Research Article

Study on Promoting Intelligent Manufacturing Path Choice of Manufacturing Enterprises Based on Coevolution Strategy

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The basic guarantee of promoting intelligent manufacturing ability of manufacturing enterprises is to enhance the comprehensive strength of the country and realize industrialization. Based on the coevolution strategy, considering the time and space structure, this paper determines that the path of manufacturing enterprises to promote intelligent manufacturing is adaptive, visionary, planned, and emerging. According to the factors influencing the promotion of intelligent manufacturing by manufacturing enterprises, the paper proposes the following steps: adaptive strategy path, vision strategic path, planned strategic path, and emerging strategy path. The paper constructs an evaluation system for manufacturing enterprises to promote the selection of intelligent manufacturing path with 25 evaluation indexes and establishes the three-dimensional model of promoting intelligent manufacturing path selection by using the combination of Choquet fuzzy integral method and SPACE method. Through the empirical analysis of ARR, it is found that the planned strategic path is the most suitable path to promote intelligent manufacturing, and the scientificity and objectivity of the three-dimensional path selection model are shown. It is of great theoretical innovation and practical significance to develop a new perspective for manufacturing enterprises to promote the research and selection of intelligent manufacturing path.

1. Introduction

With the development of information and Internet technology, there have been profound changes in manufacturing. These changes have brought new products, modes, and technologies and also promoted the development of manufacturing enterprises in intelligence and individuation. Recently, the development of manufacturing has been in a key stage. An important issue, which is how to stimulate manufacturing enterprises’ vitality and innovation and how to overcome the bottleneck during intelligence promotion, has attracted a great attention recently.

Intelligent manufacturing and its promoting path have been studied intensively in the literature. From the perspective of research, Humphrey et al. [1] developed the path “OEM-ODM-OBM,” which was based on gradually improving the value chain, to help the enterprise realize intelligent manufacturing. Stanescuet al. [2] proposed three paths, that is, from top to bottom, form bottom to top, and jump-over service, for promoting intelligent manufacturing based on the viewpoint of discrete time, intelligent information, synergic production, and advanced business information control. From the perspective of open innovation, Laursen and Salter [3] proposed four paths for manufacturing enterprises to promote intelligent manufacturing: promoting industrial innovation resource agglomeration, acquiring innovative teams, building open innovation multiparty support, and participating in global technological innovation alliance. Tanaka et al. [4] proposed the path for small- and medium-sized manufacturing enterprises to realize intelligent manufacturing from the perspective of global value chain, including the process and product upgrading, value chain reconstruction, and the upgrading path of integrating their own resources and capabilities. Zhou et al. [5] proposed the path of “parallel promotion of integrated development” to promote the development of intelligent manufacturing in manufacturing enterprises according to the basic paradigm of enterprise intelligent manufacturing. Based on the theory of service ecosystem,
Sklyar et al. [6] emphasized that enterprises should regard service as the center and make full use of digitalization in the process of promoting intelligent manufacturing, rather than purely pursuing technological progress.

From the aspect of research contents, some researchers take the development of intelligent manufacturing as the starting point to explore the path of intelligent manufacturing: Pang [7] proposed two paths to realize intelligent manufacturing: the high-end embedding of low value chain and upstream and downstream embedding of manufacturing service integration. Xu et al. [8] considered that the enterprises are the main of implementing intelligent manufacturing and proposed three spiral development paths of intelligent manufacturing: the top-down oriented to the overall situation, bottom-up based on the actual situation of enterprises, and snowball oriented to customers. Felderer et al. [9] analyzed the typical centralized mode of intelligent transformation of manufacturing enterprises and summarized the upgrading path of information resource sharing, “hierarchical” ladder type, step-by-step, and “breakthrough intermediately, power at both ends” enterprise intelligent transformation. Li et al. [10] considered that the intelligent manufacturing is a new driving force for the transformation and upgrading of manufacturing enterprises and proposed the “two-step” path of “smart manufacturing” and “energy conversion of manufacturing industry.” Oliff et al. [11] proposed the path for manufacturing enterprises with “human-computer interaction and two-way cooperation” to promote intelligent manufacturing. Bittencourt et al. [12] emphasized the important role of the subjectivity of manufacturing enterprises and proposed three ways to realize intelligent manufacturing in manufacturing enterprises, namely, market type, network transportation type, and vertical chain type.

Some researchers explored the path of intelligent manufacturing based on the change of external macro environment: Brassaia and Iantovicsb [13] proposed that the enterprises can realize intelligent manufacturing through the path of “supply side,” “demand side,” and “pilot before investment” according to the new situation and policy requirements of China’s intelligent manufacturing development. Qiu [14] constructed the industrial cluster upgrading model of “butterfly effect-path dependence-butterfly effect-path transformation and new path dependence,” so as to better promote the realization of intelligent manufacturing. Qian et al. [15] summed up three nonlinear upgrading paths of manufacturing enterprises, bidirectional embedded/reconstructed value chain innovation drive, technology capital cross industry innovation drive, and integrated intelligent innovation drive, in the environment of big data and Internet. Simeone et al. [16] proposed an intelligent cloud manufacturing platform according to the characteristics of large fluctuations in the demand of modern manufacturing industry. Enterprises can use the intelligent module of the platform to realize the transformation and upgrading of intelligent manufacturing.

In conclusion, many researchers have realized the importance and urgency of intelligent manufacturing for manufacturing enterprises and have achieved some enlightening research results, but most of the research work focuses on the construction of intelligent manufacturing path, without considering the selection of intelligent manufacturing path, and the quantitative analysis is mainly based on a single method. At the same time, there are few studies on the use of strategic thinking to analyze manufacturing enterprises to promote intelligent manufacturing. As a result, the intelligent manufacturing theory is lack of practical application value in current stage. This paper constructs the path selection of manufacturing enterprises to promote intelligent manufacturing based on the coevolution strategy and considering the time factor and spatial structure. According to the influencing factors of manufacturing enterprises to promote intelligent manufacturing, we construct the evaluation system of manufacturing enterprises to promote intelligent manufacturing path selection and establish the three-dimensional model of manufacturing enterprises to promote intelligent manufacturing path selection by using the combination method of Choquet fuzzy integral and SPACE, which provides a scientific method for manufacturing enterprises to promote intelligent manufacturing path selection.

2. Theoretical Background

The coevolution strategy is the common evolution strategy, which emphasizes systematic thinking. The essence of enterprise development is the process of coevolution among various elements of the enterprise. The theoretical framework of coevolution strategy includes three parts: the four elements of coevolution strategy, the four stages of coevolution strategy, and the four paths of coevolution strategy. Analyzing enterprises strategy from strategic elements, strategic stages, and strategic paths can solve basic strategic issues closely related to the survival and development of enterprises.

2.1. Four Elements of Coevolution Strategy. Due to the complexity of the enterprise environment, the future development direction of the enterprise is uncertain, and the future development path is discontinuous. The coevolution strategy starts from the two dimensions of the object of enterprise management and the boundary of the enterprise and proposes four strategic elements of product, organization, user, and market. The four elements of coevolution strategy reflect the essence of strategy. Among them, products and organizations are the internal elements of an enterprise, and users and markets are the external elements of an enterprise. At the same time, organizational elements and user elements are related to “people,” while product elements and market elements are related to “things.” In general, user factors analyze people outside the company, organizational factors analyze people inside the company, market factors analyze things outside the company, and product factors analyze things inside the company. Therefore, the coevolution strategy is based on the two dimensions of “people and things” and “inside and outside” and follows the principles of “people first, things second” and “first outside, second inside” [17].
2.2. Four Stages of Coevolution Strategy. The coevolution strategy theory divides the enterprise life cycle into four stages: lean startup stage, specialized growth stage, gain expansion stage, and boost transformation stage. At the same time, it also analyzes the development characteristics of the enterprise at each stage, as shown in Table 1.

2.3. Four Paths of Coevolution Strategy. Following the principles of continuity, accuracy, systemicity, and criticality, the coevolution strategy considers that manufacturing companies are facing two major problems of uncertain development direction and discontinuous development path in a complex and changeable business environment. According to the level of the two major problems, it analyzes the corresponding environmental characteristics in different situations. Different situations match different driving forces and finally get manufacturing companies to promote smart manufacturing paths. Smart manufacturing paths include adaptive strategic path, visionary strategic path, planned strategic path, and emergent strategic path. The adaptive strategic path means that manufacturing companies adjust their smart manufacturing policies in a timely manner as the environment changes. The visionary strategic path refers to the use of ambitious missions and visions by business leaders to guide manufacturing companies to promote smart manufacturing. The planned strategic path means that the leaders of manufacturing enterprises plan ahead of time the strategic direction and path for the promotion of smart manufacturing in the next few years based on the existing foundation and development goals. The emergent strategic path refers to stimulating the vitality of the enterprise through emergence and self-organization, allowing grassroots employees to participate in decision-making and promoting smart manufacturing.

3. Research Methodology

3.1. Analysis on the Factors Influencing the Promotion of Intelligent Manufacturing by Manufacturing Enterprises Based on Coevolution Strategy. Researchers have made active explorations of the factors that influence the promotion of intelligent manufacturing by manufacturing enterprises, with substantial findings.

Lin et al. [18] demonstrate the positive correlation between the informationalized level and the realization of intelligent manufacturing by manufacturing enterprises. Elena and Orietta [19] believe that technology system integration ability, technology learning ability, technology detection ability, and organizational system integration ability are the core foundation for manufacturing enterprises to promote intelligent manufacturing. Cichocki et al. [20] believe that the processing cost, labor cost, inventory cost, and other factors constrain the collaborative allocation of resources in the job shop and affect the transformation to intelligent manufacturing. Dennis and Detlef [21] indicate that the intelligent manufacturing level of an enterprise is influenced by the ability of operators to perceive production problems and errors, data collection of products and production lines, and production planning and scheduling. Stephan et al. [22] believe that the key for enterprises to realize the transformation of intelligent manufacturing lies in technological innovation, comprehensive integration of systems, and application of digital technology. Ivanov et al. [23] put forward that organization, personnel, and other factors are the basic guarantee for an enterprise to realize intelligent manufacturing, while the degree of information fusion and system integration and other factors determine the degree of manufacturing intelligence improvement. Esmaeilian et al. [24] propose that the level of production technology, the degree of sustainable manufacturing, and the integration degree between manufacturing and operation are the factors that affect the intelligent manufacturing level of enterprises. Yew et al. [25] believe that the information perception ability of different types of workers and the degree of collaboration between workers and equipment are the key factors affecting the flexibility of intelligent manufacturing system. Thomaset al. [26] find that acquiring user knowledge is beneficial to guiding the development direction of enterprise intelligent manufacturing. In the research, Adriana et al. [27] find that the speed of information transmission and processing, the complexity of the environment, and user requirements are the keys to realize service-oriented intelligent manufacturing system. Pan [28] believes that the degree of product innovation, the level of technology, and the advanced degree of industrial chain are the keys for manufacturing enterprises to realize intelligent manufacturing. Goncalves et al. [29] put forward that enterprises’ innovation ability, business performance, and informatization level are important factors affecting enterprises intelligent transformation. Han et al. [30] find that the flexibility of information technology is the critical factor affecting the development of enterprise intelligence. Burger et al. [31] point out that the technology level of information system and Internet of Things is the key factor affecting the flexibility of manufacturing system. Bürger et al. [32] regarded the number of researchers and research and development institutions as endogenous determinants and industrial research and development willingness as exogenous influencing factors to jointly promote the transformation of enterprises to intelligence. Jay et al. [33] analyze the influence of internal core factors such as enterprise technological innovation ability and digital informatization level and external factors such as national policy and industry competition on the development of intelligent manufacturing. Stadnicka et al. [34] believe that the reserve of high-end talents is a key factor in creating and improving intelligent manufacturing systems.

In conclusion, the influencing factors of intelligent manufacturing enterprises can be summarized as external and internal factors. However, this paper argues that, in addition to the external and internal factors, the development stage of manufacturing enterprises should also be considered. Therefore, based on the coevolution strategy, it is considered that the influencing factors of manufacturing enterprises to promote intelligent manufacturing are external influencing factors, internal influencing factors, and the development stage of enterprises. The external
influencing factors include user factors and market factors, and the internal influencing factors include organization factors and product factors. Measure the matching degree between the development stage of manufacturing enterprises and a certain path to promote intelligent manufacturing [35].

3.2. Design Principles for Manufacturing Enterprises to Promote the Intelligent Manufacturing Path Selection System. The design of the evaluation index system directly affects the accuracy of the evaluation results of the manufacturing enterprises, path selection to promote intelligent manufacturing, and then affects the manufacturing enterprises to choose the correct path of intelligent manufacturing. Therefore, the following principles should be followed when designing the evaluation index system:

1. **Systematic Principle.** It is a complex decision-making process for manufacturing enterprises to promote intelligent manufacturing, and it is the final decision-making based on the full understanding and evaluation of the external and internal influencing factors of manufacturing enterprises and the development stage of enterprises. Therefore, the selected indicators should include the influencing factors of manufacturing enterprises to promote intelligent manufacturing as far as possible, make it meet the requirements of integrity and coordination, and form a complete evaluation system according to the logical relationship between the indicators.

2. **Scientific Principle.** The construction of path selection evaluation index system should be based on the influencing factors of manufacturing enterprises to promote intelligent manufacturing. According to the internal logic between the indexes, the evaluation index system should be designed, and the data should be processed with scientific methods, so that the results of manufacturing enterprises to promote intelligent manufacturing path selection can reflect the actual situation of the evaluated object scientifically and accurately.

3. **Feasibility Principle.** The evaluation indexes for manufacturing enterprises to promote intelligent manufacturing path selection include qualitative indexes and quantitative indexes. When designing the index system, we should fully consider the reliability of data sources, ensure the reliability and accuracy of index measurement, and guarantee the objective and fair evaluation results.

4. **Pertinence Principle.** The evaluation index system should be designed for the influencing factors of intelligent manufacturing in manufacturing enterprises. At the same time, the design and evaluation of the index system are to guide the selection of paths. Therefore, the index system should also reflect the commonness and difference among the paths, which is conducive to improving the rationality and accuracy of the path selection.

3.3. Manufacturing Enterprises Promoting the Construction of the Evaluation Index System for Intelligent Manufacturing Path Selection. On this basis, according to the principles of systematization, scientificity, feasibility, and pertinence, and based on the influencing factors of coevolution strategic manufacturing enterprises to promote intelligent manufacturing, 25 evaluation indexes are selected from five aspects of users, market, organization, products, and the development stage of enterprises to form the evaluation index system, as shown in Table 2.

4. Promoting Intelligent Manufacturing Path Choice of Manufacturing Enterprises Based on Coevolution Strategy

4.1. Indicator Quantitative Analysis—Choquet Fuzzy Integral Method. Choquet fuzzy integral method is a comprehensive evaluation method for fuzzy objects using fuzzy measure. This method can analyze indicators with correlation and is suitable for evaluation and processing of subjective value judgment [8]. Some indicators of intelligent manufacturing path choice are fuzzy and difficult to be quantified, and some
Table 2: Evaluation index system of promoting the choice of intelligent manufacturing path for manufacturing enterprises.

| Primary index | Tertiary index | Secondary index | Four-level index | Index description |
|---------------|----------------|----------------|------------------|-------------------|
| User factors  | "Degree of demand for personalized products (D1)" | "The degree of user's demand for product customization." | "It reflects the demand degree of the user for product customization." | |
|               | "Speed of change in user requirements (D2)" | "The speed of change in user requirements." | "It reflects the speed of change in user requirements." | |
|               | "External factors (C1)" | "The trend of industry transformation (D3)" | "The trend of industry transformation." | "It reflects the trend of industry transformation." |
|               | "Internal factors (C2)" | "Product factors (D2)" | "Product factors." | "It reflects the product factors." |

| The path choice of promoting intelligent manufacturing enterprises (A) | Advantages of the development stage of enterprise (C2) | Product factors (D2) | Organization factors (C1) | External factors (B) |
|---------------------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| "Intelligence awareness and decision-making (D21)" | "The advantage of organizational awareness to advance digital manufacturing (D21)" | "Degree of data connectivity in intelligent manufacturing (D22)" | "Degree of data connectivity in intelligent manufacturing (D22)" | "Degree of demand for extensional products (D12)" |
| "Management level of intelligent manufacturing (D23)" | "The advantage of organizational awareness to advance digital manufacturing (D21)" | "Accuracy of product market positioning (D23)" | "Accuracy of product market positioning (D23)" | "External factors (B)" |
| "Employee recognition for advancing intelligent manufacturing (D24)" | "The advantage of organizational awareness to advance digital manufacturing (D21)" | "Degree of knowledge management in intelligent manufacturing (D24)" | "Degree of knowledge management in intelligent manufacturing (D24)" | "Degree of demand for extensional products (D12)" |
| "Degree of cooperation with users, suppliers, and competitors (D25)" | "The advantage of organizational awareness to advance digital manufacturing (D21)" | "Management level of intelligent manufacturing (D26)" | "Management level of intelligent manufacturing (D26)" | "External factors (B)" |
indicators are related to each other but not completely independent.

Therefore, the Choquet fuzzy integral method is used in this paper to quantitatively analyze the evaluation indexes for the path choice of intelligent manufacturing in manufacturing enterprises. The steps are as follows:

Step 1: determine the target path of evaluation; based on the coevolution strategy, there are adaptive strategic path, vision strategic path, planned strategic path, and emergent strategic path for manufacturing enterprises to promote intelligent manufacturing.

Step 2: determine the total evaluation value of external indicators. The specific calculation steps are as follows:

1. Determine the fuzzy evaluation value of each index
   Invite senior managers and related employees of manufacturing enterprises to score each index in the index system and determine the evaluation value of each index. For quantitative indicators, the corresponding numerical range of each grade was determined according to the relevant statistical yearbook and relevant statistical bulletin, and then the values of each index were obtained through questionnaire. As for the qualitative index, the specific evaluation value is directly given by the senior management and related employees of the manufacturing enterprise according to the actual situation and their own knowledge and experience of the manufacturing enterprise. Because of the fuzziness of description, the semantic variable represented by trapezoidal fuzzy number is used to represent the subjective evaluation value in the scoring process of the index value. Experts are invited to give the semantic value of each indicator according to the semantic change scale, and the semantic value set \( \bar{f} \) of the indicator is constituted.

\[
\bar{f}_i = \{ \bar{f}_j(X^k_i) | k = 1, \ldots, n_i; j = 1, \ldots, m \},
\]

where \( \bar{f}_j(X^k_i) \) is a trapezoidal fuzzy number, representing the semantic value given by the \( j \)th expert to the \( i \) evaluation indexes \( X^k_i \) in the evaluation layer \( X_k \), represented by \( (a^k_i, b^k_i, c^k_i, d^k_i) \), \( \in [0, 1] \), \( b^k_i \in [0, 1] \), \( c^k_i \in [0, 1] \), \( d^k_i \in [0, 1] \). \( n \) represents the number of evaluation layers. \( n_k \) represents the number of evaluation indicators of \( X_k \) in the evaluation level; \( m \) is the number of specialists.

2. Determine the fuzzy weight value of each index
   Relevant experts were invited to score each evaluation index according to semantic variables, and the semantic value of trapezoidal fuzzy number was also used to score at different layers, and the semantic value was obtained as follows:

\[
\bar{g}_i = \{ \bar{g}_j(X^k_i) | k = 1, \ldots, n_i; i = 1, \ldots, n_k \},
\]

where \( \bar{g}_j(X^k_i) \) is a trapezoidal fuzzy number, representing the semantic value given by the \( j \)th expert to the \( i \) evaluation indexes in the evaluation layer \( X_k \), represented by \( (a^k_i, b^k_i, c^k_i, d^k_i) \), \( \in [0, 1] \), \( b^k_i \in [0, 1] \), \( c^k_i \in [0, 1] \), \( d^k_i \in [0, 1] \). \( n \) represents the number of evaluation layers. \( n_k \) represents the number of evaluation indicators of \( X_k \) in the evaluation level; \( m \) is the number of specialists.

3. Calculate the fuzzy value of each index
   According to the opinions of experts, the fuzzy operation is carried out on the semantic value of the index, and the fuzzy value set \( \bar{f} \) of the index is obtained.

\[
\bar{f}(X^k_i) = \frac{1}{m} \oplus \{ \bar{f}_j(X^k_i) \oplus \bar{f}_j(X^k_i) \oplus \cdots \oplus \bar{f}_m(X^k_i) \},
\]

where \( \bar{f}(X^k_i) \) is the fuzzy value of the \( i \) index \( X_k \), the evaluation layer \( X^k_i \) after integrating the opinions of \( m \) experts. + and \( \oplus \) are fuzzy operators. The same method is applied to the semantic value set of fuzzy weight.

4. The explicit values of fuzzy evaluation and fuzzy weight are obtained by defuzzification operation
   Relative distance formula \( (M_1) \), center value method \( (M_2) \), and center of gravity value method \( (M_3) \) are used to transform fuzzy number into explicit value. The calculation method for converting the fuzzy value \( f(X^k_i) \) of the \( i \) qualitative index \( X^k_i \) in the evaluation level \( X_k \) into the explicit index value \( f(X^k_i) \) is as follows:

\[
f(X^k_i) = \frac{M_1(\bar{f}(X^k_i)) + M_2(\bar{f}(X^k_i)) + M_3(\bar{f}(X^k_i))}{3},
\]

where

\[
M_1(\bar{f}(X^k_i)) = \frac{d^k_i}{d^k_i + d^k_i}, \quad (i = 1, \ldots, n_k),
\]

\[
d^k_i = \sqrt{\frac{1}{4} \left( (a^k_i)^2 + (b^k_i)^2 + (c^k_i)^2 + (d^k_i)^2 \right)},
\]


$$d_{i}^{k+1} = \sqrt[4]{\frac{1}{6} \left[ (1 - d_{i}^{k})^4 + (1 - b_{i}^{k})^4 + (1 - c_{i}^{k})^4 + (1 - d_{i}^{k})^4 \right]},$$  \hspace{1cm} (7)

$$M_2(\overline{f}(X_k)) = \frac{(b_{i}^{k} + c_{i}^{k})}{2} + \frac{\left[ (a_{i}^{k} - c_{i}^{k}) - (b_{i}^{k} - a_{i}^{k}) \right]}{6} = \frac{2b_{i}^{k} + 2c_{i}^{k} + a_{i}^{k} + d_{i}^{k}}{6},$$  \hspace{1cm} (8)

$$M_3(f(X_k)) = \begin{cases} a_{i}^{k}, & a_{i}^{k} = b_{i}^{k} = c_{i}^{k} = d_{i}^{k}, \\ (d_{i}^{k})^2 + (c_{i}^{k})^2 - (b_{i}^{k})^2 - (a_{i}^{k})^2 + c_{i}^{k}d_{i}^{k} - a_{i}^{k}b_{i}^{k}, & \text{else.} \end{cases}$$  \hspace{1cm} (9)

Through the calculation of the above formula, the fuzzy values of each index can be, respectively, defuzzified and converted into explicit values, and the explicit values of fuzzy evaluation can be obtained. The calculation method of explicit value of fuzzy weight is the same as described above.

(5) Determine the λ value
The value of parameter λ is uniquely determined by the following equation:

$$\lambda + 1 = \prod_{i=1}^{n} \left[ 1 + \lambda \cdot G(x_i) \right].$$  \hspace{1cm} (10)

(6) Calculate the λ fuzzy measure
According to equation (11), the λ value and the fuzzy weight value $g(x_i)$ of each index are substituted to obtain the λ fuzzy measure of each evaluation layer, and the following is obtained:

$$g_1([X_1^k, X_2^k]), g_1([X_1^k, X_3^k]), \ldots, g_1([X_1^k, X_n^k]),$$

$$\ldots g_1([X_1^k, X_2^k, \ldots, X_n^k]), \ldots, g_1([X_1^k, X_2^k, \ldots, X_n^k]).$$

$$g_{i}([x_1, \ldots, x_n]) = \sum_{i=1}^{n} g(x_i) + \lambda \sum_{i=1}^{n} \sum_{l=i+1}^{n} g(x_i) g(x_l)$$

$$+ \ldots + \lambda^{n-1} g(x_1) g(x_2) \ldots g(x_n)$$

$$= \frac{1}{\lambda} \prod_{i=1}^{n} (1 + \lambda g(x_i)) - 1 \ | \lambda \in [-1, \infty), \lambda \neq 0. $$  \hspace{1cm} (11)

(7) Calculate the fuzzy integral evaluation value of each evaluation layer
The calculation steps of fuzzy integral evaluation value of each evaluation layer are as follows:

$$f(X_{i_1}^k) \geq \cdots \geq f(X_{i_n}^k)$$

$$\{ \{i, j = 1, \ldots, n_k\} \} \{ i/j = 1, \ldots, n_k \}.$$  \hspace{1cm} (12)

Firstly, the index value $f(X_{i}^k)(i = 1, \ldots, n_k)$ under the evaluation layer $X_k$ is reordered according to its size.

Secondly, the fuzzy integral formulas (5)–(8) are used to obtain the evaluation layer of the evaluation layer.

$$f(X_k) = f(X_{i_1}^k) g_{i_1}(\{X_{i_1}^k, X_{i_2}^k, \ldots, X_{i_n}^k\})$$

$$+ \cdots + f(X_{i_n}^k) - f(X_{i_1}^k) g_{i_n}(\{X_{i_1}^k, X_{i_2}^k, \ldots, X_{i_n}^k\}).$$  \hspace{1cm} (13)

(8) Calculate the total evaluation value
Combined with the evaluation value of fuzzy integral at all layers, the fuzzy integral total evaluation value can be obtained by adopting the fuzzy integral method.

Step 3: determine the total evaluation value of internal indicators, using the same method as Step 2.

Step 4: determine the total evaluation value of the development stage of the enterprise. The method is the same as Step 2.

4.2. Construction of the Path Selection Evaluation Model Based on the SPACE Method
SPACE method is the strategic position and action evaluation method. It can accurately judge the strength of manufacturing enterprises, seek advantages and opportunities, weaken disadvantages, and reduce external threats. It uses space coordinate diagram to build a path selection model for manufacturing enterprises to promote intelligent manufacturing. The obtained overall evaluation value of external indicators for manufacturing enterprises to promote intelligent manufacturing path selection is placed on the Y-axis, the total evaluation value of internal indicators is placed on the X-axis, and the development stage of the enterprise is placed on the Z-axis, thus forming a spatial point $I(X_i, Y_i, Z_i)$, as shown in Figure 1. Then, the comprehensive index method is used to calculate the degree of proximity between point I and the ideal solution, and each path is sorted according to the degree of proximity. The path with the largest degree of proximity indicates the best, that is, the most appropriate path for manufacturing enterprises to promote intelligent manufacturing.
Total evaluation value of internal environment \( Z_i \), and the total evaluation value of the external indicators, and the total evaluation value of the internal environment \( Z_i \) can be obtained: \( I_1, I_2, I_3, \) and \( I_4 \). We need to calculate the distance from \( I_i(X_i, Y_i, Z_i) \) \( (i = 1 \) represents the adaptive strategic path. \( i = 2 \) represents the vision strategic path. \( i = 3 \) represents the planned strategic path. \( i = 4 \) represents emergent strategic path) to the ideal solution \( P \) and \( \text{distance from the negative ideal solution} \), As shown in Figure 2, the formulas are as follows:

\[
S_{1i} = \sqrt{(1 - X_i)^2 + (1 - Y_i)^2 + (1 - Z_i)^2}, \tag{14}
\]

\[
S_{2i} = \sqrt{(X_i - 0)^2 + (Y_i - 0)^2 + (Z_i - 0)^2} = \sqrt{X_i^2 + Y_i^2 + Z_i^2}. \tag{15}
\]

According to the four points known above, the approximate degree \( C_i \) of \( I_1, I_2, I_3, \) and \( I_4 \) to the ideal solution is calculated and compared, respectively. The smaller \( C_i \) is, the more suitable the corresponding path is, that is, the appropriate path for manufacturing enterprises to promote intelligent manufacturing.

5. Empirical Analysis

ARR is a manufacturer of crystal materials and equipment. The company has strong capital and large scale of production. Some technologies are in a leading position in the industry. Its products have a high market share and stable customer relationships. Under the guidance of market demand and based on the judgment of future market development trends, the company has done a lot of work in equipment research and development. At present, under the background of the rapid development of the industry, the company will continue to build smart manufacturing industry ecosphere. The self-developed advanced equipment is gradually turning to smart innovative design, accumulating resources in the field of smart manufacturing, and developing one-stop integrated production line solution business, resulting in the loss of some traditional superior products or part of the original product advantages. Therefore, this paper analyzes the path selection of ARR to promote intelligent manufacturing. In order to further clarify the objectives and measures of ARR to promote intelligent manufacturing, according to the analysis of the reality of ARR, it is in the boost transformation stage.

According to the steps of manufacturing companies to promote intelligent manufacturing path selection, first, obtain the fuzzy integral value of the four-level indicators for the four paths of ARR enterprises to promote smart manufacturing, that is, adaptive strategic paths (Table 3),
visionary strategic paths (Table 4), planned strategic paths (Table 5), and emergent strategic paths (Table 6).

Second, obtain the fuzzy integral value table of the three-level indicators of ARR to promote the smart manufacturing path selection, as shown in Table 7.

Finally, the total evaluation value table for ARR to promote smart manufacturing path selection is obtained, as shown in Table 8.

It can be concluded from Table 7 that the total evaluation value of ARR is $I_1 = (0.3759, 0.3552, 0.3682)$ under the adaptive strategic path, $I_2 = (0.4939, 0.3957, 0.4642)$ under the visionary strategic path, $I_3 = (0.4053, 0.3878, 0.4895)$ under the planned strategic path, and $I_4 = (0.4493, 0.6984, 0.3659)$ under the emerging strategic path.

Then, the approximation degree of $I_1, I_2, I_3$, and $I_4$ to ideal solution is calculated and compared; thus the appropriate path for ARR to promote intelligent manufacturing is selected. According to equations (11)–(14), the approximate degree of each path to the ideal solution can be obtained as follows:

Adaptive strategic path: $S_{11} = 1.0974$, $S_{21} = 0.6349$, and $C_1 = 0.6335$

Visionary strategic path: $S_{12} = 0.9531$, $S_{22} = 0.7849$, and $C_2 = 0.5484$

Planned strategic path: $S_{13} = 0.8779$, $S_{23} = 0.8839$, and $C_3 = 0.4958$

Emerging strategic path: $S_{14} = 0.8924$, $S_{24} = 0.9075$, and $C_4 = 0.4983$

Obviously, $C_3 < C_4 < C_2 < C_1$, indicating that the planned strategic path is the most suitable path for ARR enterprises to promote intelligent manufacturing.

According to the planned strategic path, ARR leaders plan the strategic direction and path of intelligent manufacturing in the next 5 years in advance according to the existing foundation and development goals. In the specific implementation process, do the following: ☛ Pay attention to the incremental market and the stock users. The market share of ARR in the early stage is the basis for the later research and development of enterprises. For the better development of ARR, it is necessary to plan the technical R&D arrangement, constantly meet the needs of users, and establish a perfect user feedback information management and transmission mechanism, so as to ensure the effective implementation and promotion of intelligent manufacturing. ☛ Apply advanced technology in the whole value chain of product design, production, and management, while advanced technology can be realized through enterprises-independent innovation supplemented by technology integration innovation and cooperative innovation with universities and research institutions. Build information exchange platform. Building an information exchange platform is the quickest way to realize the efficient allocation of enterprise resources. With the help of the platform, building an information platform will integrate multiple resources into the operation decision-making, capital flow, cost accounting, and warehousing logistics of ARR enterprises, so as to speed up the level of enterprise intelligent manufacturing. ☛ Strengthen the core competitiveness of enterprises, provide technical support for the realization of intelligent manufacturing, and avoid the inertia of enterprise development. Talent is the source of intelligence, and the knowledge reserve and innovation ability of talent are the cornerstone of ARR to promote intelligent manufacturing. Therefore, while recruiting high-tech talents from the outside, ARR should also encourage the existing talents of the enterprise, so as to ensure the long-term vitality of the enterprise and support the implementation of the intelligent...
Table 4: ARR advance intelligent manufacturing-vision strategic path four-level index and fuzzy technique integral value.

| Index | External factor evaluation index | Internal factor evaluation index | Evaluation index system of enterprise’s development stage |
|-------|---------------------------------|---------------------------------|--------------------------------------------------------|
| $f_{11}$ |                         |                                 |                                                      |
| $f_{12}$ |                         |                                 |                                                      |
| $f_{13}$ |                         |                                 |                                                      |
| $f_{14}$ |                         |                                 |                                                      |
| $f_{15}$ |                         |                                 |                                                      |
| $f_{16}$ |                         |                                 |                                                      |
| $f_{21}$ |                         |                                 |                                                      |
| $f_{22}$ |                         |                                 |                                                      |
| $f_{23}$ |                         |                                 |                                                      |
| $f_{24}$ |                         |                                 |                                                      |
| $f_{25}$ |                         |                                 |                                                      |
| $f_{26}$ |                         |                                 |                                                      |

Table 5: ARR advance intelligent manufacturing-planned strategic path four-level index and fuzzy technique integral value.

| Index | External factor evaluation index | Internal factor evaluation index | Evaluation index system of enterprise’s development stage |
|-------|---------------------------------|---------------------------------|--------------------------------------------------------|
| $f_{11}$ |                         |                                 |                                                      |
| $f_{12}$ |                         |                                 |                                                      |
| $f_{13}$ |                         |                                 |                                                      |
| $f_{14}$ |                         |                                 |                                                      |
| $f_{15}$ |                         |                                 |                                                      |
| $f_{16}$ |                         |                                 |                                                      |
| $f_{21}$ |                         |                                 |                                                      |
| $f_{22}$ |                         |                                 |                                                      |
| $f_{23}$ |                         |                                 |                                                      |
| $f_{24}$ |                         |                                 |                                                      |
| $f_{25}$ |                         |                                 |                                                      |
| $f_{26}$ |                         |                                 |                                                      |

Table 6: ARR advance intelligent manufacturing-emerging strategic path four-level index and fuzzy technique integral value.

| Index | External factor evaluation index | Internal factor evaluation index | Evaluation index system of enterprise’s development stage |
|-------|---------------------------------|---------------------------------|--------------------------------------------------------|
| $f_{11}$ |                         |                                 |                                                      |
| $f_{12}$ |                         |                                 |                                                      |
| $f_{13}$ |                         |                                 |                                                      |
| $f_{14}$ |                         |                                 |                                                      |
| $f_{15}$ |                         |                                 |                                                      |
| $f_{16}$ |                         |                                 |                                                      |
manufacturing path. We can start from the material, spiritual, and institutional aspects to encourage high-tech talents and stimulate the potential and power of talents.

6. Conclusions

With the rapid development of the Internet and information technology, intelligent manufacturing has become the trend of the development of manufacturing industries all over the world. The promotion of intelligent manufacturing by Chinese manufacturing enterprises can not only solve the development problems of enterprises but also enable our country to extricate itself from the predicament of being big but not strong. Based on the coevolution strategy, this paper analyzes the influencing factors of manufacturing enterprises to promote the intelligent manufacturing and constructs an evaluation index system for manufacturing enterprises to choose the way to promote the intelligent manufacturing; the Choquet (fuzzy technique integral value)-SPACE combination method is used to establish a three-dimensional model for the path selection of the manufacturing enterprise to promote the intelligent manufacturing. At the same time, this model is used for empirical analysis of ARR. Firstly, Choquet fuzzy integral method is used to quantify the evaluation index, which fully considers that some indexes of ARR promoting intelligent manufacturing path selection are difficult to quantify and fuzzy, and there is a certain correlation between some indexes, so as to ensure that the constructed evaluation index system can significantly affect its evaluation results. Then improve the space coordinate diagram, accurately judge the strength of ARR, seek advantages and opportunities, weaken disadvantages and reduce external threats, ensure the comprehensiveness and reliability of the final evaluation results, and finally get that the planned strategic path is the most suitable path for ARR enterprises to promote intelligent manufacturing, and put

Table 6: Continued.

| Internal factor evaluation index | Fuzzy technique evaluation value | Fuzzy technique evaluation value | Fuzzy technique evaluation value | Index | Fuzzy technique evaluation value | Fuzzy technique evaluation value | Fuzzy technique evaluation value |
|----------------------------------|---------------------------------|---------------------------------|---------------------------------|-------|---------------------------------|---------------------------------|---------------------------------|
| $f_{21}$                         | 0.7657                          | 0.8092                          | 0.6341                          | $f_{22}$                         | 0.6091                          | 0.8484                          |
| $f_{22}$                         | 0.5915                          | 0.7096                          | 0.7191                          | $f_{23}$                         | 0.7906                          | 0.6195                          |
| $f_{23}$                         | 0.6240                          | 0.9592                          | 0.8350                          | $f_{24}$                         | 0.6295                          | 0.7194                          |
| $f_{24}$                         | 0.6715                          | 0.8598                          |                                 |                                 |                                 |                                 |
| $f_{25}$                         | 0.6316                          | 0.6395                          |                                 |                                 |                                 |                                 |
| $f_{26}$                         | 0.6439                          | 0.7194                          |                                 |                                 |                                 |                                 |

Table 7: ARR advanced intelligent manufacturing path selection three-level index and fuzzy technique integral value.

| Evaluation index system of enterprise’s development stage | Fuzzy technique evaluation value | Fuzzy technique evaluation value | Fuzzy technique evaluation value |
|----------------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
| $f_3$                                                     | 0.9076                          | 0.8088                          | 0.3659                          |

Table 8: Total evaluation value table of path selection for ARR to promote intelligent manufacturing.

| Overall value | Adaptive strategic path | Vision strategic path | Planned strategic path | Emergent strategic path |
|---------------|-------------------------|-----------------------|------------------------|-------------------------|
| External evaluation indicator | 0.3759                 | 0.4939                | 0.4053                 | 0.4493                 |
| Internal evaluation indicators | 0.3552                 | 0.3975                | 0.3878                 | 0.6984                 |
| The stage of development of an enterprise | 0.3682                 | 0.4642                | 0.4895                 | 0.3659                 |
forward the measures for ARR to promote intelligent manufacturing. It can effectively solve the problem of promoting intelligent manufacturing path selection.

Choquet fuzzy integral-SPACE combination method is used to establish a three-dimensional model of manufacturing enterprises to promote intelligent manufacturing path selection, which can comprehensively analyze the current situation of manufacturing enterprises to promote intelligent manufacturing, and provide strategic guidance for future development; it is of great practical significance for manufacturing enterprises to speed up intelligent manufacturing, realize industrial supply-side reform, form strategic emerging industrial clusters, break the lock-in of traditional industrial structure, and cultivate new economic growth drivers.

However, due to its own limited level, it will continue to deepen its research in this area, focusing on the two following points:

(1) The selection of evaluation indicators. In this paper, the influence factors of promoting intelligent manufacturing by manufacturing enterprises are used to construct their evaluation index system, but the influence factors are a complex system; it needs to be more perfect in the selection of evaluation index of promoting the intelligent manufacturing path choice of manufacturing enterprises.

(2) Path construction and selection. In the next stage of research, in the future research, the advance of intelligent manufacturing path constructed in this paper is based on the theory of coevolution strategy; we can design various ways to promote smart manufacturing according to the internal strength of manufacturing enterprises, as well as technology trends, market changes, and national policies, so as to improve the diversity and practical application of promoting the path choice of intelligent manufacturing in manufacturing enterprises.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] Humphrey, "Upgrading in global value chains," Working Paper, Vol. 28, Humphrey, New York, NY, USA, 2004.

[2] A. Stanesco, D. Karagiannis, M. A. Moisescu, I. S. Sacala, and V. Manoiu, "Towards a holistic approach for intelligent manufacturing systems synthesis," IFAC Proceedings Volumes, vol. 41, no. 3, pp. 193–198, 2008.

[3] K. Laursen and A. Saltor, "Open for innovation: the role of openness in explaining innovation performance among U.K. manufacturing firms," Strategic Management Journal, vol. 27, no. 2, pp. 131–150, 2010.

[4] K. Tanaka, T. Inoue, R. Matsuhashi, and K. Yamada, "Global value chain assessment based on retrospectively introduced economic costs associated with technology application: a case study of photovoltaic power system in Japan," Journal of Cleaner Production, vol. 181, no. 20, pp. 460–472, 2018.

[5] J. Zhou, P. Li, Y. Zhou, B. Wang, and L. Meng, "Toward new-generation intelligent manufacturing," Engineering, vol. 4, no. 4, pp. 11–20, 2018.

[6] A. Skyllar, C. Kowalkowski, B. Tronnov, and D. Sörrhammar, "Organizing for digital servitization: a service ecosystem perspective," Journal of Business Research, vol. 104, pp. 450–460, 2019.

[7] R. Alto, "Path of green and intelligent manufacturing in the Internet era," Ecological Economy, vol. 3, pp. 277–286, 2015.

[8] Y. Xu, G. Chen, and J. Zheng, "An integrated solution—KAGFM for mass customization in customer-oriented product design under cloud manufacturing environment," International Journal of Advanced Manufacturing Technology, vol. 84, no. 4, pp. 85–101, 2016.

[9] M. Felderer, F. Piazzolo, W. Ortner, L. Brehm, and H. J. Hof, Research Challenges of Industry 4.0 for Quality Management, Vol. 10, Springer International Publishing, New York, NY, USA, 2016.

[10] B.-H. Li, B.-C. Hou, W.-T. Yu, X.-B. Lu, and C.-W. Yang, "Applications of artificial intelligence in intelligent manufacturing: a review," Frontiers of Information Technology & Electronic Engineering, vol. 18, no. 1, pp. 86–96, 2017.

[11] H. Oliff, Y. Liu, M. Kumar, and M. Williams, "A framework of integrating knowledge of human factors to facilitate HMI and collaboration in intelligent manufacturing," Procedia CIRP, vol. 72, pp. 135–140, 2018.

[12] V. L. Bittencourt, A. C. Alves, and C. P. Leão, "Industry 4.0 triggered by lean thinking: insights from a systematic literature review," International Journal of Production Research, vol. 59, no. 5, pp. 1496–1510, 2021.

[13] S. T. Iantovics and C. Enăchescu, "Artificial Intelligence in the path planning optimization of mobile agent navigation," Procedia Economics and Finance, vol. 3, pp. 243–250, 2012.

[14] S. Qiu, "The path choice of transformation and upgrading of manufacturing industry in China based on supply side structural reform," Conference: 3rd International Conference on Economics, Management, Law and Education, vol. 104, pp. 503–506, 2017.

[15] F. Qian, W. Zhong, and W. Du, "Fundamental theories and key technologies for smart and optimal manufacturing in the process industry," Engineering, vol. 3, no. 2, pp. 154–160, 2017.

[16] A. Simeone, A. Caggiano, L. Boun, and B. Deng, "Intelligent cloud manufacturing platform for efficient resource sharing in smart manufacturing networks," Procedia CIRP, vol. 79, pp. 233–238, 2019.

[17] J.-Y. Lu, "Co-performance Strategy: Redefining Enterprise Life Cycle," China Machine Press, Beijing, China, 2018.

[18] X. Y. Liu, Q. Cheng, and K. Guo, "Influencing factors of intelligent manufacturing: empirical analysis based on SVR model," Procedia Computer Science, vol. 122, pp. 1024–1030, 2017.
[19] C. Elena and M. Orietta, “Born to flip. Exit decisions of entrepreneurial firms in high-tech and low-tech industries,” *Journal of Evolutionary Economics*, vol. 21, no. 3, pp. 473–498, 2011.

[20] A. Cichocki, D. Mandic, L. De Lathauwer et al., “Tensor decompositions for signal processing applications: from two-way to multiway component analysis,” *IEEE Signal Processing Magazine*, vol. 32, no. 2, pp. 145–163, 2015.

[21] K. Dennis and Z. Detlef, “Lean automation enabled by industry 4.0 technologies,” *IFAC Papers On Line*, vol. 48, no. 3, pp. 1870–1875, 2015.

[22] S. Weyer, M. Schmitt, M. Ohmer, and D. Gorecky, “Towards Industry 4.0—standardization as the crucial challenge for highly modular, multi-vendor production systems,” *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 579–584, 2015.

[23] D. Ivanov, A. Dolgui, B. Sokolov, F. Werner, and M. Ivanova, “A dynamic model and an algorithm for short-term supply chain scheduling in the smart factory industry 4.0,” *International Journal of Production Research*, vol. 54, no. 1, pp. 386–402, 2016.

[24] B. Esmaeilian, S. Behdad, and B. Wang, “The evolution and future of manufacturing: a review,” *Journal of Manufacturing Systems*, vol. 39, pp. 79–100, 2016.

[25] A. W. W. Yew, S. K. Ong, and A. Y. C. Nee, “Towards a grid-enabled distributed manufacturing system with augmented reality interfaces,” *Robotics and Computer-Integrated Manufacturing*, vol. 39, pp. 43–55, 2016.

[26] A. Thomas, P. Matti, and K. Laura, “The role of users and customers in digital,” *Information & Management*, vol. 53, no. 3, pp. 324–335, 2016.

[27] G. Adriana, G. Emilia, and B. Vicente, “An engineering framework for service-oriented intelligent,” *Computers in Industry*, vol. 81, pp. 116–127, 2016.

[28] Y. Pan, “Heading toward artificial intelligence 2.0,” *Engineering*, vol. 2, no. 4, pp. 409–413, 2016.

[29] R. Goncalves, D. Romero, and A. Grilo, “Factories of the future: challenges and leading innovations in intelligent manufacturing,” *International Journal of Computer Integrated Manufacturing*, vol. 30, no. 1, pp. 4–13, 2017.

[30] J. H. Han, Y. Wang, and M. Naim, “Reconceptualization of information technology flexibility for supply chain management: an empirical study,” *International Journal of Production Economics*, vol. 187, pp. 196–215, 2017.

[31] N. Burger, M. Demartini, F. Tonelli, F. Bodendorf, and C. Testa, “Investigating flexibility as a performance dimension of a manufacturing value modeling methodology (MVMM): a framework for identifying flexibility types in manufacturing systems,” *Procedia CIRP*, vol. 63, pp. 33–38, 2017.

[32] J. Bürger, D. Strüber, S. Gärtner, T. Ruhroth, J. Jürjens, and K. Schneider, “A framework for semi-automated co-evolution of security knowledge and system models,” *Journal of Systems and Software*, vol. 139, pp. 142–160, 2018.

[33] L. Jay, D. Hossein, S. Jaskaran, and P. Vibhor, “Industrial artificial intelligence for industry 4.0-based manufacturing systems,” *Manufacturing Letters*, vol. 18, pp. 20–23, 2018.

[34] D. Stadnicka, P. Litwin, and D. Antonelli, “Human factor in intelligent manufacturing systems—knowledge acquisition and motivation,” *Procedia CIRP*, vol. 79, pp. 718–723, 2019.