Evaluation of Intelligent Level of Regional Manufacturing Industry Based on Entropy Weight-Partial Ordered Set Theory

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Abstract. Aiming at the problem that the evaluation results are not robust and credibility is low due to the disputes over the weights of evaluation indexes in the existing intelligent evaluation of manufacturing industry, a regional intelligent manufacturing level evaluation model based on entropy weight and POSET theory was proposed. Firstly, the evaluation model is constructed based on POSET theory, and the entropy weight method is adopted to determine the importance degree of evaluation indicators. Secondly, using the data of 30 provinces from 2015 to 2019, Hasse graph is constructed. The results show that the eastern region has the highest level of intelligent manufacturing and the most stable development. The intelligence level of the central region is in a medium position and its development is relatively stable. The intelligence level of the western region is at the bottom and its development is relatively unstable. The intelligence level of northeast China is in the middle and lower position, and its development is the most unstable. Finally, in view of the large gap among the four regions in the intelligent level of manufacturing industry, put forward to strengthen the strategic overall planning, optimize the distribution of resources, narrow the regional intelligent gap.

Keywords: manufacturing · intelligent manufacturing · entropy weight-POSET theory

1 Introduction

In recent years, the United States, the United Kingdom, Germany and other developed countries are trying to revitalize manufacturing. The UK put forward the "Future Manufacturing" development strategy and the vision of "Making Manufacturing smarter". The "Industry 4.0" strategy issued by Germany and the "German Industry 2035" plan further proposed focus on intelligent manufacturing and several advanced manufacturing fields respectively. In 2019, the United States further proposed the "US-Led Advanced Manufacturing Strategy" [1].

S. H. B. D. M. Zailani et al. (Eds.): ICMSEM 2023, 259, pp. 87–101, 2024.
https://doi.org/10.2991/978-94-6463-256-9_10

Manufacturing industry is the main pillar of the national economy, and also the main battlefield of "innovation-driven, transformation and upgrading" of China's economy in the future [2]. In order to change the status quo of "big but not strong" manufacturing industry, China implemented the "Made in China 2025" strategy in 2015, focusing on intelligent manufacturing. China's regional development is uneven, and the intelligent level of manufacturing industry is also different. In this context, the scientific and accurate evaluation of the intelligent level of regional manufacturing industry helps the government and industry understand the transformation and upgrading and intelligent development of regional manufacturing industry, and provides a basis for the improvement of the intelligent level.

2 Current Situation and Problem Analysis

2.1 The Present Situation

(1) Building a reasonable evaluation index system is the premise of scientific evaluation. Based on the connotation of intelligent manufacturing, Li Jianxuan [3] constructed an intelligent evaluation index system of manufacturing industry from three levels: intelligent technology layer, intelligent application layer and intelligent benefit layer. Based on the five-dimensional characteristics of intelligent manufacturing, Wu Minjie [4] evaluated the regional intelligence level from the five dimensions of product, production, service, equipment and management. Based on the purpose of intelligent manufacturing, Ji Liangyu [5] constructed the evaluation index system of intelligent manufacturing level from the three levels of infrastructure layer, production application layer and market practice layer.

(2) Index weighting has a direct impact on the evaluation results [6]. Du Jinsong, YU Yayun, Zhao Ni et al. [7] used the analytic hierarchy process with subjective weighting when evaluating the maturity of intelligent manufacturing capability of different types of garment enterprises. Dong Zhixue, Liu Yingji [8] chose the factor analysis method with objective weight to evaluate the intelligent manufacturing capacity of major provinces and cities in China.

2.2 The Problem

(1) As the main direction of China's "Made in China 2025" national strategy, the construction of intelligent manufacturing evaluation index system not only needs to consider the purpose, connotation, characteristics, but also conforms to the basic policy of "Made in China 2025", which is innovation-driven, quality-first, green development, structural optimization and talent-oriented.

(2) Subjective weighting method and objective weighting method have the limitations of being greatly influenced by subjective factors and highly dependent on samples respectively, which makes it difficult to guarantee the accuracy of evaluation results, and how to accurately assign weights is still controversial.

Therefore, based on the background of intelligent manufacturing, combined with the connotation, characteristics and purpose of intelligent development of manufacturing industry, this paper constructs the evaluation index system of regional manufacturing intelligent level from five aspects of "innovation-driven, quality-first, green development, structural optimization and talent-oriented". Based on entropy- partial ordered set theory, an evaluation model [9–11] was constructed to evaluate and study the regional manufacturing intelligence level.

3 Entropy Weight Partial Ordered Set Theory

3.1 Basic Principles of Partial Ordered Set

The definition of partial ordered set [9] is: Let S be a binary relation on set Q, when S satisfies reflexivity, anti symmetry and transitivity, S is the partial ordered set relation " $\leq$ " on Q, and Q and $\leq$ are partial ordered set (Q, $\leq$).

Evaluation set N = (Q, TF, G) constructed $\leq$ compliance condition: for$\forall$a, b $\in$ Q there is $a \leq b \Leftrightarrow (a) \leq (b), j = 1,2,\ldots, n$

For any (Q, $\leq$), the upper and lower sets and incomparable sets of Q are $L(a) = \{b \in Q \mid a \leq b\}$; $P(a) = \{b \in Q | a \geq b\}$; K(a); among them:

$$K(a) = Q - P(a) - L(a) \quad (1)$$

$$|P(a)| + |L(a)| + |K(a)| = e + 1 \quad (2)$$

In formula (2), the absolute values of P (a), L(a) and K (a) are their own numbers, and e represents the number of schemes.

Height of scheme determines the sorting position of the scheme.

$$hav(a) = \frac{|P(a)|}{|P(a)| + |L(a)|} \cdot (|P(a)| + |K(a)|) + \frac{|L(a)|}{|P(a)| + |L(a)|} \cdot |P(a)| \quad (3)$$

Let the evaluation set N = (Q, TF, G), given the partial order set (Q, $\leq$), for $\forall a_i$, $a_j \in$ Q, if $a_i \geq a_j$ is satisfied, then r_{ij}=1; If $a_i \leq$aj or ai is not comparable with aj, then r_{ij}=0, s = (r_{ij}) m × n is the comparison relation matrix of (Q, $\leq$), and S can be transformed into Hasse matrix HS according to formula (4)

$$H_S = (S - T) - (S - T)^2 \quad (4)$$

T is the identity matrix,(S-T)2 is Boolean algebra.

Theorem 1 [10]: given the evaluation set M = (A,IC,D), set the criterion weight $\omega_1 \geq \omega_2 \geq \cdots \geq \omega_n \geq 0$, if

$$\sum_{i=1}^{t} g_i \leq \sum_{i=1}^{t} d_i (t = 1, 2, \cdots n)$$

Then f(H) $\leq$ f(U).

In the above formula, $f(H) = \omega_1 g_1 + \omega_2 g_2 + \cdots \omega_n g_n$; $f(U) = \omega_1 d_1 + \omega_2 d_2 + \cdots \omega_n d_n$.

If the above example is represented by a matrix, then given the upper triangular.

matrix $Z = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 0 & 1 & \cdots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}$, when $c_1 \geq c_2 \geq \cdots \geq c_n \geq 0$, the upper triangular matrix Z and A perform the following operations to obtain the matrix.

$$D = \left(d_{ij}\right)_{m\times n} = A \cdot Z = \begin{bmatrix} g_{11} & g_{11} + g_{12} & \cdots & g_{11} + g_{12} + \cdots + g_{1n} \\ g_{21} & g_{21} + g_{22} & \cdots & g_{21} + g_{22} + \cdots + g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{m1} + g_{m2} & \cdots & g_{m1} + g_{m2} + \cdots + g_{mn} \end{bmatrix} \tag{5}$$

In matrix D, if $d_{it} \leq d_{jt}$ $(t = 1,2,\cdots n)$, then $a_i \leq a_j (i,j \in 1,2,\cdots m)$.

3.2 Basic Principle of Entropy Weight Method

To evaluate the level of regional manufacturing intelligence with the partial ordered set evaluation model, we only need to get the importance order of evaluation indexes. In this paper, the entropy weight method is used to determine the importance degree of regional manufacturing intelligent level evaluation index. The specific calculation steps are as follows [11]:

Step 1: build the initial evaluation matrix $X = (X_{ij})_{m\times n}$, And dimensionless processing of the data. Its dimensionless model is:

$$V_{ij} = \frac{X_{ij} - \min(X_j)}{\max\left(X_j\right) - \min(X_j)} \tag{6}$$

m represents the number of evaluated objects, n represents the number of evaluation indicators, X_{ij} represents the jth index value of the ith evaluation object.
Step 2: calculate the characteristic proportion of the ith evaluation object under the j-th index. The formula is:

$$P_{ij} = \frac{V_{ij}}{\sum_{i=1}^{m} V_{ij}} \tag{7}$$

Step 3: calculate the entropy e_j of the j-th index:

$$e_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} P_{ij} \ln(P_{ij}) \tag{8}$$

When P_{ij}=0 or P_{ij} =1时, it is considered that $P_{ij}\ln(P_{ij})$=0.
Step 4: calculate the difference coefficient d_j of index J. Define the difference coefficient d_j:

$$d_j = 1 - e_j \tag{9}$$

Step 5: determine the entropy weight of each index:

$$W_{ij} = \frac{d_j}{\sum_{k=1}^{n} d_k} \tag{10}$$

3.3 Evaluation Procedure of Entropy Weight Partial Ordered Set Model

1. Determine the evaluation target set according to formula (1) and formula (2);
2. Use entropy weight method to determine the index weight reduction sequence;
3. Accumulate according to the first level index data to obtain a new relationship matrix R;
4. Transform relation matrix R into Hasse matrix by Boolean operation, and draw the Hasse diagram;
5. Do structural interpretation combined with Hasse diagram.

4 Establishment and Application of Model

4.1 Establishment of Intelligent Evaluation Index System for Regional Manufacturing Industry

"Made in China 2025" is an overall strategy to mobilize all social forces to build a manufacturing power. Its basic principles are: innovation driven, quality first, green development, structural optimization, talent oriented. The evaluation of the intelligent level of regional manufacturing industry should be consistent with its basic principles.

(1) Innovation driven: the transformation and upgrading of manufacturing industry cannot be separated from innovation, which is an important driving force [2]. The increase of R&D investment can enrich the knowledge base of enterprises and improve the absorptive capacity of enterprises, that is, improve the information processing capacity of enterprises, so as to strengthen the relationship between intelligent manufacturing and innovation performance [12]; The more R&D funds are invested, the better the innovation performance will be [13]. Therefore, the R&D expenditure of Industrial Enterprises above Designated Size and the proportion of the sales revenue of new products of Industrial Enterprises above Designated Size in the industrial added value of the province are used to reflect the innovation ability.

(2) Quality first: quality is the foundation of building a manufacturing power and the necessary condition for the benign development of manufacturing industry [2]. In industry 4.0 mode, intelligent manufacturing plays an important role in improving the quality and efficiency of enterprises, and produces the best quality products in the shortest time [14]. To take the development path of winning by quality, we should not only rely on quality upgrading, but also pay attention to variety optimization. The product quality qualification rate and the number of effective invention patents of Industrial Enterprises above designated size are used to reflect the regional quality upgrading and variety optimization respectively.

(3) Green development: the emissions of environmental pollution produced by manufacturing industry account for the highest proportion of the total environmental pollution emissions [15]. High resource consumption and high pollutant emissions are the main constraints to achieve green manufacturing. Therefore, the utilization efficiency of regional resources is measured by the proportion of industrial solid waste in GDP and the comprehensive utilization rate of solid waste.

(4) Structural optimization: there is a significant positive correlation between the intelligent level of manufacturing industry and the upgrading of industrial structure [16]. The transformation of high-tech industries needs to be driven by the improvement of information technology, which guides or forces the transformation of labor-intensive and resource intensive industries to knowledge intensive industries [17]; The improvement of information technology and the use of computers can significantly promote the production efficiency of enterprises [18]. Therefore, the income from information technology services and the number of computers per 100 people in enterprises are used to reflect the upgrading of regional manufacturing structure.
(5) Talent oriented: talent is always the foundation of building a manufacturing power [2]. Talent directly affects the intelligent manufacturing level of the region. The number of R&D personnel and the proportion of employees in high-tech industries are used to express the talent structure of the region.

According to the background of intelligent manufacturing, combined with the connotation, characteristics and purpose of intelligent development of manufacturing industry, the evaluation index system of intelligent level of regional manufacturing industry is constructed from the five aspects of "innovation driven, quality first, green development, structural optimization and talent oriented", as shown in Table 1.

4.2 Sample Data Selection and Index Weight Calculation

Firstly, establish the initial evaluation matrix according to formula (6), then calculate the feature ratio of the i-th evaluation object under the jth indicator according to formula (7), and calculate the entropy of the index according to formula (8). Secondly, define the difference coefficient according to formula (9), and finally determine the entropy weight of each indicator according to formula (10). According to the evaluation index system of regional manufacturing intelligence level constructed in Table 1, this paper collected the relevant index data of 30 provinces in China (excluding Tibet, Hong Kong, Macao and Taiwan) from 2015 to 2019. The data comes from China Statistical Yearbook and China Industrial statistical yearbook over the years. According to the principle of entropy weight method, the weight of each index is shown in Table 2.

It can be seen from Table 2 that the importance of indicators from high to low is B2 > D1 > E1 > A1 > E2 > A2 > D2 > C2 > B1 > C1.

4.3 Comparison Relation Matrix

Determine the ranking of solutions according to formula (3), According to the order of importance B2 > D1 > E1 > A1 > E2 > A2 > D2 > C2 > B1 > C1, the sample data from 2015 to 2019 are cumulatively transformed, and the comparison relationship matrix from 2015 to 2019 is obtained respectively according to the comparison of row vectors. Due to space constraints, the comparison relationship matrix only intercepts the data from the eastern region of 2019, as shown in Table 3.

4.4 Hasse Diagram

Through Eq. (4) and (5), the comparison relationship matrix can be transformed into Hasse matrix, and then the Hasse diagram can be drawn from the Hasse matrix. The

Table 1. Evaluation Index System of intelligence level of regional manufacturing industry

Index code	Name of primary indicator	Index code	Name of secondary indicator
A	Innovation driven	A1 A2	The R&D expenditure of Industrial Enterprises above Designated Size The proportion of the sales revenue of new products of Industrial Enterprises above Designated Size in the industrial added value of the province
B	Quality first	B1 B2	The product quality qualification rate The number of effective invention patents of Industrial Enterprises above designated size(piece)
C	Green development	C1 C2	The industrial solid waste/GDP The Comprehensive utilization of solid waste/The industrial solid waste
D	Structural optimization	D1 D2	The income from information technology services The number of computers per 100 people in enterprises
E	Talent oriented	E1 E2	The full-time equivalent of R&D personnel in industrial corporate enterprises above the designated size Employees in high-tech industry/Total number of employees

Hasse diagram for 2019 is shown in Fig. 1. Due to space limitations, the Hasse images from 2015 to 2018 are presented in the appendix, The Hasse diagram for 2015 is shown in Fig. 2. The Hasse diagram for 2016 is shown in Fig. 3. The Hasse diagram for 2017 is shown in Fig. 4. The Hasse diagram for 2018 is shown in Fig. 5.

From the Hasse diagram, we can intuitively see the stratification and clustering between samples. From Fig. 1, we can see that 30 provinces are divided into multiple levels by hierarchical clustering. The manufacturing intelligence level of the top provinces and cities is better. And provinces and cities at the same level cannot be compared. As shown in Fig. 1, Beijing and Guangdong are at the first level, Jiangsu is at the second level, Shanghai, Zhejiang and Shandong are at the third level, and Qinghai is at the last level.

Table 2. Index weight of intelligent evaluation of regional manufacturing industry

Primary indicator	Primary index weight	Secondary indicator	Secondary index weight	Weight sorting
A	0.212	A1	0.150	4
		A2	0.062	6
B	0.233	B1	0.017	9
		B2	0.216	1
C	0.041	C1	0.006	10
		C2	0.035	8
D	0.268	D1	0.213	2
		D2	0.055	7
E	0.246	E1	0.167	3
		E2	0.079	5

Table 3. Eastern regional comparison Matrix 2019

	Bei jing	Jiang su	Guang dong	Shang hai	Tian jin	Shan dong	Zhe jiang	Fu jian	He bei	Hai nan
Beijing	0	0	0	0	0	0	0	0	0	1
Jiangsu	0	0	0	0	0	0	0	0	0	0
Guangdong	0	0	0	0	0	0	1	0	0	0
Shanghai	0	0	0	0	1	0	0	0	0	0
Tianjin	0	0	0	0	0	0	0	0	0	0
Shandong	0	0	0	0	0	0	0	0	0	0
Zhejiang	0	0	0	0	0	0	0	0	0	0
Fujian	0	0	0	0	0	0	0	0	0	0
Hebei	0	0	0	0	0	0	0	0	0	0
Hainan	0	0	0	0	0	0	0	0	1	0

4.5 Result Analysis

According to the Hasse diagram of 2015–2019, the levels of 30 provinces in 2015–2019 are sorted in the order of eastern region, central region, western region and northeast region, as shown in Table 4.

It can be seen from Table 4 that the development level of manufacturing intelligence in each region is different.

(1) Eastern Region: except for Hebei and Hainan, other provinces and cities are at level 1 to level 9; And Beijing and Guangdong Province are always at the first level;

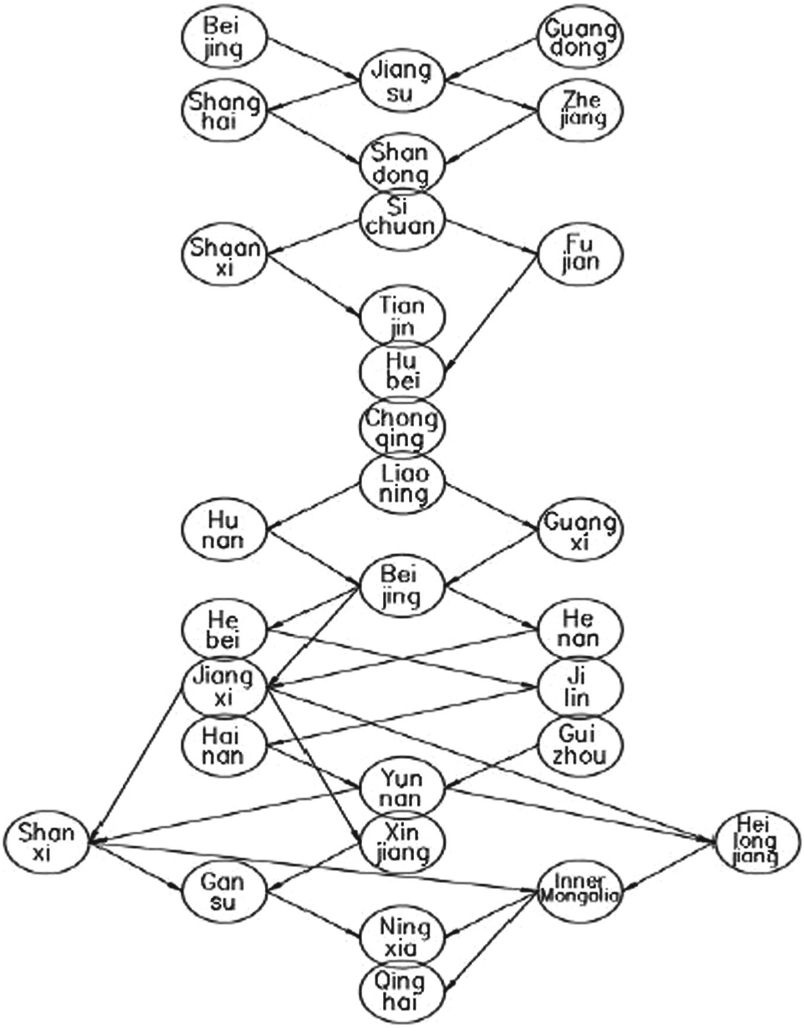

Fig. 1. 2019 Hasse Chart

Jiangsu Province is always at the second level; Zhejiang Province is always at the third level; The eastern region has an absolute advantage in the level of intelligent development.

(2) Central region: Hubei Province is relatively strong, at the 8th to 10th levels; Shanxi is relatively weak, at the 14th-18th level; The remaining provinces are at levels 9 to 15 respectively; The overall development level of intelligence in the central region is at a medium level.

(3) Western region: Sichuan's intelligent development performance is excellent, at the 4th to 6th levels, surpassing some eastern provinces and all central provinces; Shaanxi province takes the second place, at the 6th to 8th levels; Chongqing is

Table 4. Ranking of manufacturing intelligence level by province and city

Region	Province	2015	2016	2017	2018	2019
Eastern Region	Beijing	1	1	1	1	1
	Jiangsu	2	2	2	2	2
	Guangdong	1	1	1	1	1
	Shanghai	3	3	4	4	3
	Tianjin	7	7	8	9	7
	Shandong	3	3	4	5	4
	Zhejiang	3	3	3	3	3
	Fujian	6	5	6	7	6
	Hebei	10	11	12	14	13
	Hainan	15	15	15	15	15
Middle Region	Anhui	11	11	12	15	12
	Hubei	8	8	9	10	8
	Henan	9	10	11	13	13
	Hunan	10	9	10	14	11
	Jiangxi	12	12	13	13	14
	Shanxi	15	14	16	18	17
Western Region	Chongqing	8	8	9	11	9
	Shaanxi	7	7	8	8	6
	Sichuan	5	4	5	6	5
	Guizhou	13	13	14	16	15
	Guangxi	13	13	15	16	11
	Ningxia	16	16	18	21	19
	Inner Mongolia	14	14	17	19	18
	Yunnan	14	14	15	17	16
	Xinjiang	14	14	16	18	17
	Gansu	15	15	17	19	18
	Qinghai	17	17	19	22	20
Northeast Region	Liaoning	4	6	7	12	10
	Jilin	9	9	10	13	14
	Heilongjiang	12	12	13	20	17

at the 8th to 11th level, and its overall performance is relatively good; However, the remaining six provinces are not satisfactory, and are concentrated at the bottom level; There are obvious internal differences in the intelligent development level of the western region, and the overall development level is at the bottom.

(4) Northeast China: Liaoning Province performs relatively well, at the 4th to 12th levels; Jilin Province and Heilongjiang Province are in general, at the 9th to 20th level; The intelligence level of Northeast China is in the middle and lower position.

Analyze the change trend from the level difference, and record the difference between the highest level and the lowest level of provinces and cities in 2015–2019 as the level difference. The smaller the level difference is, the more stable the intelligent level of manufacturing industry is, and vice versa.

(1) Eastern Region: 1/2 of the 10 provinces and cities (Beijing, Jiangsu, Guangdong, Zhejiang, Hainan) have a level difference of 0, and there is no change in the level; Among the other provinces, except Hebei Province, whose level difference is 4, the level difference of the other four provinces (Shanghai, Tianjin, Shandong and Fujian) is between 1 and 2; The eastern region is the most stable. (2) Central region: the level difference of the six provinces and cities is between 2 and 4, which is relatively stable. (3) Western region: 6 of the 11 provinces and cities (Guangxi, Ningxia, Inner Mongolia, Xinjiang, Gansu, Qinghai) have a level difference of 4–5, which is relatively unstable. (4) Northeast China: the level difference of Jilin is 5, and the level difference of Liaoning and Heilongjiang is 8. The downward trend is obvious, the decline range is large, and it is the most unstable.

5 Countermeasures and Suggestions

To solve the unbalanced and unstable development of intelligent manufacturing regions in China, we should strengthen strategic overall planning, optimize resource layout, and narrow the gap of regional intelligence.

(1) Strengthen the guidance of strategic overall planning and promote the development of regional manufacturing industry with the improvement of intelligent level

Strengthen top-level design, from the perspective of the integration system view of intelligent manufacturing industry, make overall planning and supporting policy support for the manufacturing industry, and improve the policy system covering the whole life cycle of the intelligent manufacturing industry chain; Strengthen the strategic layout, commit to improving the basic ability of intelligent manufacturing, focus on key core technologies, and increase the frequency of iterative upgrading of intelligent manufacturing technology; We should improve the institutional guarantee, improve the relevant policies on talent, innovation and financial support, and remove institutional obstacles for the development of intelligent manufacturing.

(2) Balance the layout of regional resources and promote the stable development of intelligent manufacturing industry

According to the differences of resource endowments and industrial technological advantages in different regions, the rational layout of regional resources is very important to realize the balanced development of intelligent manufacturing. Compared with other regions, the eastern region has gathered talents, science and technology, capital and other production factors. The central, Western and northeast regions should increase their support for talents, science and technology in the field of Intelligent Manufacturing in the province, attract the return of human resources in the province by exploring ways such as “flexible” talent introduction, and transform the advantages of natural resources such as land, labor and energy into technological resources.

(3) Narrow the gap of regional intelligence and lead the balanced development of regional manufacturing industry

There is a certain imbalance in the industrial foundation of China’s manufacturing industry. Compared with the eastern region, the central, Western and northeastern regions have obvious differences in the basis of manufacturing industry. Therefore, the central, Western and northeastern regions should first consolidate the foundation of manufacturing development and provide basic support for the development of intelligent manufacturing. Secondly, the development of intelligent manufacturing needs the support of information technology such as big data and cloud computing. The central, Western and northeast regions should pay attention to the construction of network resources and data resource system, so as to create a good scientific and technological information environment for giving full play to the optimization and integration of intelligent technology in the manufacturing industry.

6 Conclusion

Based on the guidelines of “made in China 2025”, this paper constructs an evaluation index system for the intelligent level of China’s manufacturing industry, and uses the partial set model to evaluate the intelligent level of manufacturing industry in 30 provinces in China from 2015 to 2019. The evaluation results are more robust and have a high degree of confidence. The results show that there is a large gap in the level of manufacturing intelligence between the four regions. On the whole, the eastern region has the highest level of manufacturing intelligence and the most stable development; The intelligence level of the central region is in a medium position, and its development is relatively stable; The intelligence level of the western region is at the bottom, and its development is relatively unstable; The intelligence level of Northeast China is in the middle and lower position, and its development is the most unstable. In view of the above analysis results, it is proposed that we should strengthen the guidance of strategic overall planning, balance the layout of regional resources, and narrow the gap of regional intelligence.

Appendix A

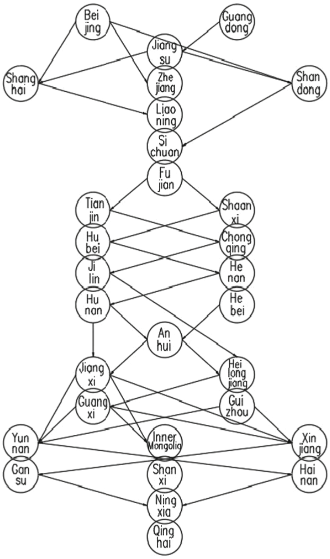

Fig. 2. 2015 Hasse Chart

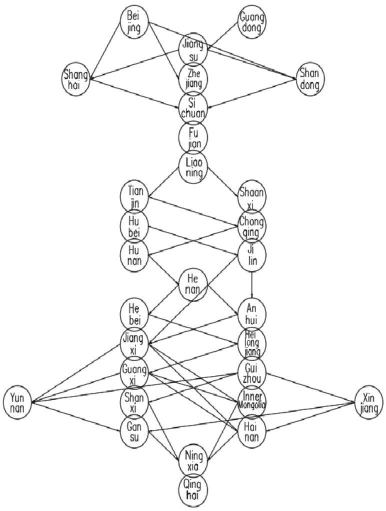

Fig. 3. 2016 Hasse Chart

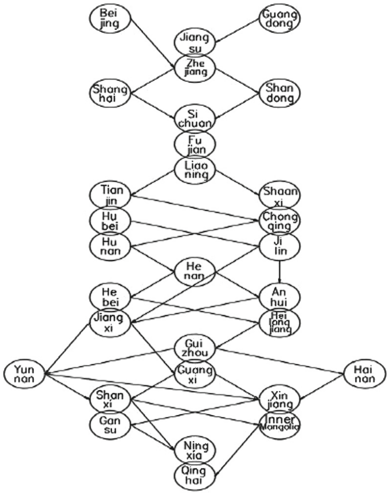

Fig. 4. 2017 Hasse Chart

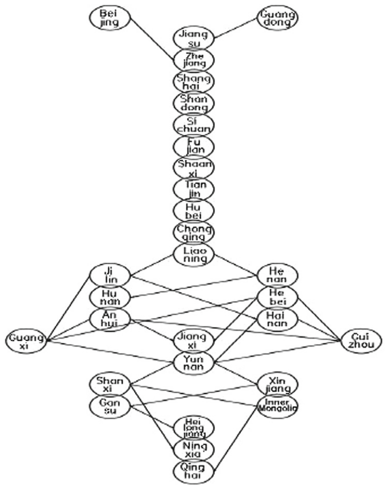

Fig. 5. 2018 Hasse Chart

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