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Research on the evaluation of Chinese intelligent manufacturing policy under the four-dimensional analysis framework

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Abstract. This paper utilizes the entropy TOPSIS method to evaluate the effectiveness of China's intelligent manufacturing policies under a four-dimensional analysis framework, which encompasses policy objectives, policy intensity, policy tools, and policy subjects. By selecting the intelligent manufacturing-related policy texts released between 2015 and 2024, this study aims to identify deficiencies and provide references for subsequent policy adjustments and formulations. Through empirical analysis, the echelon differences in policy evaluation results are revealed. The findings contribute to a deeper understanding of China's intelligent manufacturing policies and provide suggestions for future policy-making.

1 Introduction

In the ongoing evolution of the new industrial revolution, the digital, networked, and intelligent transformation of manufacturing has emerged as a prominent development direction. Intelligent manufacturing, as a novel production method, has become the focal point of competition among global industrial powers. It serves not only as a new driving force for the transformation and upgrading of the manufacturing sector but also as a crucial avenue for cultivating and establishing new quality productive forces. For China, the onset of the intelligent manufacturing era presents both challenges and opportunities.

Today, Chinese manufacturing has taken its place on the global stage. However, in the competitive realm of high-precision industrial products, we continue to encounter significant "bottleneck" issues in cutting-edge manufacturing and testing technologies, indicating a gap in core technological research compared to traditional manufacturing powerhouses. National policy plays a crucial role as a guiding framework for the development of intelligent manufacturing, providing essential support. Countries worldwide are actively implementing intelligent manufacturing policies to foster their manufacturing sectors. Therefore, investigating the effectiveness of China's intelligent manufacturing policies and conducting comparative evaluations of their strengths and weaknesses is vital for advancing the development of intelligent manufacturing in China.

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2 Literature review

Current research on intelligent manufacturing primarily focuses on the connotations of intelligent manufacturing within the context of Industry 4.0 and the development models of intelligent manufacturing across various countries. [1] The mechanism of intelligent manufacturing operates by leveraging various smart sensors, adaptive decision-making models, advanced materials, intelligent devices, and data analytics to enhance the entire product lifecycle [2], thereby improving production efficiency, product quality, and service levels [3]. This is realized through Intelligent Manufacturing Systems (IMS), which provide collaborative, customizable, flexible, and reconfigurable services to end-users via a service-oriented architecture (SOA) over the Internet, thus achieving a highly integrated human-machine manufacturing system [4].

For instance, the Festo Didactic Cyber-Physical Factory, part of the German government's Industry 4.0 strategy, offers technical training and certification for major suppliers, universities, and schools [5]. In the United States, the emphasis is mainly on top-level IT aspects, such as cloud computing, big data, and virtual reality (VR) [6]. General Electric's Industrial Internet of Things (IIoT) platform, Predix, reportedly enables industrial-scale analytics for asset performance management and operational optimization by providing standardized methods for connecting machines, data, and people [7]. Japan has initiated the Industrial Value Chain Initiative (IVI), a forum that integrates manufacturing and information technology to design a new society and create collaborative spaces for enterprises [8]. Cloud manufacturing, as an innovative form of intelligent manufacturing, was first proposed by China [9] and has been widely cited and applied in numerous academic works [10]. Furthermore, China has made significant contributions in specific areas of intelligent manufacturing, such as high-end CNC machine tools, industrial robots, smart instruments, and additive manufacturing, establishing an initial standard system for intelligent manufacturing [6].

Compared to countries like the United States, Japan, and Germany, China still lacks a series of leading enterprises in mobile internet, big data, and cloud computing that support the development of intelligent manufacturing. To facilitate the transformation of the manufacturing sector, the Chinese government has proposed strategic plans such as the "Intelligent Manufacturing Development Plan (2016-2020)", which have yielded certain results but still have room for improvement. National policy serves as the foundation for promoting the development of intelligent manufacturing; however, academic research and comparative evaluations of these intelligent manufacturing policies remain largely absent.

Based on this context, to further expand and enrich research on China's intelligent manufacturing policies, a four-dimensional policy analysis framework encompassing policy objectives, policy intensity, policy tools, and policy subjects is proposed. This framework will utilize policy texts related to intelligent manufacturing released in China between 2015 and 2024 as research samples. Through policy text analysis and the entropy weight TOPSIS method, this study will evaluate and analyze China's intelligent manufacturing policies since 2015, identifying deficiencies and providing a reference for the subsequent adjustment and formulation of intelligent manufacturing policies.

3 Research design

3.1 Construction of the four-dimensional policy analysis framework

In 1980, Paul Sabatier and Daniel Mazmanian proposed a comprehensive model for policy implementation in their work, "The Implementation of Public Policy: A Framework of

Analysis" [11]. This model, which examines the variables involved in policy execution, has had a groundbreaking impact on the field of Western policy studies. It emphasizes the significant influence of the characteristics of policy texts on implementation outcomes and adopts a top-down analytical perspective to explore the processes of policy formulation and execution.

Building upon the policy execution concepts of Sabatier and Mazmanian, this study further integrates current research findings in the field of intelligent manufacturing policy. It comprehensively examines China's policies on intelligent manufacturing since 2015 and constructs a top-down four-dimensional policy analysis framework (see Figure 1). This framework includes four core variables: "Policy Objectives," "Policy Intensity," "Policy Tools," and "Policy Subjects," aiming to provide a systematic theoretical support for intelligent manufacturing policy by analyzing policy texts to reveal the multidimensional characteristics of the policies and their inherent logic and execution mechanisms. Among these, policy objectives serve as the starting point for policy analysis, defining the expected outcomes of the policy and providing direction for its execution [12]; policy intensity refers to the hierarchy and coordination of the issuing bodies, which significantly impacts the authority of the policy itself and the influence and constraints on its subjects; policy tools are the means to achieve policy objectives, encompassing various types such as legal, economic, and administrative tools, acting as a bridge between policy objectives and outcomes; and policy subjects are the direct targets of policy influence, including individuals, organizations, and society, whose interactions have a direct impact on policy execution and effectiveness. In the context of discussing the development of intelligent manufacturing in China, the four-dimensional analysis framework demonstrates high adaptability and foresight. This framework not only meets the evolving and deepening demands of intelligent manufacturing but also reflects the special requirements arising from significant social power disparities in the era of Industry 4.0 regarding social governance objectives, policy intensity, policy tools, and policy subjects.

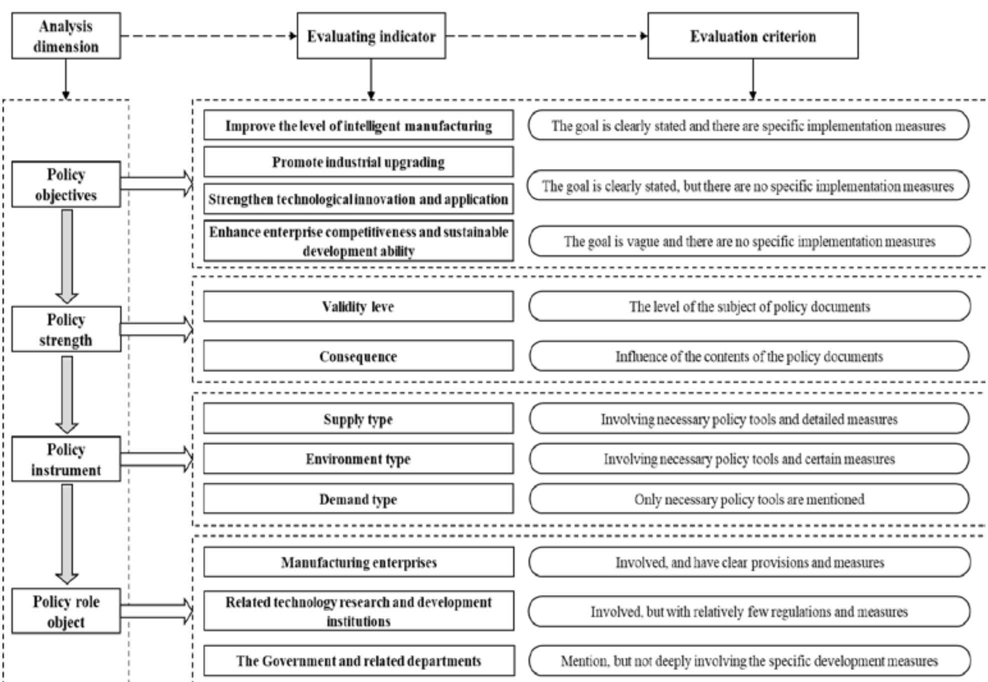

Fig. 1. Top-down four-dimensional policy analysis framework.

3.2 Research methods

The entropy weight TOPSIS method is a comprehensive evaluation approach that integrates the entropy weight method and the TOPSIS method. The entropy weight method, based on information entropy theory, objectively assigns weights according to the differences in indicator values; the greater the variability in indicator data, the richer the discernible information contained in the indicators, thus leading to higher weights. The TOPSIS method is a dual-benchmark evaluation approach that first selects the best and worst solutions for each indicator to form positive and negative ideal solutions, and then calculates the relative closeness degree of each evaluation unit to these ideal solutions to assess the quality of the options. The entropy weight method provides a way to determine weights based on the information content of the data itself, significantly overcoming the influence of subjective human factors. The TOPSIS method fully utilizes data information and is conducive to integration with other methods. By combining the two, the entropy weight TOPSIS method can objectively evaluate the effectiveness of intelligent manufacturing policies, yielding persuasive results in policy evaluation.

The entropy weight TOPSIS method is illustrated as below.

(a) Assume there are M evaluation units and N indicators. Build the original matrix $\boldsymbol{X} = [x_{ij}]_{M \times N}$, where x_{ij} denotes the original data of the j -th indicator of the i -th evaluation unit.

(b) We use Eq. (1) for normalization, so as to achieve dimensionless transformation. The resulting normalized matrix is denoted as $\boldsymbol{Z} = [z_{ij}]_{M \times N}$.

$$z_{ij} = \frac{x_{ij} - \min\limits_{1 \le i \le M}(x_{ij})}{\max\limits_{1 \le i \le M}(x_{ij}) - \min\limits_{1 \le i \le M}(x_{ij})}, \quad i = 1, \cdots M; j = 1, \cdots N \tag{1}$$

(c) Compute the proportion of the j -th indicator of the i -th evaluation unit (p_{ij}):

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{M} z_{ij}}, \quad i = 1, \cdots M; j = 1, \cdots N \tag{2}$$

(d) Calculate the entropy e_j of the j -th indicator in the following:

$$e_j = -\frac{1}{\ln M} \sum_{i=1}^{M} p_{ij} \ln p_{ij}, \quad j = 1, \cdots N \tag{3}$$

Note that $p_{ij} \ln p_{ij} = 0$ when $p_{ij} = 0$.

(e) As in Eq. (4), calculate the weight v_j of indicator j :

$$v_j = \frac{1 - e_j}{M - \sum_{j=1}^{N} e_j}, \quad j = 1, \cdots N \tag{4}$$

(f) By using Eq. (5), we can gain the weighted normalized matrix:

$$\boldsymbol{R} = [r_{ij}]_{M \times N} = [v_j \bullet z_{ij}]_{M \times N} \tag{5}$$

(g) Derive the positive ideal-solution S_j^+ and the negative ideal-solution S_j^- through Eqs. (6) and (7), respectively:

$$S_j^+ = \max_{1 \le i \le M} r_{ij}, \quad j = 1, 2, \cdots, N \tag{6}$$

$$S_j^- = \min_{1 \le i \le M} r_{ij}, \quad j = 1, 2, \cdots, N \tag{7}$$

(h) Compute the Euclidean distances of the all evaluation units from the positive and negative ideal-solutions (D_i^+ and D_i^-), as shown in Eqs. (8) and (9), respectively:

$$D_i^+ = \sqrt{\sum_{j=1}^{N} \left(r_{ij} - S_j^+ \right)^2}, \quad i = 1, \cdots M \tag{8}$$

$$D_i^- = \sqrt{\sum_{j=1}^{N} \left(r_{ij} - S_j^- \right)^2}, \quad i = 1, \cdots M \tag{9}$$

(i) Calculate the relative closeness degrees C_i of the evaluation units:

$$C_i = \frac{D_i^-}{D_i^- + D_i^+}, \quad i = 1, \cdots M \tag{10}$$

The higher the relative closeness degree, the better the evaluation unit.

3.3 Selection of intelligent manufacturing related policy texts

North of this big magic weapon, the Chinese government network, the Ministry of Industry and Information Technology, the state Internet information office and other official intelligent manufacturing policy platform as the foundation, with "intelligent manufacturing" "industry", "information", "artificial intelligence" as the key words, in 2015 China about intelligent manufacturing specialized comprehensive policy "made in China 2025" of intelligent manufacturing related policy documents for retrieval. In order to ensure the representativeness and authority of the policy text, the screening criteria include: first, select the policy text at the national level, such as the documents issued by the CPC Central Committee, The State Council and its directly affiliated institutions; second, the content of the text is closely related to "intelligent manufacturing"; third, select the documents of work guidelines and plans, and fourth, to ensure that the text is currently effective. After screening and sorting, 8 policy documents were finally identified as the research basis (Table 1).

3.4 Construction of the evaluation index system

Based on the basis of the classification framework of policy dimensions, this paper establishes three-level indicators of policy evaluation from four dimensions: policy objectives, policy intensity, policy tools and policy action objects, with a total of 12 items, as shown in Table 2.

3.5 Index quantification standard

The essence of policy quantification is to score the relevant indicators according to certain standards. In order to better study the intelligent manufacturing policy, the policy text is assigned value refinement from four dimensions: policy objectives, policy strength, policy tools, and policy action objects. Combined with the characteristics of different indicators and the impact on the intelligent manufacturing policy, the score standard of each intelligent manufacturing policy is set, and the quantitative standards are shown in Tables 3~6.

Table 1. Policy texts related to smart manufacturing.

Number	Name	Promulgated time
T1	Made in China (2025)	2015.5.8
T2	Smart Manufacturing Development Plan (2016 - 2020)	2016.9.28
T3	Guiding Opinions of the State Council on Deepening the “Internet plus Advanced Manufacturing” and Developing the Industrial Internet	2017.11.19
T4	Notice of the General Office of the Ministry of Industry and Information Technology on Issuing the "5G+Industrial Internet" 512 Project Promotion Plan	2019.11.19
T5	Industrial Internet Innovation and Development Action Plan (2021-2023)	2020.12.22
T6	"14th Five-Year Plan" Intelligent Manufacturing Development Plan	2021.12.21
T7	Notice of five departments on launching the 2023 smart manufacturing pilot demonstration action	2023.7.28
T8	Notice of the General Office of the Ministry of Industry and Information Technology and the General Office of the State Administration for Market Regulation on launching the application process for the 2024 Smart Manufacturing System Solution	2024.10.21

Table 2. Intelligent manufacturing policy evaluation index system.

Evaluation target	Analysis dimension	Evaluating indicator
Effectiveness of the intelligent manufacturing policy	Policy objectives	Improve the level of intelligent manufacturing
		Promote industrial upgrading
		Strengthen technological innovation and application
		Enhance enterprise competitiveness and sustainable development ability
	Policy strength	Validity level
		Consequence
	Policy instrument	Supply type
		Environment type
		Demand type
	Policy role object	Manufacturing enterprises
		Related technology research and development institutions
		The Government and related departments

Table 3. Judgment criteria for policy objectives.

Evaluation criterion	Score
The goal is clearly stated and there are specific implementation measures	3
The goal is clearly stated, but there are no specific implementation measures	2
The goal is vague and there are no specific implementation measures	1

(For policy objectives, we select 4 evaluating indicators: ① Promote the development of intelligent manufacturing and improve the level of intelligent manufacturing; ②

Promote industrial upgrading and improve the core competitiveness of manufacturing industry; ③ Strengthen technological innovation and application, and break through key core technologies; ④ Enhance corporate competitiveness and sustainable development capabilities.)

Table 4. Judgment criteria for policy strength.

Evaluating indicator	Evaluation criterion	Score
Validity level	Regulation	4
	Normative documents of The State Council	3
	Normative documents of The State Council departments	2
	Notice file	1
Consequence	A national long-term strategic plan released by the State Council.	4
	Plan for specific industries issued by The State Council	3
	Strategic plans for specific industries issued by ministries and commissions under The State Council	2
	Policies released by State Council ministries and commissions	1

Table 5. Judgment criteria of policy instruments.

Evaluating indicator	Evaluation criterion	Score
Supply type	It involves the supply of necessary funds, talents, facilities, technology, information and other elements to achieve policy goals, and is accompanied by detailed regulations and measures.	3
	It involves the supply of necessary funds, talents, facilities, technology, information and other elements to achieve policy goals, with certain regulations and measures	2
	Only provide the necessary funds, talents, facilities, technology, information and other elements to achieve policy goals	1
Environment type	It involves the use of policy sub-tools such as target planning, tax subsidies, supervision and management, unified standards, monitoring and evaluation, etc., which are necessary to shape the environment for achieving policy goals, and is equipped with detailed regulations and measures.	3
	It involves the use of policy sub-tools such as target planning, tax subsidies, supervision and management, unified standards, monitoring and evaluation, etc., which are necessary to shape the environment for achieving policy goals, and is equipped with certain regulations and measures.	2
	Only the necessary policy sub-tools such as target planning, tax subsidies, supervision and management, unified standards, monitoring and evaluation, etc. are mentioned to shape the environment for achieving policy goals.	1
Demand type	It involves the use of policy sub-tools such as purchasing services, international cooperation, and policy subsidies that are necessary to achieve policy goals, and is accompanied by detailed regulations and measures.	3
	It involves the use of policy sub-tools such as purchasing services, international cooperation, and policy subsidies that are necessary to achieve policy goals, and is accompanied by certain regulations and measures.	2
	Only mentions the use of policy sub-tools such as purchasing services, international cooperation, and policy subsidies necessary to achieve policy goals	1

Table 6. Criteria for policy objects.

Evaluation criterion	Score
Involve the rights and obligations of the relevant subjects, and provide detailed requirements and guidance	3
It involves the rights and obligations of the relevant subjects, but the regulations and measures are not comprehensive enough	2
Only the relevant subjects are mentioned, but the specific measures are not detailed	1

(For policy objects, we select 3 evaluating indicators: ① Manufacturing Enterprises; ② Intelligent manufacturing related technology research and development institutions (universities, research institutes, etc.; ③ The Government and relevant departments.)

4 Empirical analysis of policy evaluation

According to the principle of entropy weight method, the twelve evaluation indicators of the above eight regulations and policies are calculated according to formula (1) ~ (4), and the results of the entropy right weight of the first-level indicators are obtained as shown in Table 7.

Table 7. Entropy weight value of policy evaluation index.

Evaluating indicator	Policy objectives	Policy strength	Policy instrument	Policy role object
Weight w	0.178	0.377	0.242	0.172

As can be seen from Table 7, the weights of policy strength, policy tools, policy objectives and policy objects are 0.178,0.377,0.242 and 0.172 respectively, and the gap between the entropy weight of each index is small. Among them, the policy tool evaluation index has the greatest impact on the intelligent manufacturing policy evaluation, and the policy action object evaluation index has the least impact on the intelligent manufacturing policy evaluation.

Table 8. Comprehensive evaluation value of intelligent manufacturing policy.

Number	Policy name	Relative closeness degree	Sort
T1	Made in China (2025)	0.7318	2
T2	Smart Manufacturing Development Plan (2016 - 2020)	0.4646	3
T3	Guiding Opinions of the State Council on Deepening the “Internet plus Advanced Manufacturing” and Developing the Industrial Internet	0.8209	1
T4	Notice of the General Office of the Ministry of Industry and Information Technology on Issuing the "5G+Industrial Internet" 512 Project Promotion Plan	0.3318	6
T5	Industrial Internet Innovation and Development Action Plan (2021-2023)	0.3327	5
T6	"14th Five-Year Plan" Intelligent Manufacturing Development Plan	0.4407	4
T7	Notice of five departments on launching the 2023 smart manufacturing pilot demonstration action	0.1359	7
T8	Notice of the General Office of the Ministry of Industry and Information Technology and the General Office of the State Administration for Market Regulation on launching the application process for the 2024 Smart Manufacturing System Solution	0.1193	8

According to the evaluation principle of TOPSIS method, and calculated according to Eqs. (5)~(10), the relative closeness degree of each policy text, i.e., the comprehensive evaluation value of the policy text, is obtained. The results are shown in Table 8.

T3, T1, T2, and T6 were ranked high, mainly for the following reasons:

(1) Clear, comprehensive goals encompassing intelligent manufacturing development, industry upgrading, tech innovation, enterprise competitiveness, and sustainability.

(2) Strong policy impact, significantly promoting intelligent manufacturing.

(3) Comprehensive policy tools used.

(4) Emphasis on manufacturing enterprises, industrial ecosystem, and government coordination.

T5, T4, T7, and T8 ranked low reasons:

Limited, short-term goals focusing on specific areas, lacking overall planning.

Low policy effectiveness, mainly impacting specific fields or participants.

(3) Single policy tool use, lacking specificity, innovation, and flexibility.

(4) Narrow policy target, focusing on specific projects or solutions, with limited enterprise coverage and support for diverse enterprises. Insufficient attention to tech R&D institutions and local governments.

5 Conclusion and suggestion

5.1 Conclusion

This study created a four-dimensional policy analysis framework (policy objectives, strength, tools, objects) and quantitatively evaluated China's intelligent manufacturing policies from 2015 to 2024 using data and scholarly opinions. To ensure objectivity and persuasiveness, the study applied the entropy weight TOPSIS method, considering information from each indicator to determine weights, calculate relative closeness to the ideal solution, and assess policy quality. Results indicate progress but also challenges. Policies fall into tiers: T3, T1, T2, and T6 excel in all dimensions (clear objectives, combined tools, high impact, wide coverage). T5, T4, T7, and T8 perform poorly: limited objectives, single tool use, low impact, narrow coverage.

5.2 Suggestions

Clarify and refine China's smart manufacturing policy objectives, setting clear, measurable, and time-limited goals across multiple dimensions like technology, industry, corporate competitiveness, talent, and green manufacturing. Ensure objectives are interconnected and forward-thinking, with cross-departmental collaboration.

Enhance policy effectiveness for strategically important smart manufacturing policies, ensuring authority and enforcement through robust implementation and supervision.

Utilize multiple policy tools tailored to smart manufacturing stages and needs, innovating designs and coordinating types to avoid conflicts and duplications.

Formulate inclusive and relevant policies considering various manufacturing enterprises. Support tech R&D institutions, promoting production-learning-research integration. Strengthen local government-enterprise cooperation, clarifying roles and responsibilities, with effective assessment and incentives.

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