Risk Measurement of Industry Chain Based on Set Pair Analysis - Variable Fuzzy Set with Improved Binary Semantics

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Abstract**—**Under the current complex and severe new situation, China's industry chain is facing huge risks caused by the superposition of multiple factors, such as the shortage of supply of "neck-breaking" technologies and the "decoupling and chain breakage" caused by anti-globalization, which urgently needs to strengthen the risk control of the industry chain fundamentally. Implementing industry chain risk measurement is a necessary precondition for risk control. In this study, based on the construction of the industry chain risk measurement indicator system, the comprehensive weights of the indicators are determined by the BWM-CRITIC method. Then, the industry chain risk is measured by binary semantics improved set pair analysis - variable fuzzy set model. Finally, an empirical study is conducted on the example of China's integrated circuit industry to verify the scientificity and effectiveness of the model. The results of the empirical study show that the model can effectively reflect the risk level of the industry chain by analyzing the relationship between the sample data and the level of each indicator; at the same time, it can better solve the problem of information loss, comprehensively reveal the risk status of the industry chain, and provide a decision-making reference for effectively resisting the risk of the industry chain and realizing the sustainable development of the industry chain.

Keywords—Risk Measurement; Industry Chain; Set Pair Analysis-Variable Fuzzy Set; Binary Semantics

I. INTRODUCTION

Accompanied by the accelerated restructuring of the global industrial chain, the new round of technological change and intensified market competition have put the sustainable development of the industry chain under tremendous risk pressure. In particular, the impact of global epidemics and other emergencies, as well as the restriction of "De-Sinicization" by Western developed countries, has led to a serious crisis in China's industry chain system, bringing great uncertainty to the steady progress of various industries. Nowadays, many industry chains are facing risks such as reduced export capacity, blocked resource flow, and limited independent innovation in "neckline" areas, such as the semiconductor industry chain showing structural imbalance and imbalance between supply and demand, with limited independent R&D capacity and part of the core technology restricted; marine ship industry chain upstream ancillary product supply encountered "neck" problem, ship demand weakened, the risk of chain breakage increased; aviation equipment industry chain in the field of technology is relatively weak, part of the high-end products rely on imports of the phenomenon is evident. Therefore, fully grasping the industry chain risk issues and identifying the shortcomings and weaknesses is an important task to effectively prevent the risks of the key links of the industry chain.

The industry chain is an organic unity that accumulates the industrial rings step by step. Its essence is the supply and demand relationship between the enterprises in the upstream and downstream industries; the industry chain risk measurement needs to focus on the internal and external risks in the industry chain and nodes, including the risks in the environment, management, supply, and technology dimensions. Given this, this study proposes an improved binary semantic set pair analysis -variable fuzzy set measurement model for industry chain risk, which can effectively deal with the ambiguity and uncertainty among risk indicators in the industry chain system, to quantify the industry chain risk more accurately. Based on constructing the industry chain risk measurement indicator system, considering the correlation and difference between the indicators, taking into account the experience of experts and the amount of information of raw data, the best-worst method (BWM) and the CRITIC method are used to determine the comprehensive weights of the indicators, to avoid the bias of the results caused by a single assignment, and to make the setting of the weights more objective and accurate. Since the set pair analysis -variable fuzzy set model measurement may have too many results of the same level when measuring the industry chain risk, this study introduces the binary semantic

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theory for model optimization, aiming to more accurately reveal the degree of risk of each link in the industry chain, and conducts empirical research on the example of China's integrated circuit industry, to provide decision-making references for the measurement of industry chain risk.

The contributions of this study include: (1) Constructing the industry chain risk measurement indicator system based on the connotation of industry chain risk and its complex structure, combined with the internal and external risks in the industry chain and nodes. (2) Aiming at the problem of bias of single weighting results that may occur in the weight setting process, the BWM and CRITIC methods are utilized for the combination of weighting to determine the comprehensive weights of the industry chain risk measurement indicators. (3) Introducing the idea of binary semantics, constructing the set pair analysis -variable fuzzy set model with improved binary semantics for measuring the risk of the industry chain, and conducting empirical research with the China's IC industry chain as an example.

The rest of this study is organized as follows. Section II is a literature review on industry chain risk, risk measurement, and set pair analysis - variable fuzzy set. Section III constructs the industry chain risk measurement indicator system. Section IV constructs a binary semantically improved set pair analysis -variable fuzzy set industry chain risk measurement model. Section V presents an empirical study. Finally, conclusions and future work are presented in Section 6.

II. LITERATURE REVIEW

A. Industry chain risk

Presently, domestic and foreign scholars' research on the industry chain mainly focuses on the development path, innovation synergy and structural evolution. Wang et al. revealed the carbon peak mode and development path of the seven major industry chains under the carbon peak goal.[1] Ma found that the coordinated innovation of upstream and downstream enterprises positively impacts upgrading industrial technology and the modernization of the industry chain.[2] Li et al. aimed at the structural evolution of the industry chain, and constructed a chrome industry chain trade and competition network to clarify the industry chain's evolution in the global competitive relationship. [3] In today's complex and changing international economic environment, more and more scholars have begun to pay attention to the risk management of the industry chain, and the research mainly centers on risk identification and transmission. Zeng et al. sorted out the key node risks of China's semiconductor industry chain based on the perspective of autonomous control.[4] Li et al. utilized the complex network and the newly established three-dimensional risk assessment model assess the commodity supply risk of China's copper industry chain.[5] Ouyang et al. used the minimum spanning tree and connectivity methodology to study the risk transmission among China's energy futures from the perspective of the industry chain.[6] In the post-epidemic era, academics further focus on studying the risk status of the global industry chain supply chain in the context of the epidemic, Mustafa et al. concluded the mitigation strategy of the potential risk of the supply chain under the influence of the global epidemic[7], and Li et al. explored the risk spillover effect within the supply chain system during the epidemic crisis.[8]

B. Risk measurement

Risk measurement is the foundation of risk management, and selecting reasonable risk measurement indicators and scientific metrics is critical. He et al. constructed a hesitant fuzzy risk house model by analyzing the correlation between supply chain risk factors and transforming risk factors into risk treatment for risk management.[9] Harish proposed a conceptual framework for comprehensively assessing supply chain risks of small and medium-sized enterprises in uncertain times, including supply chain risk factors and their associated attributes, to assess the overall risk indicator of SMEs.[10] There are numerous risk measurement models available that can be applied to a variety of different domains. Ma et al. classified and measured local government debt risk at the provincial level in China based on the AHP-TOPSIS method.[11] Liu et al. constructed the Dtrarch model to assess the volatility of financial asset returns and measure financial risk effectively.[12] Wang et al. measured the risk of price fluctuations of supply chain finance pledges using MIDAS-SVQR.[13] Xue et al. used the fuzzy AHP-DEMATEL method to quantify ships' ice distress risk.[14] Feng et al. based on optimized BP neural network to evaluate the risk of the fresh grape supply chain.[15]

C. Set pair analysis -variable fuzzy set

Set pair analysis theory is a systematic approach to dealing with the uncertainty caused by random, fuzzy, mediated and incomplete information. Variable fuzzy set theory is a breakthrough and development of classical, static fuzzy sets, which can be better adapted to the study of complex systems characterized by vagueness, dynamics and uncertainty. At present, set pair analysis -variable fuzzy set model is widely used in environmental assessment, traffic level measurement, risk evaluation, etc. Li et al. applied the coupled set pair analysis -variable fuzzy set evaluation model of the environmental impact of dam failure to the Shaheji Reservoir dam, which more comprehensively reflects the nonlinear and variable fuzzy nature of the environmental impact system of the dam failure.[16] Ma et al. used the improved set pair analysis -variable fuzzy set model to measure the level of green transportation in urban agglomerations comprehensively.[17] Zhang constructed a coal mine water damage risk evaluation model based on set pair analysis -variable fuzzy set coupling to effectively identify and determine the risk of coal mine water damage.[18]

D. Summary of literature review

Industry chain risk is an important research topic, and most of the existing research focuses on industry chain risk identification and risk transmission. At the same time, more quantitative studies on industry chain risk measurement need to be conducted. Most existing risk measurement models start from the financial aspect and measure risk based on value at risk or risk volatility, which is challenging to fit the industry chain risk measurement. There are also some risk measurement models (e.g., TOPSIS[11], DEMATEL[14], etc.) that can be used to evaluate the risk of the industry chain. Still, there is a high degree of subjectivity or loss of information, which makes it difficult to highlight the degree of risk of the industry chain. Therefore, this study proposes an improved binary semantic set pair analysis -variable fuzzy set measurement model applicable to industry chain risk to solve the problem of ambiguity and uncertainty among risk indicators in the industry chain system, to reveal the degree of risk of each link of the industry chain more precisely.

III. CONSTRUCTION OF INDUSTRY CHAIN RISK MEASUREMENT INDICATOR SYSTEM

Industry chain risk refers to a series of uncertainties that may impact a link in the industry chain and affect the realization of the value of the industry chain.[19] Considering the complexity of the industry chain system, it involves many factors and evaluation indicators, so it is crucial to select reasonable core indicators for measurement and analysis. Most of the existing studies either focus on a single aspect of the study, such as policy changes [20], supply risk [21], etc., or summarize the risk indicators for a particular industry as a specific object, which cannot be widely used in the study of each industry chain.

Since there is no complete indicator system for risk measurement, most are constructed from the perspectives of environment, market, policy, management, logistics, supply chain, technology, etc., to build a risk indicator system applicable to the research object. Therefore, this paper will be based on the connotation of industry chain risk and the structure of the industry chain, drawing on Ye’s oil industry chain risk categorization matrix[22] (external and internal risks in politics, economy, society, and technology), He et al.’s supply chain risk factors[9] (increase in demand, insufficient supply capacity, and limited access to information), and Harish et al.’s supply chain risk variables[10] (policy change, transportation risk, inflexible supply sources, poor inventory management) and Chitea et al.’s supply chain risk evaluation study [23] (global economic instability, financial assistance, lack of expertise), comprehensively consider the internal and external risks on the industry chain and nodes and construct the industry chain risk measurement indicator system from four dimensions: environmental risk, management risk, supply risk, and technology risk (as Table I), to measure and assess the risks in the industry chain comprehensively.

Table I. Industry Chain Risk Measurement Indicator System

Guideline hierarchy	Indicator hierarchy	Description of indicators
Environmental risk T1	industrial policy environment R1	extent to which relevant national policies pose a risk to the industry chain
	global market risk R2	extent to which the international market environment poses a risk to the industry chain
	government support R3	government funding subsidies/R&D funding
Management risk T2	external dependence R4	total exports and imports of enterprises/gross output
	information management risk R5	risks in the delivery of information by information management systems
	decision-making response level R6	ability to make decisions based on programmatic implementation
	Emergency management risk R7	risk of making decisions and implementing plans to respond to emergencies
	Risk-bearing capacity R8	ability of an enterprise to withstand and deal with risk
Supply risk T3	product-demand convergence level R9	production/sales of the enterprise’s main product
	critical material redundancy R10	critical material inventory/sales
	dynamic logistics management R11	ability to dynamically monitor logistics status and ensure timely delivery of goods
	partner relationship R12	dependence of enterprises on top five suppliers

	nodal enterprise synergy capabilities R13	capacity for collaborative trust, integration and knowledge sharing among nodal enterprises
	resource reorganization capacity R14	ability to schedule, integrate and adjust work schedules with internal and external resources
Technology risk T4	employee's education level R15	percentage of personnel with bachelor's degree or above
	innovation funding R16	R&D investment/sales
	innovation output level R17	revenue from sales of new products/revenue from main operations
	technical R&D capacity R18	number of active patents

IV. SET PAIR ANALYSIS-VARIABLE FUZZY SET INDUSTRY CHAIN RISK MEASUREMENT MODEL BASED ON BINARY SEMANTIC IMPROVEMENT

For the industry chain risk measurement problem, this paper adopts the measurement method combining set pair analysis and variable fuzzy set to effectively deal with the ambiguity and uncertainty among risk indicators in the industry chain system.[17] By combining the set pair analysis connection degree and variable fuzzy set relative difference degree, it makes up for the shortcomings of the traditional set pair analysis evaluation results that do not conform to reality and have the problem of information loss, as well as the variable fuzzy set evaluation process that relies too much on experience and is not easy to carve out the qualitative indicators.[24] On this basis, this paper introduces the idea of binary semantics to improve the set pair analysis -variable fuzzy set model to reflect the risk level of the industry chain more clearly, making the measurement results more detailed and accurate. The steps of model building are as follows:

1) Determine the set of measurement indicators and the set of measurement grade criteria. Let the set of sample data values of industry chain indicators be $R=\{r_1,r_2,r_3,\cdots,r_n\}$, and the set of indicator grading criteria G be composed of each grade threshold $M_{j,g}(j=1,2,\cdots,n;g=0,1,2,\cdots m)$. Set R and set G are constructed as a set pair $H(R,G)$. Where $M_{j,g}$ denotes the *g*th grade threshold of the *j*th indicator.

2) Calculate the comprehensive connection degree of the measurement indicator and measurement level μ_g. Through the degree of numerical proximity between the sample data value r_j of industry chain indicator and measurement level *g* to express the connection degree $\mu_j(g)$ of the two sets. According to the discriminative standard of set pair analysis theory, it can be seen that, when r_j is within the discussion interval *g*, the two sets have the same relationship, and the corresponding connection degree $\mu_j(g)$ is 1. When r_j is in the neighboring interval of the discussion interval, the two sets are in the difference relationship, and the set pair connection degree $\mu_j(g)\in[-1,1]$. When r_j is in the interval of the discussion interval of the separation, the two sets are in the antagonistic relationship, and then the connection degree $\mu_j(g)$ is -1. Where the single indicator connection degree is calculated by the formula (1):

$$\mu_j(g)=\begin{cases}1-2\dfrac{M_{j,g-1}-r_j}{M_{j,g-1}-M_{j,g-2}}, & r_j\in(M_{j,g-2},\ M_{j,g-1}]\\ 1, & r_j\in(M_{j,g-1},\ M_{j,g}]\\ 1-2\dfrac{r_j-M_{j,g}}{M_{j,g}-M_{j,g+1}}, & r_j\in(M_{j,g},\ M_{j,g+1}]\\ -1, & others\end{cases} \tag{1}$$

Based on the comprehensive weights of the indicators, the comprehensive connection degree of the measurement object to each measurement level is calculated, as shown in formula (2), where A is the combined weight of the indicators.

$$\mu_g=\sum_{j=1}^{n}W_j\mu_j(g) \tag{2}$$

3) Calculate the relative membership degree $\eta(g)$. The connection degree of set pair analysis is the relative difference degree of the variable fuzzy set; when the connection degree is closer to -1, the more different the measurement object is from the measurement level, the closer it is to the other levels. According to the theory of variable fuzzy set, it is known that the relative membership degree is formula (3).

$$\eta(g)=\frac{1+\mu_g}{2} \tag{3}$$

4) Determination of measurement level. Following the criterion of maximum membership degree to determine measurement level, the level eigenvalue *k* is introduced to quantify the measurement results to avoid judgmental distortion. The eigenvalue *k* is shown in formula (4), where v_g is the normalized relative membership degree.

$$k=\sum_{g=1}^{m}g\left|\frac{\eta(g)}{\sum_{g=1}^{m}\eta(g)}\right|=\sum_{g=1}^{m}gv_g \tag{4}$$

To further improve the accuracy of the measurement results, the confidence criterion is used to judge the measurement results, and the measurement level of the measurement object is the *g* level corresponding to h_g. The expression is formula (5), where λ is the confidence level, which is generally taken within [0.5,0.7], and the larger λ is, the more the results of the measurement tend to be robust.

$$h_g = \min\left\{ g \left| \sum_{g=1}^{m} v_g > \lambda, g = 1, 2, \cdots, m \right.\right\} \tag{5}$$

5) Combined with the eigenvalue *k*, the binary semantic method is introduced further to classify the internal rank of the industry chain risk, to reflect the risk status of the industry chain more intuitively and meticulously. The binary semantic expression takes the form of $\vartheta(k) = (g, \rho)$, where *k* is the primary measurement level eigenvalue of the industry chain risk, $g = \mathrm{round}(k)$ is the standard measurement level of the industry chain risk, and $\rho = k - g$ is the industry chain risk level deviation, i.e., the value of the measurement level eigenvalue from the standard measurement level. The secondary subdivision level corresponding to ρ is determined by the mapping function Δ as shown in formula (6). Where *f* is the number of secondary segmentation levels, *f*=6; a is the adjustment coefficient, a=0.6; $s_i (i = 1, 2, 3, 4, 5, 6)$ is the six segmentation levels of the secondary measurement level, corresponding to very low, low, medium, upper-middle, high, and very high; and $\varepsilon \in [-0.5, 0.5]$ is the value of the second level binary semantic deviation, i.e., the value of the secondary measurement level away from the standard secondary segmentation level.[25]

$$\Delta\colon\ [-0.5, 0.5) \rightarrow S \times [-0.5, 0.5)$$

$$\Delta(\rho) = (s_i, \varepsilon) = \begin{cases} s_i, i = \begin{cases} \dfrac{f}{2} + \mathrm{round}\left(\log_{\mathrm{a}}\left(\left(\mathrm{a}^{\frac{f}{2}} - 1\right)\rho \times 2 + 1\right)\right), \rho \in [0,\ 0.5) \\ \dfrac{f}{2} - \mathrm{round}\left(\log_{\mathrm{a}}\left(\left(\mathrm{a}^{\frac{f}{2}} - 1\right)|\rho| \times 2 + 1\right)\right), \rho \in [-0.5,\ 0) \end{cases} \\ \varepsilon = \begin{cases} \log_{\mathrm{a}}\left(\left(\mathrm{a}^{\frac{f}{2}} - 1\right)\rho \times 2 + 1\right) + \dfrac{f}{2} - i, \rho \in [0,\ 0.5) \\ -\log_{\mathrm{a}}\left(1 - \left(\mathrm{a}^{\frac{f}{2}} - 1\right)\rho \times 2\right) + \dfrac{f}{2} - i, \rho \in [-0.5,\ 0) \end{cases} \end{cases} \tag{6}$$

V. EMPIRICAL STUDY

A. Data sources

As the core and foundation of modern electronic information technology, integrated circuit (IC) are the key to accelerating the realization of high-quality development in China. IC industry chain is a complex system structure. However, how to scientifically and reasonably measure the risk of the IC industry chain is crucial to ensure the sustainable development of the industry chain. Based on the regional distribution of the IC industry in China, this study takes into account the economic strength and development trend, and finally selects 27 enterprises located in the Yangtze River Delta, the Pearl River Delta, and Beijing-Tianjin-Hebei as samples, including 9 enterprises in the upstream, midstream, and downstream of the IC industry chain, i.e., among the listed enterprises of the IC industry, enterprises ranked in the front, middle, and the back of the list are selected according to the comprehensive strength of the enterprises, to reflect the risk status of the industry chain and each link of the industry chain. By reviewing the annual reports of enterprises and the information on the official websites of enterprises, the relevant data of 27 sample enterprises are obtained and organized, in which the qualitative indicator data are comprehensively measured by industry experts and professional scholars. Due to a large amount of statistical data, this study only displays the measurement indicator data of the upstream enterprises of the IC industry chain (Table II) for reference.

Table II. Partial Data of Risk Measurement Indicators of the IC Industry Chain

Measurement indicator data	Upstream enterprises (IC design)								
	A1	A2	A3	A4	A5	A6	A7	A8	A9
R1	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
R2	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
R3	10.60	1.00	8.00	23.55	1.50	23.21	1.10	7.60	2.04
R4	85.90	81.10	77.40	90.10	89.30	91.20	83.50	90.20	89.20
R5	0.87	0.90	0.86	0.88	0.91	0.89	0.88	0.83	0.85
R6	0.85	0.84	0.83	0.81	0.88	0.82	0.90	0.88	0.83
R7	0.20	0.17	0.23	0.19	0.15	0.12	0.16	0.14	0.19
R8	0.83	0.87	0.82	0.83	0.84	0.88	0.90	0.91	0.83
R9	100.00	96.00	100.00	100.00	100.00	100.00	83.00	100.00	100.00
R10	13.00	80.00	43.00	15.00	90.00	43.00	90.00	20.00	5.00
R11	0.10	0.04	0.06	0.11	0.08	0.09	0.03	0.12	0.06
R12	75.9	52.00	89.34	39.74	37.60	54.53	64.73	84.50	80.41
R13	0.82	0.84	0.85	0.83	0.87	0.84	0.88	0.85	0.81
R14	0.81	0.84	0.80	0.82	0.85	0.81	0.91	0.84	0.86
R15	91.00	96.09	93.15	61.95	86.35	39.54	65.17	97.25	87.30
R16	20.63	34.7	19.77	16.21	10.63	9.58	10.87	35.90	26.28
R17	20.64	16.24	15.23	13.20	13.27	11.40	21.76	14.20	11.40
R18	526	2414	57	35	556	14	4097	52	67

B. Risk level classification of measurement indicators

Based on the reference to domestic and international measurement standards, the industry chain risk level is divided into five levels: Level I (low risk), Level II (medium-low risk), Level III (medium risk), Level IV (medium-high risk), and Level V (high-risk). A total of 10 research scholars in the field of risk management and experts in the field of integrated circuits were invited to take the integrated circuit industry as the research object, assign subjective level boundaries according to the characteristics of each indicator, and finally take the average value as the level division standard of the risk measurement indicators to more accurately measure the risk level of IC industry chain. The specific division standard is shown in Table III.

Table III. Classification Criteria for The Level of Risk Measurement Indicators of the IC Industry Chain

Level boundaries	R1	R2	R3/%	R4/%	R5	R6	R7	R8	R9
I	0.2	0.2	100	30	1.0	1.0	0.2	1.0	100
II	0.4	0.4	80	50	0.8	0.8	0.4	0.8	90
III	0.6	0.6	60	70	0.6	0.6	0.6	0.6	70
IV	0.8	0.8	40	90	0.4	0.4	0.8	0.4	50
V	1.0	1.0	20	100	0.2	0.2	1.0	0.2	20

Level boundaries	R10/%	R11	R12/%	R13	R14	R15/%	R16/%	R17/%	R18
I	100	0.2	40	1.0	1.0	80	5	60	10000
II	80	0.4	30	0.8	0.8	60	2	30	5000
III	50	0.6	20	0.6	0.6	50	1.5	20	2000
IV	30	0.8	10	0.4	0.4	30	1	15	1000
V	10	1.0	5	0.2	0.2	10	0.5	10	100

C. Results and analysis

1) Calculation of indicator weights

To determine the weight of each indicator, the above 10 experts evaluate each indicator by BWM method and calculate the subjective weight; at the same time, according to the actual data of the enterprise and the ratings of experts in the industry, the objective weight of the indicator is calculated by CRITIC method. Considering the subjective and objective weights together, the comprehensive weights of each indicator are finally calculated and determined, and the results are shown in Table IV.

Table IV. Results of Indicator Weighting

Indicator	Subjective weight	Objective weight	Comprehensive weight
R1	0.017	0.089	0.045
R2	0.047	0.079	0.070
R3	0.006	0.039	0.018
R4	0.043	0.048	0.053
R5	0.017	0.055	0.035
R6	0.014	0.044	0.029
R7	0.021	0.051	0.038
R8	0.064	0.052	0.067
R9	0.024	0.056	0.042
R10	0.049	0.087	0.075
R11	0.016	0.053	0.033
R12	0.008	0.051	0.023
R13	0.032	0.042	0.042
R14	0.081	0.057	0.079
R15	0.074	0.074	0.085
R16	0.04	0.041	0.047
R17	0.123	0.037	0.078
R18	0.324	0.047	0.142

2) IC industry chain risk measurement results

According to formula (1)-(6), the risk level of each link of the IC industry chain is determined, and the corresponding level of the maximum connection degree of each indicator of the upstream, midstream and downstream enterprises is measured to reflect the weak parts of each enterprise, link and even the industry chain, to make up for the short boards and strengthen the weaknesses in a targeted manner, and to realize the safe and sustainable development of the industry chain. To describe the risk level of the sample enterprises more intuitively and meticulously, based on the primary measurement level, the binary semantic method is introduced to carry out the secondary measurement within the measurement level, and the subdivided level and deviation value of the risk of each enterprise are obtained. The results are shown in Table V.

Table V. Risk Measurement Results of Each Link in the IC Industry Chain

Maximum connection degree - level	Upstream enterprises (IC design)								
	A1	A2	A3	A4	A5	A6	A7	A8	A9
R1	I	I	I	I	I	I	I	I	I
R2	IV	IV	IV	IV	IV	IV	IV	IV	IV
R3	V	V	V	IV	V	IV	V	V	V
R4	IV	IV	IV	V	IV	V	IV	V	IV
R5	I	I	I	I	I	I	I	I	I
R6	I	I	I	I	I	I	I	I	I
R7	I	I	II	I	I	I	I	I	I
R8	I	I	I	I	I	I	I	I	I
R9	I	I	I	I	I	I	II	I	I
R10	IV	I	III	IV	I	III	I	IV	V
R11	I	I	I	I	I	I	I	I	I
R12	II	II	I	III	III	II	II	I	I
R13	I	I	I	I	I	I	I	I	I
R14	I	I	I	I	I	I	I	I	I

R15	I	I	I	I	I	III	I	I	I
R16	I	I	I	I	I	II	I	I	I
R17	II	III	III	IV	IV	IV	II	IV	IV
R18	IV	II	V	V	IV	V	II	V	V
Level eigenvalue	2.606	2.154	2.622	2.727	2.556	2.792	1.984	2.760	2.802
Level	III	II	III	III	III	III	II	III	III
Subdivision level	very low	upper-middle	very low	low	very low	low	medium	low	low
Deviation value	0.116	-0.459	0.240	-0.094	-0.331	0.228	-0.050	0.077	0.274

Table V. Risk Measurement Results of Each Link in the IC Industry Chain (continued)

Maximum connection degree - level	**Midstream enterprises (IC manufacturing)**								
	B1	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**
R1	I	I	I	I	I	I	I	I	I
R2	III	III	III	III	III	III	III	III	III
R3	I	IV	IV	IV	I	I	V	V	V
R4	IV	V	IV	V	V	IV	V	IV	IV
R5	I	I	I	I	I	I	I	I	I
R6	I	I	I	I	I	I	I	I	I
R7	I	I	I	II	I	I	I	I	II
R8	I	I	I	I	I	I	I	I	I
R9	I	I	I	I	I	I	I	I	I
R10	II	II	II	IV	IV	III	I	II	V
R11	I	I	I	I	I	I	I	I	I
R12	II	III	III	IV	IV	IV	IV	IV	II
R13	I	I	I	I	I	I	I	I	I
R14	I	I	I	I	I	I	I	I	I
R15	II	III	III	III	II	II	II	III	III
R16	I	II	II	II	I	I	I	II	II
R17	I	II	II	I	I	II	I	II	III
R18	I	III	II	III	IV	II	IV	IV	V
Level eigenvalue	1.834	2.351	2.155	2.526	2.630	2.110	2.758	2.490	2.698
Level	II	II	II	III	III	II	III	II	III
Subdivision level	low	upper-middle	upper-middle	very low	very low	medium	low	very high	low
Deviation value	0.411	0.316	-0.455	0.340	0.302	0.371	0.067	-0.137	-0.258

Table V. Risk Measurement Results of Each Link in the IC Industry Chain (continued)

Maximum connection degree - level	**Downstream enterprises (IC packaging and testing)**								
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**
R1	I	I	I	I	I	I	I	I	I
R2	III	III	III	III	III	III	III	III	III
R3	IV	V	V	II	II	II	III	I	II
R4	II	II	IV	IV	IV	II	IV	IV	IV
R5	I	I	I	I	I	I	I	I	I
R6	I	I	I	I	I	I	I	I	I
R7	I	I	I	I	I	I	I	I	I
R8	I	I	I	I	I	I	I	I	I
R9	I	I	I	I	I	I	I	I	I
R10	I	II	III	V	V	II	V	V	V
R11	I	I	I	I	I	I	I	I	I
R12	III	IV	IV	II	III	IV	II	III	IV
R13	I	I	I	I	I	I	I	I	I
R14	I	I	I	I	I	I	I	I	I
R15	IV	IV	I	IV	IV	IV	IV	IV	V
R16	III	II	III	II	I	II	I	II	IV
R17	I	II	I	II	II	II	II	III	III
R18	II	IV	V	V	IV	IV	V	V	V
Level eigenvalue	2.036	2.184	2.492	2.662	2.428	2.238	2.633	2.774	2.982
Level	II	II	II	III	II	II	III	III	III
Subdivision level	medium	upper-middle	very high	low	high	upper-middle	very low	low	medium
Deviation value	0.114	-0.334	-0.111	-0.478	0.177	-0.086	0.325	0.145	-0.056

Based on the data of 27 sample enterprises, the risk of the IC industry chain is measured. The degree of connection between each indicator of the industry chain and the five standardized risk levels is clarified according to formula (1), and the results are shown in Table VI. Based on the individual connection degree of each risk measurement indicator and the comprehensive weight of the indicator, the comprehensive connection degree of each indicator is calculated using formula (2), and the comprehensive connection degree of the indicator is summed up to get the comprehensive connection degree of the four aspects of “environmental risk, management risk, supply risk, and technology risk” according to the guideline hierarchy, and the relative membership degree, normalized membership degree, and the level of eigenvalue are determined by the formulas (3)-(6) to get the comprehensive measurement degree of the risk of IC industry chain in the end, as shown in Table VII.

Table VI. Connection Degree of Each Indicator of the IC Industry Chain Risk

Guideline hierarchy	Indicator hierarchy	Measurement level				
		low risk I	medium-low risk II	medium risk III	medium-high risk IV	high-risk V
T1	R1	0.045	0.027	-0.045	-0.045	-0.045
	R2	-0.070	-0.070	0.070	0.070	-0.070
	R3	-0.018	-0.018	0.010	0.018	-0.010
T2	R4	-0.053	-0.053	-0.023	0.053	0.023
	R5	0.035	0.007	-0.035	-0.035	-0.035
	R6	0.029	0.011	-0.029	-0.029	-0.029
	R7	0.038	0.024	-0.038	-0.038	-0.038
	R8	0.067	0.023	-0.067	-0.067	-0.067
T3	R9	0.042	-0.117	-0.042	-0.042	-0.042
	R10	-0.075	0.026	0.075	-0.026	-0.075
	R11	0.033	-0.008	-0.033	-0.033	-0.033
	R12	-0.023	0.009	0.023	-0.009	-0.023
	R13	0.042	0.022	-0.042	-0.042	-0.042
	R14	0.079	0.032	-0.079	-0.079	-0.079
T4	R15	-0.085	0.083	0.085	-0.083	-0.085
	R16	0.047	0.030	-0.047	-0.047	-0.047
	R17	-0.011	0.078	0.011	-0.078	-0.078
	R18	-0.142	-0.070	0.142	0.070	-0.142

Table VII. Comprehensive Risk Measurement Results of the IC Industry Chain

	Measurement level				
	low risk I	medium-low risk II	medium risk III	medium-high risk IV	high-risk V
Environmental risk T1	-0.043	-0.061	0.035	0.043	-0.125
Management risk T2	0.115	0.012	-0.192	-0.115	-0.145
Supply risk T3	0.098	-0.037	-0.098	-0.231	-0.295
Technology risk T4	-0.192	0.121	0.192	-0.137	-0.352
Comprehensive connection degree	-0.022	0.035	-0.062	-0.441	-0.916
Relative membership degree	0.489	0.517	0.469	0.280	0.042
Normalized membership degree	0.272	0.288	0.261	0.156	0.023
Level eigenvalue	2.370				
Level	II（medium-low risk）				
Subdivision level	high				
Deviation value	-0.301				

From Table V-Table VII, it can be seen that the risk level of each sample enterprise and the industry chain in the upstream, midstream, and downstream is in the range between Level II and Level III, which indicates that the overall risk level of the IC industry chain is relatively low. However, there still exists a certain degree of risk.To reflect more clearly the risk differences among enterprises in each link under the overall risk level of the industry chain, the risk level of the IC industry chain is visualized using the subdivision levels and deviation values in Table V and Table VII, as shown in Figure I.

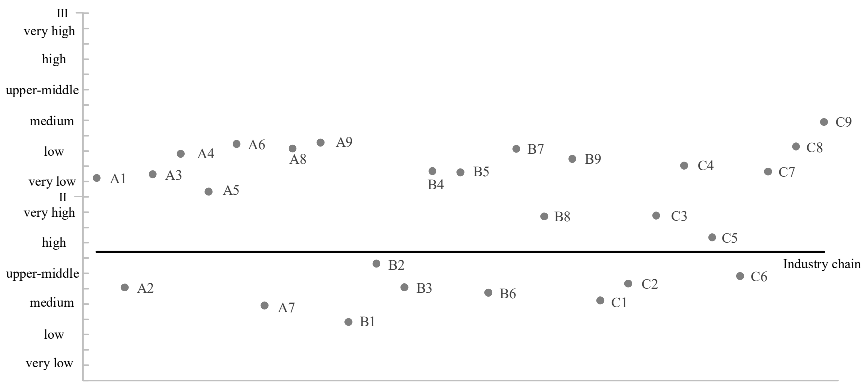

Figure I. Comparison of the Risk Level of the IC Industry Chain and Its Industry Chain Node Enterprises

The results show that the risk level of China's IC industry chain is at Level II (medium-low risk), with environmental risk and technology risk being the most serious. The risk level of the industry chain nodes is in the range of Level II - Level III, and there are apparent differences in their subdivision levels. Since each industry chain link faces different technical barriers, lack of talent, and insufficient production capacity, targeted attack strategies need to be implemented to ensure smooth upstream and downstream circulation and help optimize and upgrade the industry chain structure.

3) Discussion

According to Table V-Table VII, the risk level of China's IC industry chain is at Level II (medium-low risk). The risk level of each industry chain link is between Level II and III, which indicates that the IC industry chain at this stage has better development resilience and industrial tension. However, many weak links still need to be strengthened, and the industry chain has more short boards in the dimensions of environmental risk and technology risk. In addition, the industry chain risk measurement level subdivision reflects that there is a significant difference between the risk level of each link of the IC industry chain and the overall risk level of the industry chain, which is mainly due to the existence of different constraints such as technological barriers, lack of talent, and insufficient production capacity in the upstream, midstream and downstream of the IC industry chain. Therefore, it is necessary to attack the core problems of each industry chain link to resist the industry chain's potential risks and ensure the sound and synergistic development of upstream and downstream enterprises.[26]

Combined with Figure I and Table V, it can be seen that the risk level of IC industry chain node enterprises are all in the range of Level II - Level III, but there are apparent differences in their subdivision levels. From the measurement results, it can be seen that the risk level of the upstream design enterprises is mainly located in Level III (very low) - Level III (low); the key weak point is that foreign enterprises monopolize the core technology (IP core, EDA software, etc.), and there is an urgent need to carry out scientific and technological research and technological innovation through a large amount of capital and human resources investment and to improve the self-sufficiency rate of the home-made design software.[27] The risk level of the midstream manufacturing enterprises is distributed in Level II (low) - Level III (low); the main point of attack is to establish cooperative relations with leading international suppliers and realize the independent innovation of wafer manufacturing equipment and materials. The risk level of downstream packaging and testing enterprises in Level II (medium) - Level III (medium), the risk is mainly concentrated on the introduction of talent and technological innovation, which requires a continued increase in the investment of capital and workforce for technological innovation and expansion of production capacity.[28]

Among the 27 sample companies in the IC industry chain, IC manufacturing company B1 (SMIC) has the lowest risk level, and IC packaging and testing company C9 (KAIFA) has the highest risk level. As the leader of the IC manufacturing industry in mainland China, SMIC has leading process manufacturing capabilities, production capacity advantages, and service packages and has successfully developed a variety of technology nodes ranging from 0.35 microns to 14 nanometers, which are applied to different process technology platforms. In contrast, due to its limited independent research and development capability and its continued reliance on the introduction of advanced packaging and testing equipment, KAIFA is highly susceptible to the impact of macro-environmental and industry competition risks, which may adversely affect its production and operation and sustainable development and weaken its competitive advantages. Therefore, for the IC industry chain node enterprises, the primary task is to continue to cultivate and introduce high-skilled personnel, accelerate the core technology research and independent innovation of key technologies, and build the IC industry innovation chain headed by local enterprises to break through the foreign technology barriers and restrictions and realize the independent control of the IC industry chain at an early date, with the support of the government for chip research and development.[29]

VI. CONCLUSION

This study is carried out for the industry chain risk measurement problem, constructs the industry chain risk measurement indicator system, and establishes the industry chain risk measurement model of set pair analysis -variable fuzzy set based on determining the weights of the indicators by the BWM-CRITIC method, with the connection degree of set pair analysis and the relative difference degree of variable fuzzy set as the link. By introducing the idea of binary semantics, the industry chain risk status within the measurement level is explored, and an empirical study is carried out with the IC industry as an example to verify the practicality and effectiveness of the model. The research results show that the model can effectively reflect the risk level of the industry chain by analyzing the relationship between the sample data and each indicator level; at the same time, the model can better solve the problem of information loss in the process of linguistic information processing and differentiate the subtle differences between the sample measurement levels, reflecting the risk status of the industry chain more comprehensively, and providing decision-making reference for effectively resisting the risks of the industry chain and realizing the sustainable development of the industry chain.

Considering the complexity and uncertainty of the industry chain system, in the follow-up study, the time factor can be added to monitor the risk status of the industry chain dynamically, adjust the countermeasures promptly, and guarantee the sustainable and stable development of the industry chain. At the same time, the risk differences of the industry chain among regions can be explored in depth to optimize the layout of the regional industry chain and realize the efficient and synergistic development of the industry chain.

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