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Research Status and Future Prospects of Intelligent Manufacturing Evaluation Theory

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Abstract: Intelligent manufacturing is crucial for constructing a powerful manufacturing country. As China's intelligent manufacturing enters a comprehensive promotion stage, the scientific evaluation of intelligent manufacturing becomes a practical demand. This study provides a systematic survey of the intelligent manufacturing evaluation theories in recent years. The evaluation index systems of intelligent manufacturing are classified and summarized from three dimensions: key technology, overall system, and specific sectors. Furthermore, the methods commonly used in intelligent manufacturing evaluation are compared and analyzed. This study also investigates the major problems regarding intelligent manufacturing evaluation and discusses future research directions in the field. Currently, there are deficiencies in the standards, processes, index system, and application of intelligent manufacturing evaluation. The evaluation paradigm, evaluation system, and new technology integration must be improved to promote the research of intelligent manufacturing evaluation theories and guide the development of intelligent manufacturing. Specifically, China should improve the standards design to establish an intelligent manufacturing evaluation paradigm, optimize the index system to enrich the key evaluation content, strengthen the integration of new technologies, and promote the synergy of theory and practice.
Keywords: intelligent manufacturing; evaluation theory; index system; evaluation paradigm; new technology integration

1 Introduction

Intelligent manufacturing is the core driving force of the new round industrial revolution and an important development direction of the world's manufacturing industry. As the main path toward constructing a powerful manufacturing country, the development level of intelligent manufacturing is related to the future international competitiveness of China's manufacturing industry [1,2]. After years of continuous efforts, China's intelligent manufacturing has gradually entered the deepening application and comprehensive promotion phase after the initial concept popularization and the establishment of pilot demonstration. Intelligent manufacturing has achieved rapid development and remarkable results in some large benchmark enterprises. However, introducing intelligent manufacturing is still a unique challenge for ordinary enterprises, especially small- and medium-sized enterprises [3]. Most enterprises are in the initial stage of developing intelligent manufacturing, and cognitive confusion and practical misunderstanding remain. Enterprises fail to determine their own position in the intelligent transformation, so it is difficult for enterprises to determine a clear implementation path of intelligent manufacturing. All of the above are urgent issues to be solved in the comprehensive promotion and layout phase of intelligent manufacturing in China.

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For enterprises, making a reasonable judgment on the stage of their own intelligent manufacturing is the premise of clarifying the path of intelligent development. Building an evaluation system to accurately measure the intelligent level of enterprises can not only provide a basis for formulating macro policies of the industry but also help enterprises promptly identify bottlenecks and scientifically plan development paths to assist management decisions. At present, intelligent manufacturing evaluation research has received extensive attention from academia and industry, and relevant research findings have successively emerged. It is necessary to investigate, classify, and summarize the research achievements of intelligent manufacturing evaluation in time and scientifically refine the future development direction of the field. It should also be noted that the existing review articles focus more on the conceptual framework [4,5] and technical progress [6,7] of intelligent manufacturing and less on investigating and summarizing the advancement of intelligent manufacturing evaluation research. Given this gap, this study attempts to comprehensively review the existing literature on the research direction of intelligent manufacturing evaluation theories, provides a systematic survey of frontiers progress from the two aspects of the evaluation system and evaluation method, and strives to deeply explore the problems existing in this research direction and look forward to the future development, in order to provide a basic reference for practitioners and researchers in the field of intelligent manufacturing.

2 Research status of the intelligent manufacturing evaluation system

The early research of intelligent manufacturing evaluation mainly focuses on a specific technical field. With the growing understanding of intelligent manufacturing, the corresponding evaluation system is also developing from part to whole, from single to multivariant. In recent years, the evaluation index system of intelligent manufacturing has been established mainly in key technologies, overall system, and specific sectors.

2.1 Evaluation of key technologies for digitalization, networking, and intelligence

Intelligent manufacturing is the comprehensive application of various key technologies. The emergence, development, and application of new information technologies such as big data, cloud computing, industrial Internet, and artificial intelligence (AI) have promoted the development process of digitalization, networking, and intelligence of China's manufacturing industry [8].

Digital manufacturing may also be referred to as first-generation intelligent manufacturing, manifested by the application of information technology featured by digitization in the manufacturing industry [9]. The data management ability of enterprises is the primary evaluation content in the digital stage. The capability maturity model is one of the common methods. Some classical models include the Data Management Maturity Model and Data Management Capability Assessment Model proposed by foreign research institutions, and Data Management Capability Maturity model developed in China. These models mostly take data strategy and governance, data quality and security, platform and architecture, and other elements as the evaluation dimension of data management. Compared with first-generation intelligent manufacturing with digital technology as the core, digital transformation is a process in which organizations use digital thinking to change their business operation and value creation mode in response to environmental changes. The evaluation of digital transformation requires not only attention to digital technology but also more attention to the organization's strategy, people, process, and other elements [10].

The development and application of Internet technology have promoted the transformation of the manufacturing industry to digital-networked manufacturing. Chinese industries have accurately grasped the opportunities of Internet development and applied new technologies (e.g., industrial Internet and cloud computing) to manufacturing. The *Industrial Internet Platform Evaluation Method* (2018) issued by the Ministry of Industry and Information Technology provides a basis for evaluating and selecting industrial Internet platforms. Li et al. [11] constructed an assessment framework for an industrial Internet platform, which contains a specific evaluation index system and evaluation method, and has advantages in operability. Cloud manufacturing is an advanced manufacturing mode based on cloud computing, which can convert manufacturing resources into fully shared and circulated services [12]. The research on cloud manufacturing service evaluation systems involves service quality evaluation [13], service trust evaluation [14], and comprehensive service evaluation [15].

Intelligent manufacturing will eventually enter digital-networked-intelligent manufacturing, which may also be referred to as a new generation of intelligent manufacturing. At this stage, AI technology will fully empower intelligent manufacturing, enabling manufacturing systems to learn. Stanford University has released the *AI Index* annually since 2017. The *China AI Index 2018* follows the index system in the *AI Index* 2017 to measure the

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progress and impact of AI in China. The *Guidelines for the Construction of the National New-Generation AI Standards System* (2020) specifies that China will initially establish an AI standards system by 2023 to provide a basis for evaluating the development level of intelligent manufacturing. Most existing academic research focuses on evaluating AI's development level, and some discuss the application of AI in intelligent manufacturing [16]. However, there is a lack of systematic research evaluating AI technology's application level in the manufacturing industry.

2.2 Global evaluation of intelligent manufacturing system

The evaluation of key technologies is a partial disclosure of intelligent manufacturing, while intelligent manufacturing is a complex manufacturing system. A comprehensive and systematic evaluation system from an overall perspective can better meet practical needs. Relevant research mainly includes evaluation based on maturity theory, evaluation based on the system level of manufacturing enterprises, and evaluation oriented to enterprise benefit.

The capability maturity model can be used not only to evaluate data management capabilities but also for the global evaluation of intelligent manufacturing systems. The *Maturity model of intelligent manufacturing capability* (GB/T 39116—2020) released by China provides a model and capability element reference for intelligent manufacturing capability assessment. The United States and Germany respectively proposed the Manufacturing Readiness Level Deskbook (2012) and the Industry 4.0 Readiness (2015). The research on intelligent manufacturing capability maturity is mainly conducted at enterprise and regional levels. At the enterprise level, smart factories, small- and medium-sized enterprises, and manufacturing enterprises are the key research objects. Capability elements such as people, organization, technology, and process are the common concerns of all maturity models. Relatively speaking, the evaluation dimensions considered at the regional level are more macroscopic. For example, Castelo-Branco et al. [17] analyzed the Industry 4.0 readiness of manufacturing enterprises in European Union countries from four aspects: interconnectivity, interoperability, virtualization, and information transparency. Regional evaluation serves the formulation of macro policies to a certain extent. The strategies and policies of different regions also cause differences in the evaluation dimensions concerned by researchers.

The system hierarchy of manufacturing enterprises is another dimension that can be used to evaluate intelligent manufacturing capabilities [18]. System hierarchy refers to the hierarchical division of organizational structure related to enterprise production activities, which can be divided into equipment, unit, workshop, enterprise, and collaboration layers [19]. It is a simple and intuitive way to build an intelligent manufacturing evaluation index system according to the hierarchy of enterprise production organization. Furthermore, the production activities are raised to the management level, and the hierarchical division based on management activities provides a new perspective for evaluating an intelligent manufacturing system. For instance, a smartness assessment framework for smart factories is proposed based on operation management, which divides the management activities into strategic planning, management control, and operation control [20]. The operation control corresponds to the above hierarchical division based on production activities, including enterprise, factory, and machine levels.

Intelligent manufacturing has promoted the transformation and innovation of industrial modes. The emergence of advanced manufacturing modes such as service-oriented manufacturing has effectively improved industrial production efficiency and value creation capabilities, and has positively affected enterprise performance [21]. The evaluation of enterprise benefits is an effective means to test the implementation level of intelligent manufacturing. The *Evaluation index of Smart Manufacturing (Draft for Comments)* (2020) stipulates that the evaluation framework includes two types of evaluation indicators: process and effect. The former mainly measures the level of basic guarantee and business optimization in the process of implementing intelligent manufacturing, whereas the latter mainly measures the benefits and effects generated by the implementation of intelligent manufacturing. The economic benefit indicators are the focus of enterprise benefit evaluation in most studies. In fact, in some theoretical research and practice, green and even sustainable manufacturing are included in the intelligent manufacturing paradigm. Therefore, intelligent manufacturing evaluation is conducted from the perspective of environmental benefits and sustainability in some studies [22,23], which enriches the benefit evaluation of intelligent manufacturing enterprises.

2.3 Specific sector evaluation oriented to the manufacturing category

Depending on the material forms used in the production process, manufacturing is mainly divided into two types: discrete manufacturing and process manufacturing [24]. Discrete manufacturing includes machinery, aviation, shipbuilding, and automobile manufacturing. Process manufacturing is represented by the petrochemical industry, metallurgy, papermaking, and food manufacturing.

Discrete intelligent manufacturing represented by Industry 4.0 is the focus of specific sector evaluation. Some studies explore a general intelligent manufacturing evaluation system for the entire discrete manufacturing industry. For example, Schumacher et al. [25] proposed an Industry 4.0 maturity model of discrete manufacturing enterprises, which includes nine dimensions: products, customers, operations, technology, strategy, leadership, governance, culture, and people. The first four dimensions have been created to assess the basic enablers, and the last five allow for including organizational aspects. In addition, some studies focus on evaluating specific sectors (e.g., machinery manufacturing and textile manufacturing). For instance, Zhang et al. argue that the evaluation focuses on intelligent manufacturing broadly, whereas there are few evaluation studies in the field of machinery. Consequently, a quantitative evaluation index system of exploratory innovation and exploitative innovation is constructed to evaluate intelligent machinery manufacturing [26].

Discrete manufacturing is a physical process that mainly assembles products. Unlike discrete manufacturing, process manufacturing involves complex physical and chemical reactions with numerous interrelated process parameters [27]. Process enterprises need a smooth production process, low error rate, and real-time feedback. These factors make it challenging to evaluate the intelligent manufacturing of process enterprises, and there is a lack of systematic research and only limited literature to conduct preliminary studies, such as dividing the intelligent manufacturing capabilities of process enterprises into three categories: intelligent technology, intelligent production, and intelligent application [28]. It should also be noted that some similar studies are interlinked, for example, a multivariate statistical combination forecasting method for key performance evaluation of the process industry [29] and the method of improving the 34 key performance indicators in ISO22400 standard to make them applicable to the process industry [30]. These similar studies can provide a reference for the intelligent manufacturing evaluation of process enterprises.

In terms of the practice of industry evaluation, the State Information Center has conducted the "Research on Intelligent Manufacturing Classification Index System" under the guidance of relevant departments. The evaluation of the development level of intelligent manufacturing in enterprises is promoted by combining the evaluation of consulting service institutions and enterprise self-evaluation, which provides a basis for the government to grasp the development level of intelligent manufacturing in the industry and region [31].

3 Research status of intelligent manufacturing evaluation method

The evaluation method is a tool for obtaining evaluation results and plays an indispensable role in the entire evaluation process. Scientific design or selection of evaluation methods is conducive to the smooth progress of the evaluation process and related to the credibility and reliability of evaluation results. Numerous comprehensive evaluation theories and methods in China and abroad directly support the application of intelligent manufacturing practices.

Statistical analysis was conducted on relevant literature from the China National Knowledge Infrastructure (CNKI) database and Clarivate Analytics Web of Science core collection database. Fig. 1 shows the distribution of intelligent manufacturing evaluation methods with the top 10 occurrence frequencies. According to whether there are subjective factors in the evaluation process, the evaluation methods can be divided into three categories: (1) qualitative evaluation methods, such as the Delphi method (i.e., expert investigation method), which mainly use the knowledge, experience, or preferences of experts to rate, score, or assign weight; (2) quantitative evaluation methods, such as Factor Analysis, Neural Network (NN), Data Envelopment Analysis (DEA), Life Cycle Assessment, and Technique for Order of Preference by Similarity to Ideal Solution, mainly based on mathematical processing of statistical data to obtain objective evaluation results; (3) qualitative and quantitative methods, such as Fuzzy Theory-based methods, Analytic Hierarchy Process (AHP), and Analytic Network Process, combining the advantages of qualitative and quantitative methods. When applied to intelligent manufacturing evaluation, the aforementioned methods usually need to be adjusted and improved according to practical problems.

Fuzzy Theory-based methods, Delphi method, and AHP are the most commonly used methods in the application of intelligent manufacturing evaluation methods. These methods are more or less subjective. Although they can fully use experts' experience and knowledge, they are inevitably affected by human judgment. Quantitative evaluation methods, such as NN and DEA, can avoid human factors but cannot do without data foundation. In other words, each evaluation method has its own focuses, strengths and weaknesses, and different scopes of application, and there is no clear standards to indicate which is better or worse.

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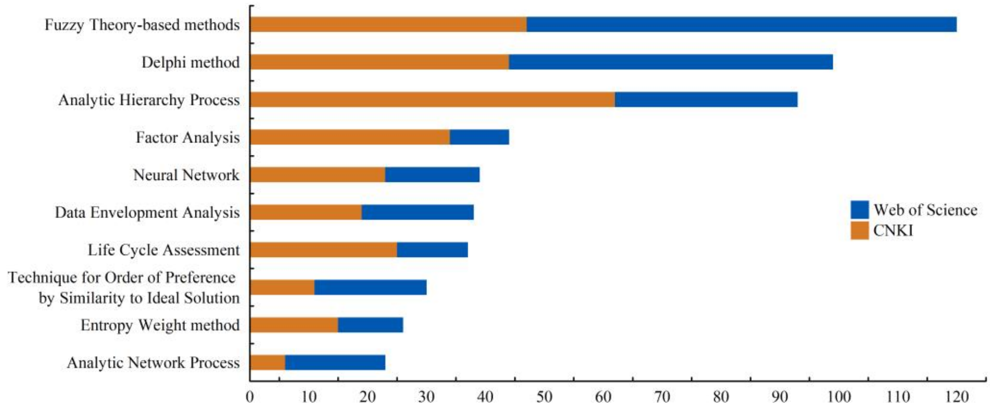

Fig. 1. Ten most frequently used intelligent manufacturing evaluation methods and their distribution.

It is worth noting that Fig. 1 shows the single evaluation methods, while in theoretical research and practical applications, the combination thought is mostly adopted; that is, the advantages of several evaluation methods are combined to achieve "learning from other's strengths to offset one's weakness." For example, Li et al. [11] used the expert investigation method to collect index data and set the index weight value through AHP; Hu et al. [15] combined the advantages of AHP and the Entropy Weight method to obtain the combined weight value, and established a fuzzy comprehensive evaluation model based on fuzzy mathematics theory. The combined evaluation method can avoid the one-sidedness of single evaluation and enhance the robustness of evaluation results. The AHP and the Delphi method have the highest frequency in all combinations. All these indicate that the evaluation research of intelligent manufacturing should be based on the accumulation of knowledge and experience.

Overall, the current intelligent manufacturing evaluation method integrates qualitative and quantitative factors and changes from traditional single evaluation to organic combination evaluation. Most existing evaluation methods are static evaluations. In fact, the evaluation process of intelligent manufacturing is dynamic. Therefore, a real-time dynamic assessment of the intelligent manufacturing system must be conducted. System simulation based on digital twin technology can realize the complete dynamic mapping interaction between the physical entity and digital model in an intelligent manufacturing system [22,32], which provides a new research idea for the dynamic evaluation of intelligent manufacturing.

4 Problems in intelligent manufacturing evaluation research

4.1 Problems in evaluation paradigm establishment

The evaluation paradigm is the technical framework and model instance followed by the scientific community that works on intelligent manufacturing evaluation. The scientific evaluation paradigm, in accord with the trend of the times, can provide a theoretical and practical basis for intelligent manufacturing evaluation. Presently, the evaluation research of intelligent manufacturing has obtained phased achievements, but some deficiencies remain in the exploration of the evaluation paradigm due to different evaluation standards and various evaluation methods.

First, the evaluation standards are incomplete. The evaluation standards are the benchmark for forming the evaluation opinion and report of intelligent manufacturing, and represents the ideal quality of the evaluated project. At present, scholars in China and abroad have constructed various intelligent manufacturing evaluation frameworks, but a real evaluation standard for intelligent manufacturing has not yet been developed. This is due to the lack of a unified and accurate understanding of intelligent manufacturing, which is both complex and systematic. The major industrial countries (e.g., the United States, Germany, and Japan) regard intelligent manufacturing as the key to industrial development and propose strategic plans such as Industry 4.0, advanced manufacturing, and interconnected industry. However, there are different focuses and different top-level designs. If the "take and use" method is adopted mechanically, it is highly likely that the evaluation standards do not conform to the local and national conditions. In China, the current intelligent manufacturing standards system is incomplete, and researchers do not have a cogent understanding of intelligent manufacturing, which leads to unclear and non-concrete evaluation standards for intelligent manufacturing.

Second, the evaluation process is not standardized. A scientific and effective evaluation process is an essential guarantee for the smooth development of evaluation activities. The existing studies have formed a general intelligent manufacturing evaluation process, including clarifying evaluation principles, determining evaluation dimensions, designing evaluation methods, and conducting empirical or case analyses. The process covers most of the evaluation activities, but some problems and defects exist in the design and implementation of key steps. Some studies overly emphasize improving the evaluation method but ignore the complexity of the evaluation object and the real purpose of the evaluation, causing the final evaluation result to deviate from the original evaluation goal. Some work only discusses the key evaluation dimensions but does not mention the evaluation methods, leading to weak operability. Most studies stop at obtaining evaluation results and omit a comprehensive discussion on the practical application of evaluation results, thus failing to play the due role of intelligent manufacturing evaluation in management practice.

Third, evaluation methodology is lacking. The evaluation paradigm is a set of norms for intelligent manufacturing evaluation activities, including but not limited to the evaluation standards determination and evaluation process design mentioned earlier. Although various intelligent manufacturing evaluation methods have been successively proposed, a recognized evaluation paradigm has not yet been formulated, and it is difficult to combine many research results effectively to serve the intelligent manufacturing industry. The existing research perspectives are relatively specific and one-sided, which weakens the systematic and holistic performance of intelligent manufacturing, so it is difficult to switch applications in different application scenarios. Overall, there is a lack of a top-level methodological basis for the intelligent manufacturing evaluation model construction; some studies directly apply the existing evaluation theories and methods to the intelligent manufacturing evaluation, resulting in doubt regarding the reliability and validity of the evaluation process and uneven evaluation effects.

4.2 Problems in evaluation system design

The evaluation index system focuses on the system characteristics of the evaluated object. A scientific and comprehensive evaluation index system is not only the key to conducting intelligent manufacturing evaluation but also the basis for applying the evaluation results to management decisions. Intelligent manufacturing is a broad and complex concept, and researchers understand it differently. Therefore, various evaluation index systems have been successively proposed. Although these evaluation index systems have promoted intelligent manufacturing development, many problems still restrict the research deepening and application of intelligent manufacturing evaluation.

First, the selection of indicators is not objective. Scientific and objective evaluation indicators are the core of intelligent manufacturing evaluation and the premise of effective evaluation. In the existing studies, most key evaluation indicators are selected based on the knowledge or experience of the personnel. This qualitative index system construction process has some problems, such as knowledge structure limitation and expert access mechanism, which makes the evaluation conclusion subjective and lacks innovation. In addition, some selected indicators are abstract and difficult to quantify, resulting in data unavailability or the need to obtain index data by questionnaire survey or expert scoring. It is challenging to ensure the authenticity and objectivity of evaluation data, which brings difficulties to the implementation of follow-up evaluation work.

Second, the evaluation dimension is not comprehensive. The intelligent manufacturing system is itself complicated, and pursuing multiple goals such as high quality, high efficiency, low consumption, green, and safety [4] leads to the complexity and diversity of evaluation dimensions. The existing index system is insufficient to fully represent the connotation of intelligent manufacturing. The relevant measurement and evaluation focus on the dimensions of intelligent production, supporting technology, organization personnel, and economic benefits, but lack attention to intelligent manufacturing mode, social and environmental benefits, and so on. In addition, the difference between the observation scale and evaluation unit will lead to the difference in spatial-temporal pattern and evaluation dimension. Regarding the spatial scale of intelligent manufacturing evaluation, relevant studies mainly focus on the evaluation on a micro scale such as manufacturing enterprises and intelligent factories, whereas the research on a macro scale such as countries, regions, and provinces/cities still needs to be conducted. Although there are evaluation studies on different spatial scales, there is a lack of attention to inter-scale correlation and inter-scale effect. As for the time scale of intelligent manufacturing evaluation, most studies are based on a specific time section. The evaluation index system fails to break through the static level, and the dynamic analysis at different moments is particularly lacking.

Third, research on specific sectors is inadequate. Manufacturing covers a wide range of sectors. There is both commonality and individuality between different manufacturing segment directions. However, most intelligent

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manufacturing evaluation studies focus on the common characteristics of the whole manufacturing industry. As for the enterprises themselves, their intelligent systems are different because of the individual differences between subdivision manufacturing directions. For example, the production structures of discrete manufacturing and process manufacturing enterprises are different; the production and business processes of steel and paper, both of which belong to process manufacturing industries, are also different. It is difficult to make a scientific and comprehensive judgment on these subdivision manufacturing directions with distinct characters in a general evaluation system that inclines toward the commonality of the manufacturing industry. Therefore, there is a lack of evaluation schemes for the individualized features of intelligent manufacturing.

4.3 Problems in new technology integration

The research on intelligent manufacturing evaluation provides a theoretical basis for judging the development stage and formulating the development plan of intelligent manufacturing. However, overall, it is still in the theoretical research stage, and the ability to solve the practical problems of intelligent manufacturing is still weak. It is worth paying attention to applying evaluation theory to intelligent manufacturing management practice effectively. In particular, the emergence and development of new information technology have provided new ideas for the practical application of intelligent manufacturing evaluation theory, but the application of this aspect is facing some constraints.

First, the ability to apply big data is relatively weak. The data generated by manufacturing systems is experiencing explosive growth. Big data technology is not only the core element to give manufacturing “intelligence” but also should be an effective means to promote the practical application of intelligent manufacturing evaluation. The ability of extant evaluation methods to connect with big data resources is discernibly insufficient, which is an important reason why the evaluation theory of intelligent manufacturing is difficult to apply. On one hand, the digitalization level of some manufacturing enterprises is low, and data collection is insufficient, which makes it challenging to ensure the completeness and pragmaticality of index data collection during evaluation. On the other hand, the rich data resources of enterprises are not fully exploited. Traditional evaluation methods usually establish an evaluation index system first and then get index data by questionnaire or manual scoring. A large amount of enterprise data is inconsistent and mismatched with the index data required by the evaluation method, making it challenging to fully reflect the value of data in the evaluation process.

Second, there are deficiencies in the construction of the evaluation service platform. An intelligent manufacturing evaluation service platform is an effective carrier to promote evaluation theory to practice, and it can provide platform support for intelligent manufacturing evaluation activities. Presently, domestic institutions have developed intelligent manufacturing evaluation service platforms, such as the intelligent manufacturing evaluation public service platform established by China Electronics Standardization Institute, which can provide self-diagnosis services for manufacturing enterprises. However, some bottlenecks remain in the construction and application of the platform, such as how to improve the flexibility of the platform to meet the diversified and personalized evaluation needs, how to improve the intelligence of the platform to meet the real-time, interactive, standardized, universal and other requirements of the evaluation, and how to effectively promote sustainable platform applications. These unsolved problems restrict the application level of intelligent manufacturing evaluation to a certain extent.

5 Future prospects of intelligent manufacturing evaluation

5.1 Improving the standards design to establish an intelligent manufacturing evaluation paradigm

5.1.1 Improving the evaluation standards system of intelligent manufacturing

According to the existing strategies, regulations, and policies, the major industrial countries should actively develop intelligent manufacturing evaluation standards in line with their national conditions. As for China, it is suggested to clarify the concept and connotation of intelligent manufacturing according to the *Guidelines for the Construction of National Intelligent Manufacturing Standards System* and promote the construction of an intelligent manufacturing standards system in line with the urgent need for industrial development. To provide a standards framework for intelligent manufacturing evaluation activities, administrative departments and research institutes can organize or participate in the formulation of intelligent manufacturing evaluation standards systems from different perspectives and levels (e.g., national evaluation standards, industrial evaluation standards).

5.1.2 Designing and optimizing intelligent manufacturing evaluation process

First, it is necessary to highlight the goal-oriented evaluation, focus on the motivation and purpose of the evaluation, and determine the time node of the evaluation (before, during, and after the event) and the evaluation object (self-evaluation, evaluation made by others). Researchers or practitioners should determine the corresponding evaluation dimensions, data sources, empowerment methods, and result application methods according to different evaluation objectives. Subsequently, in the evaluation process, attention should be paid to the changes in the evaluation object, evaluation environment, and decision-making objectives, and the adjustment and redesign of the evaluation process should be conducted duly. Second, it is necessary to play the key supporting role of the evaluation results in improving the management practice process and scientifically establish the development road map of intelligent manufacturing according to the evaluation results. Finally, an intelligent manufacturing evaluation process with problem orientation, dynamic adjustment, and practice guidance should be formed.

5.1.3 Establishing a scientific paradigm of intelligent manufacturing evaluation

Focusing on the key components of intelligent manufacturing evaluation, it should improve and standardize the evaluation criteria, purposes, objects, methods, and results. The government should play the role of top-level design, promote the theoretical framework construction of the intelligent manufacturing evaluation paradigm from top to bottom, and deepen the consensus of academia and industry on intelligent manufacturing evaluation. Simultaneously, China should focus more on transforming theory into practice, draw lessons from relatively mature evaluation practice frameworks abroad, and combine with its own basic national conditions and manufacturing industry characteristics to design practical procedures for the evaluation paradigm of intelligent manufacturing. Authorities should integrate the theoretical framework with different practical scenarios to improve the adaptability of the evaluation paradigm and maintain the dynamic update and duly transformation of the intelligent manufacturing evaluation paradigm.

5.2 Optimizing the index system to enrich the key evaluation content

5.2.1 Constructing evaluation knowledge base and database

Given the subjectivity and expert knowledge dependence in the construction of an intelligent manufacturing evaluation index system, authorities can build a national and provincial intelligent manufacturing talent expert database, collect and organize the experience and knowledge accumulated by experts in long-term research and practice with the help of information technology, and form an intelligent manufacturing evaluation knowledge base. Furthermore, manufacturing enterprises need to integrate the abundant database resources and collect and organize the evaluation data samples with different granularities and multiple dimensions to form an intelligent manufacturing evaluation database. Through collecting and refining knowledge and data, the real-time performance and authenticity of evaluation data will be improved.

5.2.2 Optimizing multidimensional evaluation index system

Based on fully understanding the connotation of intelligent manufacturing, the evaluation coverage dimension should be broadened to ensure the completeness of evaluation indicators. For example, when evaluating the benefits of intelligent manufacturing enterprises, the evaluation index system should comprehensively reflect multiple dimensions such as economy, environment, and society. It is also essential to supplement personalized indicators for different intelligent manufacturing modes. For instance, when evaluating service-oriented manufacturing, it is suggested to pay attention to the business perspective, and the intelligent service level indicators should be designed to measure the ability to meet the diversified, personalized, and customized needs of customers. In addition, the mining of different spatial and temporal scales should be strengthened. First, management institutions at various levels should guide the research on intelligent manufacturing evaluation at a macro spatial scale to accurately support policy formulation. The second is to focus on the dynamic evaluation on the time scale and promote the dynamic prediction of intelligent manufacturing development level. The third is to study the differences and transformation mechanism of evaluation indicators between scales in order to support the synchronous improvement of the universality and pertinence of intelligent manufacturing evaluation results.

5.2.3 Strengthening the research on the subdivision direction of the manufacturing industry

There are many subdivisions of the manufacturing industry. Management institutions at different levels should formulate differentiated industrial development policies according to the typical characteristics of various

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subdivisions and guide universities and research institutes to conduct intelligent manufacturing evaluation research based on the division of the manufacturing industry. Scholars can learn from the relatively mature evaluation scheme of discrete manufacturing represented by Industry 4.0, integrate the personality characteristics of process manufacturing, study the intelligent manufacturing evaluation scheme of process manufacturing, and form two kinds of intelligent manufacturing evaluation frameworks dominated by discrete manufacturing and process manufacturing. Practitioners can further introduce industry characteristics, apply the evaluation framework to the representative manufacturing subdivision direction, and form the industry subdivision solution for intelligent manufacturing evaluation.

5.3 Strengthening the integration of new technologies and promoting the synergy of theory and practice

5.3.1 Using new information technology to enable intelligent manufacturing evaluation

Manufacturing enterprises should attach great importance to the construction of industrial big data centers and realize the collection, storage, and processing of industrial data combined with the Internet of Things, intelligent sensing, and other technologies to provide a complete data foundation for the implementation of intelligent manufacturing evaluation. Authorities should get the important value out of big data in evaluation decision-making, expand the evaluation space of intelligent manufacturing combined with digital twin technology, realize the transformation of the evaluation process from static to dynamic, the transformation of evaluation environment from simple to complex, and the expansion of evaluation data from structured to unstructured. Moreover, combined with AI-related technologies, relevant departments or research institutes can develop intelligent evaluation decision support systems for human-computer interaction to match real-time, interactive, and standardized evaluation application requirements.

5.3.2 Building and improving the personalized evaluation service platform

In response to the diversified evaluation needs of manufacturing enterprises, management institutions at different levels can organize the selection of qualified evaluation agencies and form a professional evaluation institution repository to promote the construction of various core evaluation business systems; form an intelligent manufacturing evaluation service platform that is highly integrated and flexible to expand; and provide personalized and modular evaluation services for manufacturing enterprises. Manufacturing enterprises are encouraged to participate in self-evaluation activities and provide feedback about evaluation experience and opinions to optimize the evaluation effect. Management institutions at different levels exploit the data advantages of the evaluation service platform to analyze and master the overall situation of the development of intelligent manufacturing in local enterprises; formulate related policies and strategic plans to guide enterprises to develop intelligent manufacturing with high efficiency and high quality.

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