization, economic benefits, enhanced efficiency, green development, international competitiveness, and social benefits. Empirical research was then conducted on manufacturing industry developments from 2009 to 2018 in Sichuan Province, the results of which informed relevant policy recommendations for the promotion of sustainable manufacturing industry developments in China.

The remainder of this paper is organized as follows. Section 2 reviews previous studies on the implications and measurement of sustainable manufacturing development. Section 3 constructs the sustainable manufacturing development index system. Section 4 details the objective combination weighting-gray correlation-TOPSIS evaluation model. Section 5 uses the index system developed in Section 3 and the evaluation model introduced in Section 4 to empirically evaluate the sustainable manufacturing industry development levels in Sichuan Province from 2009 to 2018. Section 6 concludes the study and gives corresponding policy recommendations.

2. Literature review

2.1 Sustainable manufacturing industry development

Sustainable manufacturing industry development has been examined from many perspectives. First, many studies commented on the dialectical relationships between quality and quantity; for example, R. Ma, Luo, Wang, and Wang (2019) claimed that sustainable development was related to the coordination and unification of quality and quantity and was connected to the quality of economic growth. Gereffi et al. (2003) claimed that organizational and technological innovations were required to upgrade and transform manufacturing industry enterprises from low-end value chains to high-end value chains, and Chen and Li (2020) similarly believed that sustainable development required original innovation-driven breakthroughs in master core technologies. Barro (2002) believed that economic growth quality was related more to income equity, life expectancy, environmental conditions and political systems. Thomas et al. (2000) believed that

sustainable growth was related to the balance between human capital investment, natural capital investment and material capital investment, and Elmawazini, Saleeby, el Farouk, and Bashayer (2018) concluded that technological upgrading was key to labor productivity improvements and necessary to balance the relationship between production factors, especially innovative technological production factors. Martinez and Mlachila (2013) took a sustainability perspective and defined sustainable growth as strong, stable sustainable growth, and Mlachila, Tapsoba, and Tapsoba (2017) pointed out that the essence of sustainable growth required a greater focus on sustainable social growth; that is, sustainable development should not be at the expense of the excessive use of resources or increased environmental pollution but should involve increased production efficiencies and better social welfare through technological innovation. Jin (2018) claimed that sustainable development was connected to the meeting of various humanistic needs and should organically combine economic concepts and livelihood issues Yu (2020) proposed that the goals of sustainable manufacturing industry development were to reduce production factor inputs, improve resource allocation efficiencies, improve industrial product quality, reduce environmental pollution, and improve economic and social benefits.

Therefore, sustainable development should involve innovation, structural industrial coordination, high efficiency, green development, and the provision of economic and social effects, that is, it is a multidimensional system problem.

2.2 Measurement of manufacturing industry development

Studies related to sustainable development measurement can be divided into two categories, the first of which is the evaluation of basic elements such as innovation development levels (Calik & Bardudeen, 2016; Kuhlman et al., 2017), urban-rural/regional coordinated development levels (Ozdemir & Gul, 2019; Zhu, Deng, & Liang, 2017), and green development levels (Qu & Liu, 2017), all of which are multidimensional evaluation problems. However, as these studies focused on only certain parts of sustainable development, they did not examine the research objective as a whole; nonetheless, they provided useful references for the construction of a sustainable development index.

The second research category focuses on comprehensive urban or industry development evaluations. For example, Wei (2020) evaluated sustainable development in China's provinces from the innovation, coordination, green, openness and sharing perspectives but ignored two important sustainable development output factors, efficiency improvement and economic efficiency. Chang and Dong (2016), Liang, Zhang, Chen, and Deng (2016) and G. Zhang and Su (2020) measured sustainable development in 11 resource-based cities in Shanxi Province, 13 cities in Jiangsu Province, and central cities in the Yellow River Basin by using indicator systems that assessed the economic, social, resource and environmental aspects; however, they did not include the openness degree or international competitiveness. Industry development evaluations have also been conducted. For example, Nowak, Janulewicz, Krukowski, and Bujanowicz-Haras (2016) applied Hellwig's development model to evaluate the agricultural development levels in 25 EU member states, Z. Ma and Cao (2020) used an AHP entropy weight combination weighting and TOPSIS to evaluate the sustainable development in 1,881 A-share listed manufacturing enterprises on the basis of economic benefit, innovation and development, green development, open cooperation, and social sharing perspectives, but they did not include product quality improvements or organizational structural optimization. Shi and Han (2020) evaluated the industry development quality in 31 manufacturing sectors on the basis of economic benefit, innovation, social contribution and environmentally sustainable development ability perspectives, but they did not consider international competitiveness or industry structure; further, their research used an equal weight assignment method that did not reflect the true differences between the indicators.

Therefore, with the manufacturing industry as the research object and to ensure a comprehensive evaluation of the high-level manufacturing industry developments in China, based on previous studies, this research developed an integrated index system that encompassed seven aspects: innovation, structural optimization, economic benefit, efficiency improvement, green development, international competition, and social benefit.

Many evaluation methods have been used in previous studies, such as AHP (Huang, Sun, & Zhang, 2018; Pan, Han, Lu, Jiao, & Ming, 2020), TOPSIS (F. Jiang et al., 2020; Wang & Duan, 2019), neural networks (Lei, Chen, Xue, & Liu, 2019; Sun, Tang, & Bai, 2019) and gray correlation analysis (Ding, Wu, Zhao, Mu, & Yu, 2019; Ozcan & Tuysuz, 2016), of which the gray correlation-TOPSIS method (Liang et al., 2016; Yang & Wu, 2019) has often been used for multi-attribute evaluations because it has simple calculations and no special data requirements. In this study, therefore, an entropy weighting method was used with the traditional gray correlation-TOPSIS method, and the entropy weight, mean square deviation and maximum deviation combination weighting methods were employed to determine the weights of each index indicator, which together provided more objectivity than a single weighting method and were able to effectively reflect the objective information contained in the index indicator data.

3. Sustainable manufacturing industry development index system

This study analyzed sustainable manufacturing industry development from seven aspects: innovation, structural optimization, economic benefits, efficiency improvements, sustainability, international competitiveness, and social benefits. To ensure that each of these aspects fully and independently reflected sustainable manufacturing industry development, they were divided into 19 second-level and 23 third-level indicators to form the complete sustainable manufacturing industry development index shown in Table 1.

Table 1 High-quality Sichuan manufacturing industry development index

Primary Indicators	Secondary indicators	No.	Third-level index	Unit	Attribute
Innovation A	Innovation environment A1	A11	Proportion of science and technology expenditure in the government budget	%	+
		A21	Proportion of R&D personnel	%	+
	Innovation input A2	A22	Proportion of R&D investment	%	+
		A23	New product development expenses	100 million CNY	+
	Innovation output A3	A31	Number of invention patents per unit of R&D expenditure	Per unit/100 million CNY	+
		A32	Technology market transaction volume per 10000 scientific and technology personnel	100 million CNY	+
		A33	Proportion of new product sales revenue	%	+
Structural optimization B	Industrial structure B1	B11	Proportion of high-tech manufacturing value in total manufacturing industry output value	%	+
	enterprise structure B2	B21	Proportion of main business income in manufacturing enterprises above the designated large- and medium-sized manufacturing enterprise sizes	%	+
	Export structure B3	B31	Proportion of high-tech export delivery value in total manufacturing industry export delivery value	%	+
Economic benefits C	Growth rate C1	C11	Total output value growth rate	%	+
	production costs C2	C21	Main business income unit costs	%	-

	Profitability C3	C31	Main business manufacturing enterprise profit margin	%		+
	Assets and liabilities C4	C41	Asset/liability ratio	%		-
Efficiency improvement D	Labor efficiency D1	D11	Labor productivity	100 million CNY per people		+
	Capital efficiency D2	D21	Return on assets	%		+
	energy efficiency D3	D31	Value added per unit of energy consumption	%		+
Green development E	Green technology E1	E11	Comprehensive utilization rate for industrial solid waste	%		+
	environmental protection E2	E21	Proportion of environmental protection expenditure in government budget	%		+
International competition F	foreign investment F1	F11	Total amount of foreign investment utilized by the manufacturing industry	Million US dollars		+
	Trade competition F2	F21	Trade competitiveness index	——		+
Social benefits G	Employment contribution G1	G11	Employment contribution rate	%		+
	Income contribution G2	G21	Income contribution rate	Ten thousand CNY		+

Note: The "——" in the unit column indicates dimensionless; the "+" in the attribute column indicates a positive indicator; the larger the index value is, the better; and the "-" indicates a negative indicator; the smaller the index value is, the better).

(1) Innovation

As the most important driving force for sustainable development, the innovation indicator was divided into three secondary indicators: innovation environment, innovation input, and innovation output. The innovation environment reflects the local government's emphasis on innovation and entrepreneurship, represented by the proportion of science and technology expenditure in the budget. As labor and capital are the basic elements for innovative activities, innovation input is measured by the ratio of R&D, the balance of R&D investment, and new product development costs. Innovation output is measured by the number of invention patents obtained from the R&D expenditure per unit, the technology market transaction volume per 10,000 scientific and technological activity personnel, and the ratio of new product sales revenue, of which the new product sales revenue and the technology market transaction volume reflect the relationships between the regional innovation transformation ability and the economic benefits.

(2) Structural optimization

Structural optimization is related to "coordinated" development and is measured by many manufacturing industry improvement dimensions, such as the factor inputs, technical strengths, and product added value. Therefore, this study evaluated industrial, enterprise, and export structure optimization as part of the manufacturing structure. The industrial structure was the proportion of high-tech manufacturing output value in the total output value to reflect the proportion of the high-tech manufacturing industry in the total value chain and its position in the product value chain. The enterprise structure was related to the number of large- and medium-sized manufacturing enterprises, and the export structure was the proportion of high-tech manufacturing export delivery value to total export delivery value to reflect the high-value-added high-tech

contribution to total export volume and the export industry's competitiveness in the province.

(3) Economic benefits

Economic benefits are an intuitive economic index that reflects manufacturing industry development. Recently, because environmental protection sustainability has become a key industrial development focus, economic growth has slowed; however, economic benefits are still an important basic index for the evaluation of sustainable manufacturing industry development. The economic benefits were measured based on the growth rate, production cost, profitability, and assets and liabilities. The growth rate was expressed as the growth rate in the total manufacturing industry output value to directly reflect the manufacturing industry development speed; production cost was measured by the cost of one unit of main business income to reflect the manufacturing enterprise cost-income structure; profitability was measured by the profit margin of the main manufacturing enterprise business to reflect the manufacturing enterprise main business profitability, and the asset-liability ratio was measured as the manufacturing industry asset-liability ratio.

(4) Efficiency improvements

Efficiency improvements are the inevitable result of sustainable development because when the manufacturing industry focuses on innovation as the internal driving force, it employs advanced manufacturing, internet and green energy-conservation technologies to improve production efficiency. As production activities are comprised of labor, capital, and energy inputs (Rocco & Colombo, 2016; Wei & Liu, 2017), the input efficiency calculations for each production factor are as follows:

$$\text{Labor efficiency} = \frac{\text{Value added of manufacturing industry}}{\text{Number of manufacturing employees (annual average)}}$$

$$\text{Capital efficiency} = \frac{\text{Net profit of manufacturing enterprises}}{\text{Total assets of manufacturing enterprises}}$$

$$\text{Energy efficiency} = \frac{\text{Value added of manufacturing industry}}{\text{Terminal energy consumption of ten thousand tons of standard coal}}$$

(5) Green development

Sustainable manufacturing and environmental development are the foundation of "green" development and the reason for sustainable manufacturing industry development. Although China's early industrial development caused significant ecological damage, China has since focused on the need for "win-win" industrial economic development and environmental protection. Consequently, many environmentally unfriendly enterprises have been closed, while green factories, green parks, green products, and supply chains have been encouraged and pollution controlled. Based on some indicators extracted from the *China Green Development Index Report* (X. Li & Pan, 2012, 2015), this study measured green manufacturing industry development based on green technology and environmental governance, with green technology being represented by the total utilization rate for general industrial solid waste and ecological control calculated by the proportion of industrial pollution treatment investment in the government budget.

(6) International competitiveness

International competitiveness reflects the degree of "open" development. As China's manufacturing industry is an important foundation of its economy and one of the driving forces of the country's development, improving international competitiveness enhances China's overall competitive economic advantage. Therefore, the international competitiveness of China's manufacturing industry was examined based on foreign investment and trade competition. Foreign investment was measured by total foreign investment to reflect the importance of the manufacturing industry by foreign enterprises, and any increases in foreign investment were taken as a measure of the development of the two-way causal technological innovation

relationships necessary for sustainable development. Trade competition was measured using the trade competitiveness index, as this index evaluates the international competitiveness of China's manufacturing industry from its import and export structure.

(7) Social benefits

Social benefits reflect the "sharing" development. As sustainable manufacturing industry development attaches equal importance to economic and social benefits, it is necessary to ensure that people share the fruits of sustainable development. Therefore, as the social benefits reflect the sustainable manufacturing industry development contributions to livelihood problems (i.e., unemployment, poverty, the environment, and social management) and considering the operability and comparability of the data, three secondary indicators—employment contribution, income contribution, and tax contribution—were used for the social benefits evaluation.

4. Materials and Methods

To analyze the relevant time series data and comprehensively assess sustainable manufacturing industry development in China's regions, this study used a comprehensive gray correlation-TOPSIS evaluation model based on an objective combination weighting method. The specific implementation steps for the evaluation model are described as follows.

4.1 Objective combination weighting

As the different calculation methods for each of the index indicators would cause variations in the dimensions and orders of magnitude, to establish the index weights, it was necessary to make the index dimensionless. The more commonly used dimensionless processing methods are extremum, standardization, averaging, and standard deviation. While this study preferred the standardization method, other evaluators could choose any of the other methods based on their own needs.

First, the attribute value was set for evaluation object i on index j as x_{ij} , with the standardized value being r_{ij} .

The standardized positive index formula used was:

$$r_{ij} = \frac{x_{ij} - \min_i(x_{ij})}{\max_i(x_{ij}) - \min_i(x_{ij})} \quad (1)$$

The standardized negative index formula used was:

$$r_{ij} = \frac{\max_i(x_{ij}) - x_{ij}}{\max_i(x_{ij}) - \min_i(x_{ij})} \quad (2)$$

(1) Entropy weight method

The information entropy of each index was calculated:

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^m \frac{r_{ij}}{r_j} \ln \frac{r_{ij}}{r_j}, \quad r_j = \sum_{i=1}^m r_{ij} \quad (3)$$

The entropy weight of each index was calculated:

$$w_j = \frac{1 - E_j}{\sum_{j=1}^n (1 - E_j)} \quad (4)$$

(2) Mean square deviation weighting

The average value of each index was calculated:

$$\bar{r}_j = \frac{1}{m} r_j \quad (5)$$

The mean square deviation of each index was calculated:

$$\sigma_j = \sqrt{\frac{1}{m} \sum_{i=1}^m (r_{ij} - \bar{r}_j)^2} \quad (6)$$

The mean square error weight of each index was calculated:

$$w_j = \frac{\sigma_j}{\sum_{j=1}^n \sigma_j} \quad (7)$$

(3) Maximum deviation weighting

$H_{pkj}(w)$ was set as the difference between sample p and sample k on the j th index:

$$H_{pkj}(w) = |r_{pj} - r_{qj}| * w_j \quad (8)$$

$H_j(w)$ was set as the total deviation on the j th index between all samples and the other samples:

$$H_j(w) = \sum_{p=1}^m \sum_{q=1}^m H_{pkj}(w) \quad (9)$$

a) The objective function was constructed based on the maximum deviation principle:

$$\begin{aligned} \max \quad & H(w) = \sum_{j=1}^n \sum_{p=1}^m \sum_{q=1}^m |r_{pj} - r_{qj}| w_j \\ \text{s. t} \quad & \begin{cases} \sum_{j=1}^n w_j^2 = 1 \\ w_j \geq 0 \end{cases} \end{aligned}$$

b) The objective function was solved and normalized, and the index weight was obtained as follows:

$$w_j = \frac{\sum_{p=1}^m \sum_{q=1}^m |r_{pj} - r_{qj}|}{\sum_{j=1}^n \sum_{p=1}^m \sum_{q=1}^m |r_{pj} - r_{qj}|} \quad (10)$$

(4) Fusion weighting method for multiplication synthesis normalization

As the importance of each objective weighting method was considered to be similar, this study decided on the multiplication synthesis normalization method to fuse the three objective weight vectors (Song et al., 2015). The objective weight vector calculated using the entropy weight method was set at $W^S = (w_1^S, w_2^S, \dots, w_n^S)^T$, the objective weight vector calculated using the mean square error weighting method was $W^M = (w_1^M, w_2^M, \dots, w_n^M)^T$, and the objective weight vector calculated using the maximum deviation weighting method was $W^L = (w_1^L, w_2^L, \dots, w_n^L)^T$.

Therefore, the objective combination weight for each index was as follows:

$$w_j = \frac{w_j^S w_j^M w_j^L}{\sum_{j=1}^n w_j^S w_j^M w_j^L} \quad (11)$$

(5) Construction of the weighted standardized evaluation index matrix

The weighted normalized evaluation index matrix was $Z = (z_{ij})_{m \times n}$, where $z_{ij} = w_j r_{ij}$, $1 \leq i \leq m, 1 \leq j \leq n$

4.2 Gray correlation-TOPSIS mixed model

(1) Optimal and worst solution determination

The TOPSIS algorithm was employed to determine the optimal solution and the worst solution (Aires & Ferreira, 2019); the optimal solution was found to be $Z^+ = (z_1^+, \dots, z_n^+)$ and the worst solution was $Z^- = (z_1^-, \dots, z_n^-)$, where $z_j^+ = \max_i(z_{ij})$ and $z_j^- = \min_i(z_{ij})$.

(2) Euclidean distance calculation

The distance between each evaluation object and the optimal solution and the worst solution was

$$D_i^+, D_i^-, \text{ where } D_i^+ = \sqrt{\sum_{j=1}^n (z_j^+ - z_{ij})^2} \text{ and } D_i^- = \sqrt{\sum_{j=1}^n (z_{ij} - z_j^-)^2}.$$

(3) Gray correlation coefficient matrix construction

If the gray correlation coefficients for the j index of evaluation object i and the j index of the optimal solution and the worst solution were ξ_{ij}^+ and ξ_{ij}^- , respectively;

$$\begin{cases} \xi_{ij}^+ = \frac{\min_i \min_j (z_j^+ - z_{ij}) + \rho \max_i \max_j (z_j^+ - z_{ij})}{(z_j^+ - z_{ij}) + \rho \max_i \max_j (z_j^+ - z_{ij})} \\ \xi_{ij}^- = \frac{\min_i \min_j d(z_{ij}, z_j^-) + \rho \max_i \max_j d(z_{ij}, z_j^-)}{(z_{ij} - z_j^-) + \rho \max_i \max_j (z_{ij} - z_j^-)} \end{cases} \quad (12)$$

where $1 \leq i \leq m, 1 \leq j \leq n$; $\rho \in [0,1]$ was the resolution coefficient. To reduce the influence of the extreme value on the evaluation results, it is generally assumed that $\rho = 0.5$.

(4) Gray correlation degree calculation

The gray correlation degree for evaluation object i was set as:

$$\begin{cases} H_i^+ = \frac{\sum_{j=1}^n \xi_{ij}^+}{n} \\ H_i^- = \frac{\sum_{j=1}^n \xi_{ij}^-}{n} \end{cases} \quad (13)$$

(5) Mixed correlation degree calculation

The gray correlation analysis method and the TOPSIS method (Tang, Zhu, Liu, Jia, & Zheng, 2019) were then combined to determine the degree of relative closeness between the combination distance and the gray correlation degree. Due to the different dimensions of the two methods, dimensionless treatment was applied.

$$\begin{cases} P_i^+ = \frac{D_i^+}{\max_i D_i^+} \\ P_i^- = \frac{D_i^-}{\max_i D_i^-} \end{cases} \quad \begin{cases} Q_i^+ = \frac{H_i^+}{\max_i H_i^+} \\ Q_i^- = \frac{H_i^-}{\max_i H_i^-} \end{cases} \quad (14)$$

The larger the P_i^- and Q_i^+ were, the further evaluation scheme i was from the worst solution and the greater the relative correlation degree between evaluation scheme i and the optimal solution; and the greater the P_i^+ and Q_i^- were, the higher evaluation scheme i deviation degree was from the optimal solution and the greater the relative correlation degree between evaluation scheme i and the worst solution. A mixed correlation degree was then constructed:

$$\begin{cases} \psi_i^+ = \alpha P_i^- + \beta Q_i^+ \\ \psi_i^- = \alpha P_i^+ + \beta Q_i^- \\ \alpha + \beta = 1, \quad 0 \leq \alpha, \beta \leq 1 \end{cases} \quad (15)$$

where α and β are the decision-maker's preferences for the distance and gray correlation degree (Meng, Wang, & Xing, 2018); without losing generality, $\alpha = \beta = 0.5$ was taken.

The final gray closeness degree was $C_i^* = \frac{\psi_i^+}{\psi_i^+ + \psi_i^-}$. The index based on Euclidean distance and the gray correlation degree was taken to represent the position relationships and structural similarities between each evaluation object and the optimal and worst solutions, which was used to evaluate the relative advantages and disadvantages of each evaluation object.

As it is generally considered that a higher C_i^* is better, the sustainable manufacturing industry development level evaluation was arranged in descending order of the C_i^* value.

5. Empirical analysis

5.1 Data source

The data used in this study were from the 2009-2018 *Sichuan Statistical Yearbooks*, the *China Statistical Yearbooks*, the *China Industrial Statistical Yearbooks*, the *China Science and Technology Statistical*

Yearbooks, and the *Industrial Enterprise Science and Technology Activity Statistical Yearbook*.

To ensure statistical consistency and data comparability, the data were processed before the evaluation as described in the following.

1. To eliminate the impact of inflation on the evaluation results, all monetary unit indicators were converted to the constant 2008 price: the new product development costs; the number of invention patents per unit of R&D expenditure; and the market technology transaction volume per 10000 scientific and technological activity personnel.

2. As Sichuan manufacturing industry data for some indicators were not available, the sum of the data from 31 manufacturing subsectors above the scale was used for the first estimation.

3. When there were no data for some of the subdivided innovation-driven subordinate industry indicators, approximate industrial enterprise data were used.

4. Because there were no index data for the five major economic regions in Sichuan, only Sichuan's sustainable manufacturing industry developments in the time series were evaluated.

The descriptive statistical results for all indicators are shown in Table 2.

Table 2: Descriptive statistics for the evaluation indices

Index number	Number of samples	minimum value	Maximum value	mean value	standard deviation
A11	10	0.798	1.524	1.130	0.223
A21	10	2.168	5.309	3.271	1.001
A22	10	0.350	0.818	0.593	0.148
A23	10	100.539	315.648	185.312	66.488
A31	10	15.539	46.195	34.490	9.990
A32	10	4.092	31.471	10.471	8.131
A33	10	6.747	18.769	8.976	3.653
B11	10	10.668	17.400	14.627	1.991
B21	10	56.987	66.455	61.381	3.323
B31	10	54.068	58.966	56.825	1.775
C11	10	0.224	31.511	11.704	11.454
C21	10	82.386	84.992	83.633	0.871
C31	10	5.757	8.667	7.527	1.024
C41	10	0.541	1.006	0.613	0.139
D11	10	59.963	116.525	88.249	19.747
D21	10	6.195	9.789	7.915	1.084
D31	10	0.563	0.946	0.760	0.126
E11	10	38.460	57.500	44.966	6.607
E21	10	2.077	3.188	2.480	0.302
F11	10	284.063	658.767	523.794	104.706
F21	10	0.103	0.301	0.206	0.080
G11	10	10.835	12.561	11.931	0.528
G21	10	83.540	89.769	86.015	2.089

5.2 Evaluation results

The weighted gray correlation-TOPSIS evaluation model based on the objective combination weighting method was used to evaluate Sichuan's sustainable manufacturing industry development time series, with the specific evaluation process being as follows.

(1) Index weight determination. Three objective weighting methods, the entropy weighting method, the mean square deviation method, and the deviation maximization method, were applied to calculate the index weights, after which the multiplication synthesis normalization method was used to combine the three objective weights. The weight information for each index is shown in Table 3.

Table 3: Weight information for the evaluation indices

Index number	Entropy weight	Mean square error weight	Maximum deviation weight	Combination weight	Comprehensive weight of first level index
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A11	0.0443	0.0411	0.0427	0.0406	
A21	0.0419	0.0427	0.0431	0.0403	
A22	0.0456	0.0424	0.0448	0.0452	
A23	0.0428	0.0414	0.0428	0.0397	0.2614
A31	0.0462	0.0437	0.0443	0.0467	
A32	0.0369	0.0398	0.0351	0.0270	
A33	0.0318	0.0407	0.0324	0.0219	
B11	0.0466	0.0396	0.0410	0.0395	
B21	0.0438	0.0470	0.0488	0.0525	0.1503
B31	0.0448	0.0486	0.0513	0.0583	
C11	0.0397	0.0491	0.0498	0.0506	
C21	0.0448	0.0448	0.0472	0.0495	0.1809
C31	0.0456	0.0471	0.0483	0.0542	
C41	0.0478	0.0401	0.0266	0.0266	
D11	0.0443	0.0468	0.0498	0.0539	
D21	0.0453	0.0404	0.0427	0.0408	0.1426
D31	0.0450	0.0440	0.0463	0.0479	
E11	0.0396	0.0465	0.0467	0.0450	0.0746
E21	0.0444	0.0364	0.0351	0.0296	
F11	0.0472	0.0374	0.0365	0.0337	0.1028
F21	0.0430	0.0544	0.0566	0.0691	
G11	0.0467	0.0410	0.0410	0.0410	0.0873
G21	0.0419	0.0449	0.0470	0.0463	

(2) Gray closeness degree calculation. After determining the combination weights for each three-level index, the first-level index and the comprehensive gray closeness degree were calculated using the gray correlation TOPSIS complete evaluation method, and the results are shown in Table 4.

Table 4: Evaluation of Sichuan's sustainable manufacturing industry development

Year	Innovation	Structural optimization	Economic benefits	Efficiency improvements	Green development	International competitiveness	Social benefits	Comprehensive score
2009	0.3817	0.4540	0.6219	0.2880	0.8044	0.3124	0.2040	0.4414
2010	0.3162	0.3668	0.7354	0.3923	0.6396	0.3526	0.4901	0.4593
2011	0.2801	0.5902	0.7105	0.4972	0.4495	0.6012	0.5312	0.5137
2012	0.3672	0.6093	0.6320	0.4798	0.4240	0.7678	0.5530	0.5412
2013	0.4160	0.6552	0.5662	0.5049	0.3487	0.7492	0.7405	0.5553
2014	0.4833	0.6661	0.3804	0.4929	0.3611	0.7037	0.7081	0.5297
2015	0.4968	0.4590	0.3145	0.5659	0.3500	0.7259	0.5718	0.4911
2016	0.5134	0.3891	0.4115	0.6128	0.1956	0.3239	0.5524	0.4579
2017	0.5918	0.4213	0.4385	0.7055	0.2491	0.2812	0.5232	0.4903
2018	0.7019	0.4037	0.5767	0.7037	0.2630	0.3684	0.4961	0.5469

5.2.1 Overall analysis

Table 4 information was then used to illustrate Sichuan's sustainable manufacturing industry development in Figure 1, from which it can be seen that sustainable development had an inverted U-shaped curve from 2009 to 2016, reached its peak in 2013, and could be divided into three distinct stages.

Figure 1: Efficiency Evaluation of Sichuan Province's sustainable manufacturing industry development

The first stage was from 2009 to 2013, at which time there was a continuous growth trend rising from 0.4414 in 2009 to 0.5553 in 2013, an average increase of 5.9%. This may have been because of the Sichuan Province policy orientations outlined in the *12th Five Year Plan for Western Development*, which contained plans to build Chengdu, the capital of Sichuan Province, into a strategic inland open economy. Plans called for providing a strong economic environment for the sustainable development of Sichuan's manufacturing industry, improving the spatial layout of the equipment manufacturing industry as a key development direction that would play to the advantages of the Sichuan manufacturing industry chain, and providing advanced technological support for industry development. However, the benefits promoted by these policies did not appear to have a long-term effect on promoting Sichuan's sustainable manufacturing industry development over the observation period; only the period from 2011-2014 demonstrated sustainable industry development.

Because of the sharp decline in the international competitiveness and economic benefit subsystem values in the second stage from 2013 to 2016, the sustainable development level declined from 0.5553 to 0.4579. It reached its low point in 2016, which indicated that the industry development during this period had failed to make effective use of the valuable resources provided by the policy guidelines.

The efficiency in the third stage from 2016 to 2018 had an upward trend, indicating that Sichuan's sustainable manufacturing industry development was improving, which may have been a result of the 2015 release of the *Silk Road Economic Belt and the 21st-Century Maritime Silk Road* report that encouraged the orderly and free flow of economic elements, the efficient allocation of resources, and deeper market integration. At the same time, the government officially released the *Made in China 2025* policy, which was focused on "innovation-driven, quality first, green developments, structural optimization and talent-oriented" and outlined eight strategic countermeasures: promoting digital networked intelligent manufacturing; improving product design capabilities; improving manufacturing technological innovation systems; strengthening the manufacturing foundation; improving product quality; promoting green manufacturing; training enterprise groups and profitable industries to be globally competitive; and developing a modern manufacturing service industry.

5.2.2 Subsystem results analysis

The overall system analysis of Sichuan's sustainable manufacturing industry development had an

inverted U-shaped curve from 2009 to 2016, reached its peak in 2013, and continued to rise after 2016. The time series trends from 2009 to 2018 in the seven subsystems were more closely examined to identify the specific reasons, as shown in Table 4 and Figure 2.

Figure 2: Sustainable manufacturing industry development

(1) Innovation efficiency

Innovation-driven efficiency had an overall upward trend over the ten-year period, which indicated that the manufacturing sector had been giving greater attention to scientific and technological innovations to achieve sustainable core competitiveness and uniqueness advantages. This was also reflected in the increasing proportion of science and technology expenditures in the general Sichuan Province government spending and the increase in R&D personnel investments, R&D funds investment, and new product development funding. As the three third-level indicators of innovation output also had increasing trends over the ten years, innovation input proved effective in improving the overall manufacturing industry innovation efficiency.

(2) Structural optimization efficiency

The structural optimization efficiency had an inverted U-shaped curve that was high from 2012 to 2015 and had a downward trend to 2018 because of enterprise and export structural changes. Specifically, after 2015, the main significant and medium-sized manufacturing enterprise business income proportion of the above-scale manufacturing enterprises and the high-tech manufacturing export delivery value proportion of the manufacturing export delivery decreased, indicating that the small and microenterprise market shares were expanding. At the same time, Sichuan's high-tech manufacturing industry export share shrank, its export competitiveness declined, and its technological input efficiency decreased.

(3) Economic benefit efficiency

The economic benefit efficiency also had an inverted U-shaped curve, with the best economic development period from 2011 to 2014, which may have been because of the *12th Five Year* industrial Sichuan Province development plan that highlighted the leading role of industry in Sichuan's economic development and promoted industrial acceleration as the primary focus. Overall, Sichuan's high-level manufacturing industry growth rate and profitability during the *12th Five Year Plan* period indicated that policy guidance played an essential role in Sichuan's manufacturing industry development. However, after 2015, the economic benefit efficiency declined because production costs and the asset-liability ratio increased.

(4) Efficiency improvements

From 2009-2011 and 2014-2017, there were efficiency improvements, and from 2011-2014, the Sichuan manufacturing industry production factor input efficiency was stable. As only the returns on manufacturing industry capital efficiency declined from 2011 to 2015, the overall efficiency improvements were relatively stable from 2011 to 2014.

(5) Green development efficiency

The green development efficiency showed a downward trend over the ten years. Its low level in the last few years of the observation period implied that the relationships between economic development and environmental sustainability in the Sichuan manufacturing industry were not well coordinated. Expressly, allocations in the Sichuan government's budget for energy conservation and ecological protection declined from 2009 to 2016; however, after 2016, there was some improvement, which may have been because of the *13th Five Year Plan for Industrial Green Development of Sichuan Province* and the establishment of a regional green manufacturing industry alliance. However, there was no improvement in the industrial solid waste utilization rate, which was relatively high at 57.5% in 2009 but fell to 38.46%, 39.2%, and 38.83% in 2016, 2017, and 2018, respectively. These results indicated that there had not been any breakthroughs in waste utilization technology, which meant that the industrial solid waste disposal and utilization rate had remained the same as in 2008. If industrial solid waste is not effectively disposed of, it can cause immeasurable damage to the environment, restrict enterprise production activities, and eventually disrupt normal industry development.

(6) International competitiveness

The international competitiveness of Sichuan's manufacturing industry had an inverted U-shaped curve during the observation period. It was high and improved from 2012-2015, which may have been because the *One Belt, One Road* (Ferdinand, 2016) initiative and strategies provided an excellent political platform for Sichuan enterprises to develop more open relationships. However, after 2016, international competitiveness began to decline, possibly because of the decline in total foreign investment in Sichuan Province and its trade structure transformation. Since 2006, the Sichuan Province trade surplus has decreased because the total import growth rate was faster than the total export growth rate. As a result, the international competitiveness of Sichuan's manufacturing industry has not improved significantly.

(7) Social benefit

The social benefit index efficiency of Sichuan's manufacturing industry, evaluated based on employer contributions and income contributions, showed an inverted U-shaped curve during the observation period. Sichuan's manufacturing industry employment contribution increased over the observation decade, which indicated that manufacturing industry development still needed additional human resources. However, the average manufacturing employee wages were lower than the average across the province, and in 2017 and 2018, they were lower than those of the entire province. This indicated that Sichuan's manufacturing industry worker skills were soft, and there was a lack of highly skilled talent, which indicated that labor-intensive industries possibly made up a more significant proportion of Sichuan's manufacturing industry sector.

In general, as both innovation and overall manufacturing industry efficiency rose throughout the entire observation period, two indicators contributed the most to Sichuan's sustainable manufacturing industry development from 2009 to 2018. Innovation-led science and technology promoted factor input productivity efficiencies, which was empirically demonstrated in the consistency of the two development curves.

Poor green development performance needs to be resolved to ensure sustainable development in Sichuan's manufacturing industry. In particular, there is a need to accelerate technological upgrading to

increase the industrial solid waste utilization rate. The overall evaluation revealed that development quality during the 12th Five Year Plan period was the highest, declined in the years following, and began to rise again in some indicators after 2017. Therefore, the development experiences during the *12th Five Year Plan* period, such as optimizing industrial layouts, constructing modern industrial systems, adjusting the industrial structure, and transforming the development modes, need to inform future sustainable development efforts.

6. Conclusions and recommendations

Based on the specific sustainable manufacturing industry development indicators, this study developed a multidimensional index system to assess the development over time in seven main dimensions: innovation, structural optimization, economic benefit, efficiency improvements, green development, international competitiveness, and social use. To precisely measure the manufacturing industry development in Sichuan Province from 2009 to 2018, a combination objective weighted gray correlation TOPSIS method was employed to objectively assess the sustainable development status and provide decision advice. Findings were as follows.

(1) Sichuan's manufacturing industry's quality development had a U-shaped curve from 2009 to 2016 but a steady upward trend after 2016.

(2) From 2009 to 2018, innovation and efficiency rose and were the most important driving forces for promoting Sichuan's sustainable manufacturing industry development. However, green development was declining, which meant that energy conservation and environmental protection needed improvement to ensure further sustainable manufacturing industry development.

(3) The structural optimization, economic benefit, international competitiveness, and social benefit developments all had inverted U-shaped curves in the early part of the ten-year period. It was highest during the *12th Five Year Plan* period, which provided an historical reference for promoting future sustainable manufacturing industry development.

Therefore, based on these empirical results, the following policy recommendations were developed.

(1) Implement an innovation-driven development strategy

The theoretical analysis and empirical results revealed that innovation was an important driver of sustainable manufacturing industry development. In addition to continuing to adhere to scientific, technological, and system innovations to develop positive innovation environments, it is also necessary to increase scientific and technological innovation element inputs, strengthen scientific and technical innovation talent teams, accelerate the construction of collaborative "industry-university research" cooperation chains, and integrate information and industrialization to harness industry advantages.

(2) Transform traditional manufacturing industries to promote green development

There is an urgent need to complete intelligent industrial manufacturing upgrading and transformation to reduce environmental pollution and improve production efficiency and product quality, and green energy-saving manufacturing technology needs to be implemented to reduce ecological damage. Further, management efficiency should be improved and the industrial transformation and upgrading process accelerated.

(3) Fulfill the social responsibilities and improve the social benefits

Enterprise development must, in essence, improve society by enhancing people's sense of gain and honoring employees to improve their business level and happiness index. Corporate social responsibility also includes environmental protection; therefore, enterprises need to vigorously promote green manufacturing and develop sustainable manufacturing industry development modes that grow with employees, progress

with society and are environmentally friendly so that the sustainable development results can be shared with the people.

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Author contributions

Conceptualization: [MY]; Methodology: [QW]; Formal analysis and investigation: [MY]; Writing - original draft preparation: [MY]; Writing - review and editing: [QW]; Funding acquisition: [FD]; Supervision: [FD]. All authors read and approved the final manuscript.

Additional Information (including a Competing Interests Statement)

The authors declare that they have no competing interests.

Figure legends

Figure 1: Efficiency Evaluation of Sichuan Province's sustainable manufacturing industry development. It can be seen that sustainable development had an inverted U-shaped curve from 2009 to 2016, reached its peak in 2013, and could be divided into three distinct stages.

Figure 2: Sustainable manufacturing industry development. In general, as both innovation and overall manufacturing industry efficiency rose throughout the entire observation period, two indicators contributed the most to Sichuan's sustainable manufacturing industry development from 2009 to 2018. Innovation-led science and technology promoted factor input productivity efficiencies, which was empirically demonstrated in the consistency of the two development curves.

Tables

Table 1 High-quality Sichuan manufacturing industry development index

Primary Indicators	Secondary indicators	No.	Third-level index	Unit	Attribute
Innovation A	Innovation environment A1	A11	Proportion of science and technology expenditure in the government budget	%	+
	Innovation input A2	A21	Proportion of R&D personnel	%	+
		A22	Proportion of R&D investment	%	+
		A23	New product development expenses	100 million CNY	+
	Innovation output A3	A31	Number of invention patents per unit of R&D expenditure	Per unit/100 million CNY	+
		A32	Technology market transaction volume per 10000 scientific and technology personnel	100 million CNY	+
		A33	Proportion of new product sales revenue	%	+
Structural optimization B	Industrial structure B1	B11	Proportion of high-tech manufacturing value in total manufacturing industry output value	%	+
	enterprise structure B2	B21	Proportion of main business income in manufacturing enterprises above the designated large- and medium-sized manufacturing enterprise sizes	%	+
	Export structure B3	B31	Proportion of high-tech export delivery value in total manufacturing industry export delivery value	%	+
Economic benefits C	Growth rate C1	C11	Total output value growth rate	%	+
	production costs C2	C21	Main business income unit costs	%	-
	Profitability C3	C31	Main business manufacturing enterprise profit margin	%	+
	Assets and liabilities C4	C41	Asset/liability ratio	%	-
Efficiency improvement D	Labor efficiency D1	D11	Labor productivity	100 million CNY per people	+
	Capital efficiency D2	D21	Return on assets	%	+
	energy efficiency D3	D31	Value added per unit of energy consumption	%	+
Green development E	Green technology E1	E11	Comprehensive utilization rate for industrial solid waste	%	+
	environmental protection E2	E21	Proportion of environmental protection expenditure in government budget	%	+
International competition F	foreign investment F1	F11	Total amount of foreign investment utilized by the manufacturing industry	Million US dollars	+
	Trade competition F2	F21	Trade competitiveness index	—	+
Social benefits G	Employment contribution G1	G11	Employment contribution rate	%	+
	Income contribution G2	G21	Income contribution rate	Ten thousand CNY	+

Table 2: Descriptive statistics for the evaluation indices

Index number	Number of samples	minimum value	Maximum value	mean value	standard deviation
A11	10	0.798	1.524	1.130	0.223
A21	10	2.168	5.309	3.271	1.001
A22	10	0.350	0.818	0.593	0.148
A23	10	100.539	315.648	185.312	66.488
A31	10	15.539	46.195	34.490	9.990
A32	10	4.092	31.471	10.471	8.131
A33	10	6.747	18.769	8.976	3.653
B11	10	10.668	17.400	14.627	1.991
B21	10	56.987	66.455	61.381	3.323
B31	10	54.068	58.966	56.825	1.775
C11	10	0.224	31.511	11.704	11.454
C21	10	82.386	84.992	83.633	0.871
C31	10	5.757	8.667	7.527	1.024
C41	10	0.541	1.006	0.613	0.139
D11	10	59.963	116.525	88.249	19.747
D21	10	6.195	9.789	7.915	1.084
D31	10	0.563	0.946	0.760	0.126
E11	10	38.460	57.500	44.966	6.607
E21	10	2.077	3.188	2.480	0.302
F11	10	284.063	658.767	523.794	104.706
F21	10	0.103	0.301	0.206	0.080
G11	10	10.835	12.561	11.931	0.528
G21	10	83.540	89.769	86.015	2.089

Table 3: Weight information for the evaluation indices

Index number	Entropy weight	Mean square error weight	Maximum deviation weight	Combination weight	Comprehensive weight of first level index
A11	0.0443	0.0411	0.0427	0.0406	0.2614
A21	0.0419	0.0427	0.0431	0.0403	
A22	0.0456	0.0424	0.0448	0.0452	
A23	0.0428	0.0414	0.0428	0.0397	
A31	0.0462	0.0437	0.0443	0.0467	
A32	0.0369	0.0398	0.0351	0.0270	
A33	0.0318	0.0407	0.0324	0.0219	
B11	0.0466	0.0396	0.0410	0.0395	0.1503
B21	0.0438	0.0470	0.0488	0.0525	
B31	0.0448	0.0486	0.0513	0.0583	
C11	0.0397	0.0491	0.0498	0.0506	0.1809
C21	0.0448	0.0448	0.0472	0.0495	
C31	0.0456	0.0471	0.0483	0.0542	
C41	0.0478	0.0401	0.0266	0.0266	
D11	0.0443	0.0468	0.0498	0.0539	0.1426
D21	0.0453	0.0404	0.0427	0.0408	
D31	0.0450	0.0440	0.0463	0.0479	
E11	0.0396	0.0465	0.0467	0.0450	0.0746
E21	0.0444	0.0364	0.0351	0.0296	
F11	0.0472	0.0374	0.0365	0.0337	0.1028
F21	0.0430	0.0544	0.0566	0.0691	
G11	0.0467	0.0410	0.0410	0.0410	0.0873
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Table 4: Evaluation of Sichuan's sustainable manufacturing industry development

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2010	0.3162	0.3668	0.7354	0.3923	0.6396	0.3526	0.4901	0.4593
2011	0.2801	0.5902	0.7105	0.4972	0.4495	0.6012	0.5312	0.5137
2012	0.3672	0.6093	0.6320	0.4798	0.4240	0.7678	0.5530	0.5412
2013	0.4160	0.6552	0.5662	0.5049	0.3487	0.7492	0.7405	0.5553
2014	0.4833	0.6661	0.3804	0.4929	0.3611	0.7037	0.7081	0.5297
2015	0.4968	0.4590	0.3145	0.5659	0.3500	0.7259	0.5718	0.4911
2016	0.5134	0.3891	0.4115	0.6128	0.1956	0.3239	0.5524	0.4579
2017	0.5918	0.4213	0.4385	0.7055	0.2491	0.2812	0.5232	0.4903
2018	0.7019	0.4037	0.5767	0.7037	0.2630	0.3684	0.4961	0.5469