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A Comprehensive Model for Evaluating Titanium Industry Security in China

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Abstract: Currently, China is the largest consumer of titanium (Ti), yet the development of its Ti industry is limited by numerous factors, such as industrial structure imbalance. This study aimed to evaluate the security of China's Ti industry from 2010 to 2020, seeking to identify relevant issues and propose policy strategies. Firstly, a comprehensive evaluation system for Ti industry security was established, encompassing aspects of availability, economics, and sustainability. Secondly, the entropy weight technique for order preference by similarity to an ideal solution (TOPSIS) combination method and gray correlation method were employed to assess the safety level of China's Ti industry chain in each year from 2010 to 2020. Additionally, the coupling degree and sensitivity were used to analyze the dimension layers and index system to determine those that negatively impact the safety level of the Ti industry chain. The analysis results reveal that the economic level exerts a significant influence on the development of the Ti industry. Accordingly, under the same level of change, while considering availability, equal attention should be provided to economic considerations for a well-rounded evaluation of the industry's safety level.

Keywords: titanium industry chain; security system; sustainability; grey correlation analysis; entropy weight-TOPSIS

Citation: Hui, X.; Qi, M.; Wang, W.; Yang, S.; Zhang, C. A Comprehensive Model for Evaluating Titanium Industry Security in China. *Processes* **2023**, *11*, 2286. https://doi.org/10.3390/pr11082286

Academic Editors: Xin Yao, Huaqing Xie and Carlos Sierra Fernández

Received: 24 June 2023
Revised: 22 July 2023
Accepted: 24 July 2023
Published: 30 July 2023

1. Introduction

As China enters a new stage of development, the security and stability of industry and supply chains play a critical role in aiding its progress. Titanium (Ti) metal and its alloys hold strategic importance as high-performance non-ferrous metals and serve as crucial military resources. Ti finds extensive applications not only in traditional industries, such as chemical, electric power, metallurgy, and salt [1], but also in emerging fields, including aerospace [2,3], national defense [4], automobile industry [5–7], marine engineering, medicine, leisure, and sports. Its role in the development of weapons and equipment is irreplaceable. Acknowledging its strategic value, the United States has listed Ti in the Key Mineral Catalogue [8], while Japan has included it in the Rare Metal Protection Strategy. Furthermore, China has recognized the significance of the Ti industry in Made in China 2025 and Guidelines for the Development of New Materials Industry [9]. Compared with the United States, Russia, and Japan [10], which have employed Ti in advanced technologies, with aerospace as the main downstream application, China exhibits a unique consumption of Ti metal. The proportion of industrial consumption is relatively high, while that of aerospace and civil products is relatively low.

Despite the abundance of Ti resources in China, the overall grade of these resources tends to be low. The ores are more commonly of average quality, and high-grade ores are relatively scarce. More than 90% of Ti ore is rock-type vanadium–Ti–magnetite, characterized by a dense structure and high gangue content, which makes beneficiation and sorting challenging [11]. Figure 1a,c illustrate the distributions of Ti ore and ilmenite, respectively. Additionally, domestic beneficiation technology is still in its nascent stages, leading to insufficient production of high-quality Ti concentrates and a heavy reliance on imports. Ti materials, especially those of high quality, have stringent requirements. While global Ti resources are abundant, high-quality rutile accounts for less than 10% of the total rutile, making it a scarce resource. Figure 1b illustrates the distribution of rutile in China, the majority of which is imported [12]. The rapid growth in demand for aviation-grade Ti sponge, coupled with the military industry's heightened requirements for stable supply and material quality, poses challenges. Most Ti sponge production enterprises in China do not possess Ti-ore resources, which impacts the long-term stable supply, product quality, and cost of high-end Ti products, resulting in difficulties in meeting long-term demand. Despite an increase in the annual production of Ti materials, the low quality of Ti in China hampers the ability to meet the requirements for high-end Ti materials in aerospace and marine engineering applications. In the current Chinese Ti sponge market, export prices are lower than import prices, with high-end imported Ti sponges having a higher proportion than high-end exported ones, highlighting the insufficiency in China's production capacity for high-quality Ti sponges [13].

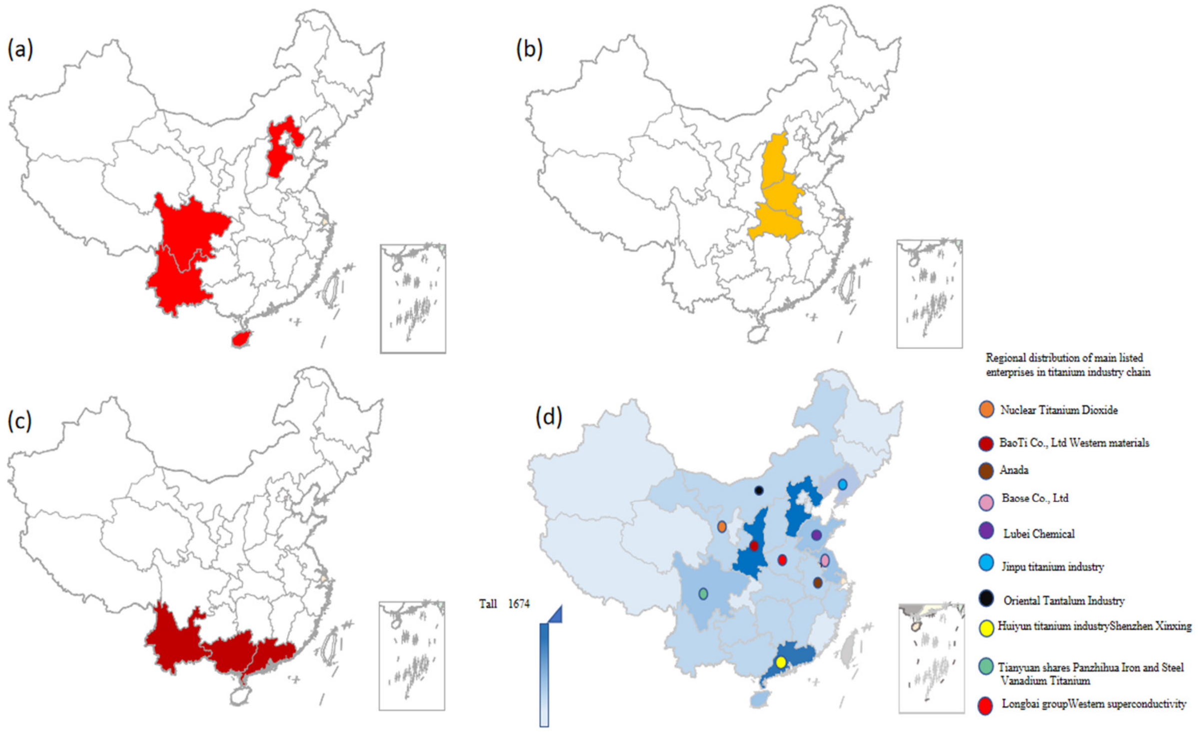

Figure 1. Distribution of (**a**) titanium ore, (**b**) ilmenite illustrates, and (**c**) rutile in China. The regional heat map of (**d**) the number of enterprises in the titanium industry chain and the distribution of major listed companies in the titanium industry chain.

Furthermore, due to the relatively late development of the Ti industry in China, most high-end products heavily rely on imports, resulting in high technical barriers. As a result, there are a limited number of enterprises in China's Ti industry, and their production scale is generally small. This constraint leads to limitations in the tonnage and capacity of existing equipment for processing Ti materials, preventing the processing of large Ti materials for aerospace and marine engineering and highlighting the need for improved industry concentration [14]. In addition, at the upstream end of the Ti industry lies the resource sector, including mining. Most enterprises are concentrated in resource-rich areas, resulting in a relatively scattered distribution. Figure 1d illustrates the distribution of Ti enterprises across various provinces in China [15].

With the rapid growth in demand for high-end Ti materials in China, challenges such as high production costs, unbalanced product structure, and low industry concentration have emerged, making it difficult to meet the requirements of high-end industries reliant on Ti metal and its alloys. Consequently, there is a requirement to update and enhance the Ti industrial chain in China.

Therefore, the assessment of the safety of China's Ti industry and subsequent updates are critical for its sustainable development. However, comprehensive safety assessment of the entire Ti industry chain is limited. Therefore, this study proposes an evaluation of the entire Ti industry chain by constructing indicators related to availability, economics, and sustainability, which are crucial for addressing the aforementioned challenges.

The main contributions of this study can be summarized as follows:

(1) Presentation of comprehensive evaluation criteria for assessing the security of the Ti industry chain. These criteria comprise 34 indicators that cover various aspects of the industry's safety.
(2) Development of a systematic method for assessing the safety of China's Ti industry chain from 2010 to 2020. This method considers the entire industrial chain, dimension layers, and individual indicators.
(3) Analyses of the changes observed in different dimensional layers and indicators of China's Ti industry, along with the formulation of policy suggestions based on the findings.

The remainder of this article is organized as follows:

Section 2 presents a literature review of the industrial chain. Section 3 introduces the evaluation standard system and methodologies employed for evaluating the Ti industry chain. Section 4 presents the results of the safety evaluation, including dimensional layer coupling analysis, sensitivity analysis, gray correlation, and sensitivity analysis of the index system. Finally, Section 5 presents policy recommendations and concludes the paper.

2. Literature Review

The term "Industrial chain" is unique to China and has not been extensively studied as an independent concept by foreign scholars. However, similar concepts, such as commodity, supply, and value chains, have been proposed by Grey and Miguel [16], Priem and Swimk [17], Reuver and Bouwman [18], and Stabell and Fjeldstad [19]. There is no consensus among academics regarding the specific connotations of industrial chain security. In the context of specific industries, researchers have conducted studies on the analysis of industrial chains and their characteristics. For example, Liu et al. [20] used the material flow analysis method to analyze the cobalt (Co) industrial chain and calculated the resource dependence between the industrial chain links in each country/region. Li et al. [21] investigated the current situation of the Co trade and the impact of national risks on Co trade patterns from the perspective of the entire industrial chain. Similarly, Li et al. [22] analyzed the global copper industry chain and trade characteristics of important countries by building a trade network of different links. Huang et al. [23] used complex network methods and extended the gravity model to analyze the evolution of international tungsten industry competition and its influencing factors. Liu et al. [24] quantified the flow of indium (In) in China from 2000 to 2019 using material flow analysis, focusing on the problems faced by China's In industry.

Compared to these metals, the Ti industry has been less researched because it is a new industry with a relatively short history. Most Ti-related research has focused on catalytic processes, such as optimization with other ions. In addition, the synergistic physicochemical effects of the forming compounds [25,26] have few studies devoted to Ti flow, partially describing the flow of metallic Ti or TD [27,28]. Li et al. [29] used a dynamic material flow analysis method to reveal the evolutionary trend of China's Ti cycle from 2005 to 2020. However, only limited studies have examined the impacts of changes in the availability, economy, and sustainability of Ti resources and products on the development of the entire industry.

Under these circumstances, by drawing on the assessment methods of energy security and the development status of the Ti industry, this study aimed to construct an index system based on the three dimensions of availability, economy, and sustainability. To comprehensively evaluate the safety of China's Ti industry, 34 indicators were selected according to Ti resources and the availability, economy, and sustainability of Ti products. To objectively and comprehensively evaluate the safety level of the Ti industry, the entropy weight technique for order preference by similarity to an ideal solution (TOPSIS) method was used in combination with gray correlation, coupling analysis, and sensitivity analysis. The evaluation process is from whole to part, which is conducive to identifying and analyzing problems. The main research ideas and innovation points are presented below.

To address the research gaps, we quantitatively measured and evaluated the system safety level of the Ti industry chain from 2010 to 2020 based on the entropy weight-TOPSIS distance function model. Subsequently, we analyzed the coordination relationship between the Ti industry and each dimension layer through coupling coordination using gray correlation and sensitivity analysis. The main innovation points are: (1) focusing on industrial chain security as a multidimensional concept, which helps eliminate the limitation of unilaterally describing industrial chain security based solely on the evaluation of trade or supply security; (2) proposing a systematic method to measure the safety performance of an industrial chain by analyzing its weak links and presenting corresponding solutions; and (3) developing an industrial chain security level index to help determine the security levels of different dimensions within the industrial chain and identify trade-offs in areas that require improvement. This allows a comprehensive evaluation and establishes a reliable risk assessment system for industrial chain security. This facilitates the formulation of a complete mechanism concerning organization, monitoring, and management when detecting early warnings. (4) Valuable insights are offered, and policies are suggested, such as better management of Ti resources and optimization of the Ti industry structure.

3. Materials and Methods

3.1. System Definition

Based on the research methods used in other metal industry chains and the existing literature on the development of the Ti industry, this study conducted a safety evaluation of the Ti industry chain. The evaluation process considered the entire industry as the evaluation object and took into account the development status and industrial composition of China's Ti industry. It analyzed the main factors affecting the safety of the Ti industry, constructed a quantifiable evaluation index system, and used certain theoretical methods to evaluate the Ti industry. The evaluation aimed to provide a comprehensive assessment of the historical and current state of the Ti industry. Due to data limitations, it was not feasible to cover every aspect of the industry. Therefore, this study focused on the quantitative analysis of important indicators upstream (raw material supply), midstream (Ti product manufacturing), and downstream (market application) in the Ti industry chain. The Ti industry chain is illustrated in Figure 2.

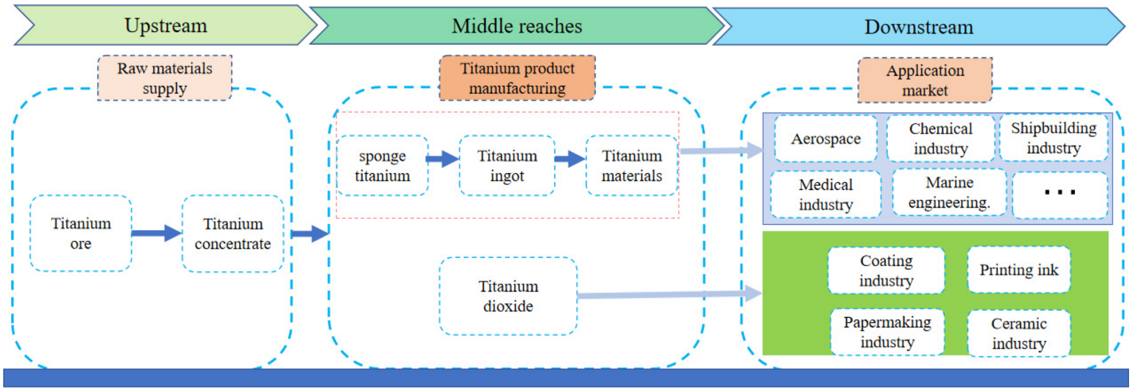

Figure 2. Titanium industry industrial chain structure.

The data analyzed in this study were complex and obtained from multiple sources, primarily from the China Nonferrous Metals Industry Association, China Titanium Industry Progress Report, China Ferroalloy Network, and USGS (USGS.gov)

3.2. Construction of Index System

To comprehensively evaluate the safety issues of the Ti industry, this study drew from the methods used in energy safety evaluation, starting from the three aspects of availability, economy, and sustainability, following the five major aspects of science, system, objectivity, comparability, and operability. Finally, 34 indicators were selected to evaluate the safety and analyze the trend of changes in the Ti industry chain.

According to the definition of Ti industry chain safety in this study, the framework of Ti industry chain safety evaluation indicators is divided into three dimensions: availability, economy, and sustainability of Ti products and resources. These three dimensions influence each other; Ti resources and the availability of Ti products are the main factors affecting economic change. Sustainability is the main factor affecting future availability and indirectly affecting economic change.

(1) Within these dimensions, there are 10 availability indicators, which mainly reflect the self-supply of Ti and its products, as well as the availability of foreign Ti resources and products.

They are mainly affected by the import concentration of Ti resources, external dependence, and the self-sufficiency rate.

(2) Additionally, there are 14 economic indicators, which reflect whether the price of Ti resources and products is reasonable and stable under the conditions of continuous and sufficient supply, the income of related enterprises, and the operational status of domestic and foreign Ti markets.

They are mainly affected by the import and export of Ti-series products, market demand, and the impact of price volatility.

(3) Furthermore, 10 sustainability indicators evaluate the future development capabilities of Ti resources and products.

They are mainly affected by factors such as energy stock and sustainable development potential.

The specific indicators and their meanings are listed in Table 1 [30].

Table 1. The safety evaluation Index System of the Titanium Industry Chain.

Dimension Layer		Basic Indicators		Indicator Attribute	Meaning and Interpretation of the Indicators
Availability	Self-security ability	A1	Titanium concentrate self-sufficiency rate	+	The ratio of the total annual production of titanium resources to the total consumption of titanium resources reflects the self-protection ability of titanium resources in my country.
		A2	The self-sufficiency rate of sponge titanium	+	
		A3	Titanium dioxide self-sufficiency rate	+	
		A4	Titanium self-sufficiency rate	+	
	Import risk	A5	Import concentration of titanium ore	–	The ratio of imports from China's top three titanium resources import source countries to the total imports reflects the market concentration risk of titanium resources imports.
		A6	Import concentration of titanium sponge	–	

Table 1. *Cont.*

Dimension Layer		Basic Indicators		Indicator Attribute	Meaning and Interpretation of the Indicators
	External dependence	A7	External dependence on titanium concentrate	−	External dependence degree = (import volume − export volume)/[output + (import volume − export volume)] × 100% It reflects the dependence of China's titanium resources on the international market.
		A8	External dependence on titanium sponge	−	
		A9	Titanium dioxide to the external dependence degree	−	
		A10	External dependence on titanium material	−	-
Reliability	Import and export trade; foreign trade	B1	Titanium sponge import and export unit price ratio	−	The ratio of the average import price of titanium resources to the average export price reflects the international trade status of titanium resources in China.
		B2	Titanium dioxides import and export unit price ratio	−	
		B3	Titanium material import and export unit price ratio	−	
		B4	Titanium sponge trade deficit	−	The ratio of the total import and export of titanium resources reflects the international trade status of titanium resources in my country.
		B5	Titanium dioxide trade deficit	−	
		B6	Titanium trade deficit	−	
	Domestic price volatility	B7	The price volatility on pure titanium plate of TA2	−	The difference between the price fluctuations of titanium products within one year, the smaller the fluctuation value, the higher the guarantee for the safe development of the titanium industry.
		B8	Level 1 sea sponge titanium price volatility	−	
	Market demand	B9	Titanium sponge production capacity utilization rate	+	The ratio of the production volume and production capacity of titanium products, that is, the operating rate size indirectly reflects the demand situation for titanium products.
		B10	Titanium dioxide production capacity utilization rate	+	
		B11	Titanium ingot production capacity utilization rate	+	
		B12	Gross domestic product	+	The size of the GDP indirectly reflects the development of the titanium industry.
	Expenditure on national defense	B13	Military spending	+	Military expenditure reflects the income and development of military titanium
	Product revenue	B14	The net interest rate of titanium products	+	The net interest rate of titanium products reflects the titanium industry earnings.
Sustainability	Resource stock	C1	The recoverable life of titanium ore	+	The ratio of the proven technical recoverable volume of titanium ore to the mining volume of the current year reflects the sustainable capacity of titanium ore.
	Sustainable development potential	C2	China Innovation Index	+	The ratio of the number of patents applied for by the titanium industry in China each year to the annual patents in the global titanium industry reflects my country's independent innovation capability.
		C3	Industrial structure	+	The proportion of high-end titanium materials reflects the sustainability of the titanium industry structure in China.

Table 1. *Cont.*

Dimension Layer		Basic Indicators		Indicator Attribute	Meaning and Interpretation of the Indicators
		C4	Sponge titanium capacity	+	The size of the production capacity of titanium products in China reflects the supply of titanium product production equipment in China.
		C5	Titanium dioxide production capacity	+	
		C6	Titanium ingot production capacity	+	
		C7	CR3	+	The output of titanium materials in my country ranks among the top three (CR3), and the ratio of the output of titanium materials in the top five (CR5) enterprises to the total output reflect the concentration of my country's titanium materials industry.
		C8	CR5	+	
		C9	The gross profit margin of titanium products	+	Gross margin = (gross margin / operating income)× 100%, reflecting the competitiveness of the enterprise
	Security capability	C10	National Defense Support Capability	+	Defense spending as a percentage of GDP. In the long run, the security of the industrial chain cannot be separated from the guarantee of strong national defense capabilities.

3.3. Assessment Model

In this study, the entropy weight-TOPSIS [31] distance function model was used to quantitatively model the safety evaluation of the Ti industry in China. The model consists of three main parts, as illustrated in Figure 3, to ensure a robust and accurate assessment process.

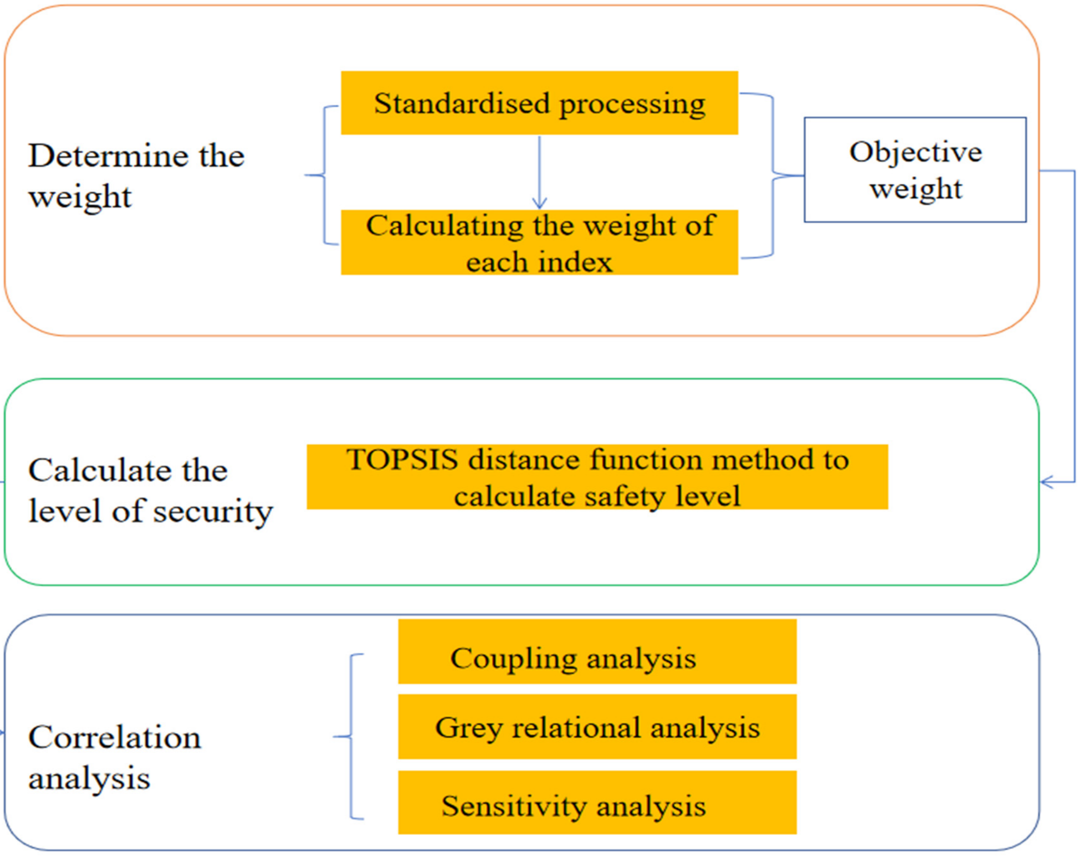

Figure 3. The model mainly has three parts.

3.3.1. Normalisation of the Raw Data

Because the measurement units of various indicators are not uniform, it is necessary to perform standardization before using and converting the absolute value of the indicator into a relative value to address the problem of homogeneous comparison of different indicators [32]. The specific standardization method is as follows: m objects and n indicators are selected, where x_{ij} is the value of the j-th indicator of the i-th object (i = 1, 2, …, m; j = 1, 2, …, n). The positive and negative indices in the index system are standardized in the following ways, and standardized non-dimensionalized evaluation index data are obtained.

(1) Positive indicators:

$$x_{ij} = \frac{x_{ij} - \min\{x_{1j}, \ldots, x_{mj}\}}{\max\{x_{1j}, \ldots, x_{mj}\} - \min\{x_{1j}, \ldots, x_{mj}\}} \tag{1}$$

(2) Negative indicators:

$$x_{ij} = \frac{\max\{x_{1j}, \ldots, x_{mj}\} - x_{ij}}{\max\{x_{1j}, \ldots, x_{mj}\} - \min\{x_{1j}, \ldots, x_{mj}\}} \tag{2}$$

where x_{ij} is the value of the j-th index of the i-th dimensional layer (i = 1, 2, … n; j = 1, 2, … m), and min { x_{1j}, …, x_{mj}} and max { x_{1j}, …, x_{mj}} represent the minimum and maximum values of the j-th column of the matrix, respectively. For convenience, the normalized data were recorded as x_{ij}.

3.3.2. Obtaining the Weights of Resource Security Evaluation Indicators

The index weight is determined using the direct right method [33]. The entropy weight method is an objective weight determination method that uses index data to determine the index weight and has good operability and practicability. Compared with the expert scoring method, the entropy weight method enhances the difference and identification of the evaluation indicators and can more objectively reflect implicit information in the data [34]. The specific process is as follows:

(1) Calculate the feature proportion of the evaluation object under the evaluation index (P_{ij}):

$$P_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \tag{3}$$

(2) Calculate the entropy of the index (e_j):

$$\begin{gathered} e_j = \frac{(-1)\sum_{i=1}^{n} p_{ij} \cdot Ln(p_{ij})}{Ln(m)} \\ In, like p_{ij} = 0, but \frac{\lim}{p_{ij} \to 0} p_{ij} \cdot \frac{Ln(p_{ij})}{1/p_{ij}} = 0, So e_{ij} > 0. \end{gathered} \tag{4}$$

(3) Calculate the direct redundancy. The greater the direct redundancy, the more important the index (d_j):

$$d_j = 1 - e_j \tag{5}$$

(4) Calculate the weight of each indicator (w_j):

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{6}$$

3.3.3. Measurement of the Safety Level of China's Titanium Industry Chain

The safety level of the Ti industry in China was quantitatively evaluated using the TOPSIS distance metric method [35]. This method makes complete use of the original data, is not affected by the selection of reference sequences, and has an intuitive geometric meaning. It is primarily used for risk decision analyses, environmental benefit evaluations, cost-effectiveness analyses, and multi-attribute optimal scheme selection. The idea behind the TOPSIS model is to construct positive and negative ideal solutions for a multi-attribute problem [36,37]. The most satisfactory solution is selected using two benchmarks: solutions that are close to the positive ideal solution and far from the negative ideal solution. These criteria are used for ranking the solutions [38]. When a solution is closest to the positive ideal solution and far from the negative ideal solution, it is considered the optimal scheme for the evaluation object and is ranked as the most advanced; otherwise, it is ranked as the worst scheme, as it is the most backward. The specific application process is as follows:

(1) Form a weighted judgment weight matrix (Y):

$$Y = \sum_{j=1}^{n} w_j \cdot p_{ij} = (y_{ij})_{m\times n} \tag{7}$$

(2) Determine the ideal solution

The ideal solution is divided into a positive ideal solution and a negative ideal solution. The positive ideal solution is represented by y_j^+, and the negative ideal solution is represented by y_j^-. The specific formula is as follows:

$$y_j^+ = \max\{y_{1j}, \ldots, y_{mj}\}\ y_j^- = \min\{y_{1j}, \ldots, y_{mj}\} \tag{8}$$

(3) The distance between each index and the ideal solution is determined:

The distance from each index to the positive ideal solution is represented by d_i^+, and that to the negative ideal solution is represented by d_i^-, according to the Euclidean distance formula:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_j^+)^2}\ d_i^- = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_j^-)^2} \tag{9}$$

(4) The closeness of the evaluation object to the ideal solution is calculated:

The higher the degree of closeness, the better the object, where the value range of the degree of closeness is [0, 1]. For the evaluation of industrial chain security, the closer the degree of closeness is to 1, the higher the degree of industrial chain security in the year; conversely, when the degree of closeness is 0, the level of industrial chain security is the lowest. The closeness is calculated as follows:

$$c_i = \frac{d_i^-}{d_i^+ + d_i^-}, (i = 1, 2, 3 \ldots m) \tag{10}$$

3.3.4. Correlation Analysis of Factors Affecting the Safety Level of the Ti Industry Chain

During the system development process, if the trends of the two factors are consistent, that is, if the degree of synchronous change is high, the degree of correlation between the two is high, and vice versa [39]. The gray relational analysis method measures the degree of correlation between each index and the level of energy security according to the similarity and dissimilarity of development trends among the factors. This is a multi-factor statistical analysis method that is mainly used to compare the strength of similar associations between items in the system and other factors. Finally, these factors are sorted according to their degree of influence, and an analysis result that is suitable for dynamic history is obtained. The specific application process is as follows:

(1) Analyze the target sequences.

The safety levels of the Ti industry in China were used as the target sequence. Safety evaluation indicators of the Ti industry chain were used as comparison sequences. The degree of correlation between the safety level of the country's Ti industry chain and each evaluation index was analyzed.

(2) Calculate the difference sequence matrix.

To find the difference sequence matrix between the target sequence and the comparison sequence, the calculation formula is (Z):

$$Z = \left|x_{ij} - c_i\right| = \left(\lambda_{ij}\right)_{m \times n} \tag{11}$$

(3) Two-level maximum and minimum values were calculated.

$$\begin{gathered} \lambda_{\max} = \max\{\lambda_{1j}, \lambda_{2j}, \ldots, \lambda_{ij}\},\ \lambda_{\min} = \min\{\lambda_{1j}, \lambda_{2j}, \ldots, \lambda_{mj}\} \\ m = \max(\lambda_{\max}),\ n = \max(\lambda_{\min}) \end{gathered} \tag{12}$$

(4) Correlation coefficients are calculated (ξ_j):

$$\xi_j = \frac{n + \rho m}{\left|x_{ij} - c_i\right| + \rho m} \tag{13}$$

Among them, $\rho \in [0, 1]$ is the resolution coefficient, which is inversely proportional to the resolution. When $\rho \leq 0.5463$, the resolution is the most ideal, usually $\rho = 0.5$.

(5) Determine the degree of correlation:

Average the formula for calculating correlation coefficients for each. The indicators are as follows:

$$\eta_j = \frac{\sum_{i=1}^{m} \xi_{ij}}{m} \tag{14}$$

4. Results and Discussions

4.1. Model Results

4.1.1. The Weight of the Safety Level Indicator

Based on Equations (1)–(6), the weight of each basic index is obtained. The weight of the index reflects the proportion of the index in the system and plays a significant role in the calculation of the safety level. Table 2 lists the weights and changes of the safety evaluation index of the Ti industry.

Table 2. The weight and index change in the safety evaluation index of the titanium industry chain.

Index	**W$_j$**	**Years**										
		2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
A1	0.029	0.662	0.6240	0.5484	0.6011	0.6543	0.6947	0.6061	0.5531	0.5738	0.6463	0.6777
A2	0.032	1.045	1.1506	1.1098	1.0464	1.0895	1.0592	0.9794	0.9740	0.9533	0.9330	0.9672
A3	0.027	0.993	1.1173	1.0556	1.1309	1.0676	1.1669	1.2586	1.2738	1.3149	1.3569	1.4232
A4	0.057	1.495	1.1445	1.1986	1.1544	1.1622	1.3001	1.3597	1.1852	1.3476	1.3428	1.1484
A5	0.017	0.648	0.5891	0.5478	0.5321	0.4264	0.2234	0.3145	0.4530	0.5474	0.5890	0.6281
A6	0.018	0.553	0.4135	0.9553	0.9344	1.0000	0.9915	0.9216	0.9325	0.8588	0.6000	0.8125
A7	0.029	0.338	0.3760	0.4516	0.3989	0.3457	0.3054	0.3941	0.4631	0.4239	0.3523	0.3204
A8	0.017	−0.003	−0.1506	−0.0599	−0.0464	−0.0895	−0.0592	0.0260	0.0208	0.0467	0.0670	0.0328
A9	0.024	0.066	−0.1033	−0.1320	−0.1073	−0.1770	−0.0430	−0.2568	−0.2732	−0.3168	−0.3568	−0.4243
A10	0.036	−0.038	−0.1056	−0.1654	−0.1544	−0.1622	−0.1622	−0.1488	−0.1860	−0.1962	−0.2049	−0.1036
B1	0.018	0.877	1.0829	1.0829	0.7370	1.3305	1.0161	1.2327	1.2773	1.0567	0.9743	1.1749
B2	0.036	1.273	1.0612	1.1351	1.1621	1.3312	1.7625	1.4908	1.1228	1.2071	1.3583	1.4715
B3	0.029	1.976	1.7236	1.7236	3.0951	3.1576	3.3439	3.1915	3.0015	2.8495	3.0036	2.6922
B4	0.011	−415.918	−8705.5954	−3204.7844	−33,418.7158	−3563.7000	−2108.1418	950.6452	1627.0000	2717.0000	4723.0000	3267.0000
B5	0.031	44,940	−45,097	−58,774	−41,743	−54,313	−45,000	−72,900	−140,900	−168,600	−170,700	−186,900
B6	0.031	10,588.328	−658.1663	−989.8339	35,091.6428	10,222.800	16,358.5376	11,068.7651	12,128.000	11,777.000	8298.000	3518.000
B7	0.039	2.000	2.000	0.500	2.000	2.200	0.500	4.600	0.800	1.500	1.900	2.000
B8	0.035	1.100	1.4000	1.3000	1.5000	0.0000	0.8000	4.6000	0.1000	1.4000	1.4000	1.5000
B9	0.027	0.558	0.5055	0.5485	0.5411	0.4522	0.7049	0.7619	0.7841	0.7005	0.5372	0.6947
B10	0.023	0.613	0.6285	0.7308	0.7714	0.7320	0.8345	0.8497	0.8969	0.8676	0.8368	0.9129
B11	0.042	0.519	0.6422	0.4372	0.5708	0.4600	0.4425	0.4924	0.4841	0.4729	0.4997	0.6027
B12	0.027	412,119	487,940.2	538,580.0	592,963.2	643,563.1	676,708.0	746,395.1	832,035.9	919,281.1	986,515.2	1,015,986.2
B13	0.030	5321.0	6011.0	6702.7	7202.0	8082.0	8869.0	9543.5	10,211.0	11,069.0	12,680.0	13,795.4
B14	0.013	4.500	4.2000	0.3000	0.5000	2.1000	−10.0000	3.3000	2.3400	7.6200	8.8300	9.2500
C1	0.020	1309.091	1090.9091	750.0000	745.0980	793.7500	898.8235	935.7143	975.0000	395.2381	404.7619	159.6330
C2	0.051	0.381	0.3942	0.3525	0.3552	0.3745	0.4007	0.4334	0.5125	0.5796	0.5783	0.5753
C3	0.043	13.500	12.5000	12.2000	14.3000	15.0000	19.8000	25.6000	24.7000	25.0000	26.0000	29.0000
C4	0.043	103,500	128,500	148,500	150,000	150,000	88,000	88,000	93,000	107,000	158,000	177,000
C5	0.026	2,400,000	2,880,000	2,600,000	2,800,000	3,060,000	2,780,000	3,060,000	3,200,000	3,400,000	3,800,000	3,845,000
C6	0.027	89,200	96,200	148,500	109,000	124,000	135,000	135,000	146,700	158,700	177,500	199,000
C7	0.023	46.000	45.0000	35.9000	32.0000	35.0000	40.1000	39.2000	36.0000	39.8000	44.0000	46.0000
C8	0.032	50.100	52.0000	45.0000	48.0000	45.8000	51.5000	50.5000	62.6000	53.0000	58.6000	59.0000
C9	0.022	16.60	17.30	18.00	14.20	19.30	18.82	20.26	22.75	24.74	21.34	25.90
C10	0.032	0.0129	0.0123	0.0124	0.0121	0.0126	0.0131	0.0128	0.0123	0.0120	0.0129	0.0136

It can be observed from Table 2 that during the evaluation period, the largest average weight is that of the titanium self-sufficiency rate (A4) indicator. The smallest indicator is the net profit margin of titanium products (B14), whose weight value is 0.013–0.057.

According to the development status of the Ti industry during the evaluation period, the weight of each index is essentially in line with the development status.

4.1.2. Safety Level of the Titanium Industry

According to the calculation of the comprehensive safety level of the Ti industry using Equations (7)–(10), Table 3 lists the safety levels in the Ti industry from 2010 to 2020.

Table 3. Titanium Industry Chain Safety Level from 2010 to 2020.

Years	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
d_i^+	0.386	0.422	0.455	0.402	0.413	0.377	0.301	0.399	0.363	0.332	0.319
d_i^-	0.317	0.261	0.210	0.261	0.232	0.291	0.349	0.290	0.303	0.341	0.407
Safety level	0.451	0.382	0.316	0.394	0.360	0.436	0.537	0.421	0.455	0.507	0.561
Security level [40–42]	General	Early warning	Early warning	Early warning	Early warning	General	General	General	General	General	General

As shown in Table 3, from 2010 to 2020, the security level of China's Ti industry first declined and then increased. The years 2011–2014 demonstrated early warning levels, while the other exhibited only general levels. In the early warning years, from the perspective of the dimension level, the levels of sustainability and economy were lower than in other years. From the perspective of basic indicators, the Ti self-sufficiency rate, GDP, and TiO_2 trade deficit were relatively low. Indicators such as the import concentration of sponge Ti, external dependence on Ti concentrate, external dependence on Ti materials, and external dependence on TiO_2 were higher than in other years. From the perspective of industrial development, this is primarily because of market demand. China emerged as a frontrunner in mitigating the repercussions of the international financial crisis from 2010 to 2012. With the rapid development of the national economy, the demand for Ti metal products was strong; however, this favorable situation only lasted until the second half of 2011, when the country began to vigorously control inflation and intensify the regulation of real estate; thus, the demand for Ti products began to decline. Since April 2012, the price and output of Ti products have declined. In 2013, the domestic demand for Ti products declined with the development of China's macro economy. Since 2013, a year of difficult economic recovery in Europe and the United States, the Japanese economy has had even more difficulty recovering, and the international demand for Ti materials has dropped sharply. Although China has excess structural capacity, the Ti industry continues to struggle. In 2014, due to the sluggish growth of the world economy and the persistent downturn in the global Ti industry, the Ti industry of China also entered a cold winter period marked by high production capacity, low profit, and low demand. This situation resulted in Ti-processing enterprises operating at a low profit.

4.2. Security Dimension Layer Analysis of the Ti-Industry Chain

4.2.1. Analysis of Coupling Coordination Degree

The degree of coupling and coordination [43] for the safety level of the Ti industry chain and economic availability sustainability level from 2010 to 2020 were calculated, as shown in Tables 4–6. The C coupling degree reflects the strength of the interaction between the systems, while the D coupling coordination model can further reflect the coordination degree of system development. T is a comprehensive coordination index, which mainly reflects the coordination level of various dimensions and industrial safety development.

Table 4. Coupling coordination values of the titanium industry chain and availability level.

Years	The Safety Level of Titanium Industry Chain	Availability Level	C	T	D	Coupling Coordination Type
2010	0.451	0.651	0.641	0.451	0.538	Grudging coordination
2011	0.382	0.435	0.392	0.382	0.387	Mild maladjustment
2012	0.316	0.419	0.618	0.316	0.442	On the verge of maladjustment
2013	0.394	0.380	0.802	0.394	0.562	Grudging coordination
2014	0.360	0.372	0.780	0.360	0.530	Grudging coordination
2015	0.436	0.465	0.508	0.436	0.470	On the verge of maladjustment
2016	0.537	0.480	0.901	0.537	0.696	Primary coordination
2017	0.421	0.374	0.676	0.421	0.534	Grudging coordination
2018	0.455	0.442	0.723	0.455	0.573	Grudging coordination
2019	0.507	0.425	0.484	0.507	0.496	On the verge of maladjustment
2020	0.561	0.425	0.480	0.561	0.519	Grudging coordination

Table 5. Coupling coordination values of the titanium industry chain and economic level.

Years	The Safety Level of Titanium Industry Chain	Economical Level	C	T	D	Coupling Coordination Type
2010	0.451	0.361	0.507	0.451	0.478	On the verge of maladjustment
2011	0.382	0.369	0.473	0.382	0.425	On the verge of maladjustment
2012	0.316	0.233	0.443	0.316	0.374	Mild maladjustment
2013	0.394	0.473	0.491	0.394	0.440	On the verge of maladjustment
2014	0.360	0.362	0.595	0.360	0.463	On the verge of maladjustment
2015	0.436	0.441	0.651	0.436	0.533	Grudging coordination
2016	0.537	0.628	0.932	0.537	0.707	Intermediate coordination
2017	0.421	0.384	0.679	0.421	0.535	Grudging coordination
2018	0.455	0.409	0.816	0.455	0.609	Primary coordination
2019	0.507	0.435	0.831	0.507	0.649	Primary coordination
2020	0.561	0.516	0.708	0.561	0.630	Primary coordination

Table 6. Coupling coordination values of the titanium industry chain and sustainability level.

Years	The Safety Level of Titanium Industry Chain	Sustainability Level	C	T	D	Coupling Coordination Type
2010	0.451	0.344	0.433	0.451	0.442	On the verge of maladjustment
2011	0.382	0.343	0.663	0.382	0.504	Grudging coordination
2012	0.316	0.310	0.425	0.316	0.367	Mild maladjustment
2013	0.394	0.271	0.548	0.394	0.465	On the verge of maladjustment
2014	0.360	0.346	0.781	0.360	0.530	Grudging coordination
2015	0.436	0.393	0.548	0.436	0.489	On the verge of maladjustment
2016	0.537	0.437	0.719	0.537	0.621	Primary coordination
2017	0.421	0.524	0.795	0.421	0.579	Grudging coordination
2018	0.455	0.525	0.660	0.455	0.548	Grudging coordination
2019	0.507	0.720	0.932	0.507	0.687	Primary coordination
2020	0.561	0.797	0.701	0.561	0.627	Primary coordination

It can be observed from the table that in the years when the safety level of the Ti industry chain was at the early warning level, the degree of coupling between the economic level and safety level of the Ti industry chain was between imminent and mild imbalance. In other words, the development of the economic level provides a great guarantee for the safety level of the Ti industry chain. In 2012, the year with the lowest safety level in the Ti industry chain within the scope of this study, the safety, economic, and sustainability levels of the Ti industry chain were in a state of mild imbalance, and the availability level was on the verge of imbalance. Thus, it is necessary to further promote the synchronous coupling development of the Ti industry and economic level to achieve benign interaction and healthy and sustainable development of the Ti industry.

4.2.2. Security Level Analysis of Dimension Layer

Availability level. From 2010 to 2020, the level of safety availability in the Ti industry in China fluctuated significantly, as illustrated in Figure 4. In 2010, the level of safety in the Ti industry was relatively high, including external dependence on Ti dioxide, external dependence on Ti materials, TiO_2 self-sufficiency rate, and external dependence on Ti sponges, which had a positive impact on the Ti industry's availability level. The self-sufficiency rate of Ti sponges, import concentration of Ti ore, import concentration of Ti sponges, self-sufficiency rate of Ti concentrate, and external dependence on Ti concentrate have negative impacts on the availability of the Ti industry. Among these, the self-sufficiency rate of Ti materials and its external dependence on Ti materials has a significant impact on the availability level.

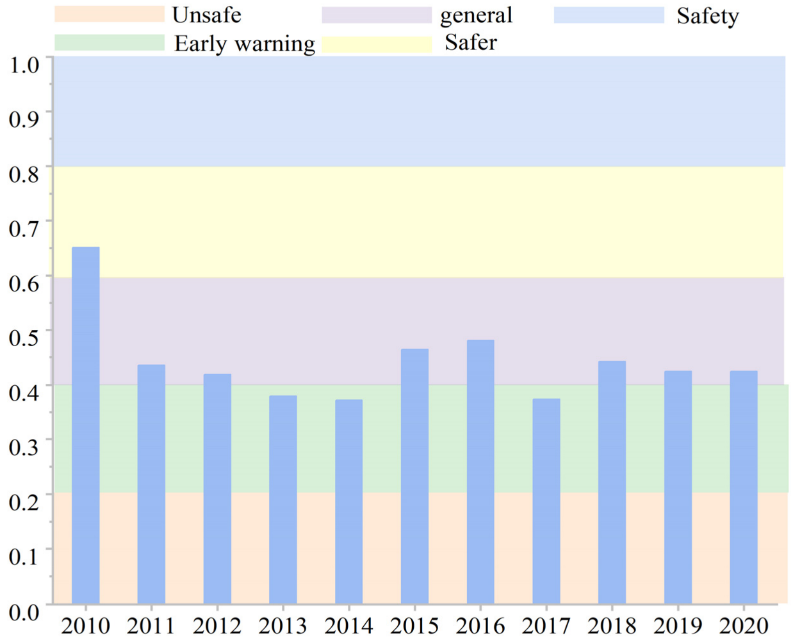

Figure 4. Safety availability level of China's titanium industry chain security from 2010 to 2020.

Economic level. From 2010 to 2020, the safety and economic levels of the Ti industry in China fluctuated significantly, as illustrated in Figure 5. The economy in 2012 was significantly lower than that in other years. In 2012, the economic level of the Ti industry was primarily affected by the operating rates. The state began to vigorously control inflation and intensify its efforts to regulate real estate, and demand for Ti products began to decline. Since April and May 2012, the price of Ti products declined, directly leading to a decline in Ti production in the second half of 2012. The economic status of the Ti industry fluctuated significantly from 2016 to 2017. In 2017, with the improvement of the TiO2 market, the pressure for environmental protection in the production of raw Ti materials in various places increased. The shortage of Ti concentrate resources led to a continuous rise in domestic raw Ti material prices, which subsequently impacted the prices of sponge Ti and Ti materials, causing significant fluctuations and reaching a bottoming point.

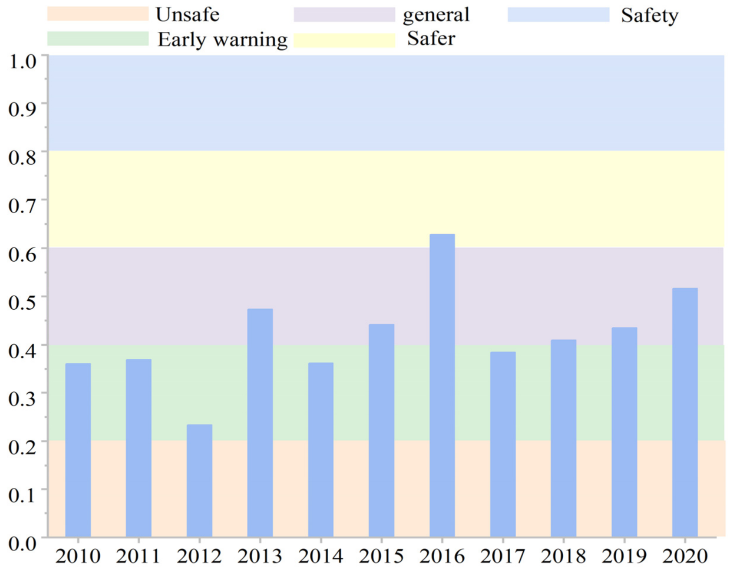

Figure 5. Safety and economic level of China's titanium industry chain security from 2010 to 2020.

Sustainability level. From 2010 to 2020, the safety sustainability level of the Ti industry in China showed an initial declining trend, followed by a rise. This is mainly due to the development of high-end industries, as illustrated in Figure 6. In 2014, under the guidance of the country's policy of stabilizing growth, adjusting structure, transforming growth modes, scientific and technological innovation and development, harmonious development with the environment, and promoting healthy and sustainable development of the industry, the main themes of economic development were as follows: capacity expansion, industrial structure optimization, and gradual improvement in the sustainable development of the Ti industry. In 2020, China's Ti processing industry, through structural adjustment, transformation, and upgrading in recent years, formed a company with Baoti Group Co., Ltd. (Baoji, China) and Western Superconducting Materials Technology Co., Ltd. Co., Ltd. (Xi'an, China) Hunan Xiangtou Jintian Titanium Metal Co., Ltd. (Changsha, China) Western Metal Materials Technology Co., Ltd. (Xi'an, China) and other leading enterprises, such as large state-owned enterprises. As such, sustainable development has reached a relatively safe level.

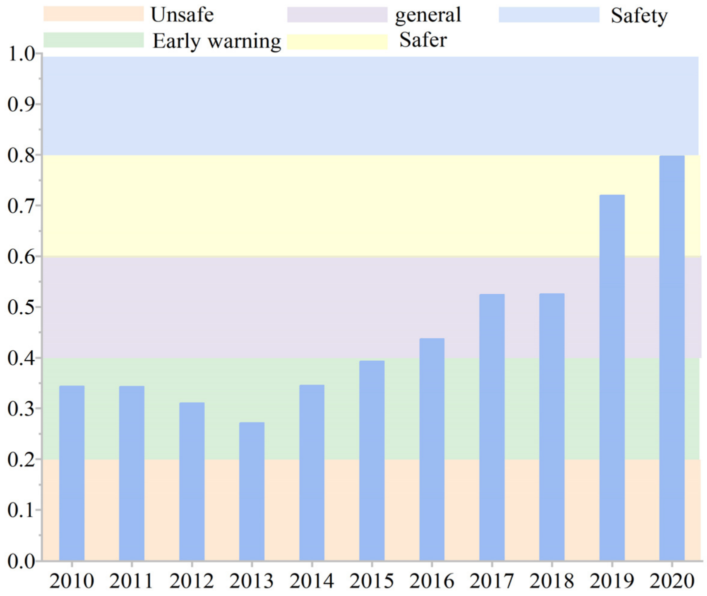

Figure 6. Safety sustainability level of China's titanium industry chain security from 2010 to 2020.

Overall, from 2010 to 2020, the safety of the availability level in the Ti industry has shown a downward trend; the economic level fluctuated less, and the sustainable safety level fluctuated significantly. Since 2013, the sustainability level has improved annually. Overall, the area of the quadrilateral enclosed by each dimension layer continued to increase, particularly the sustainable safety level, as illustrated in Figure 7.

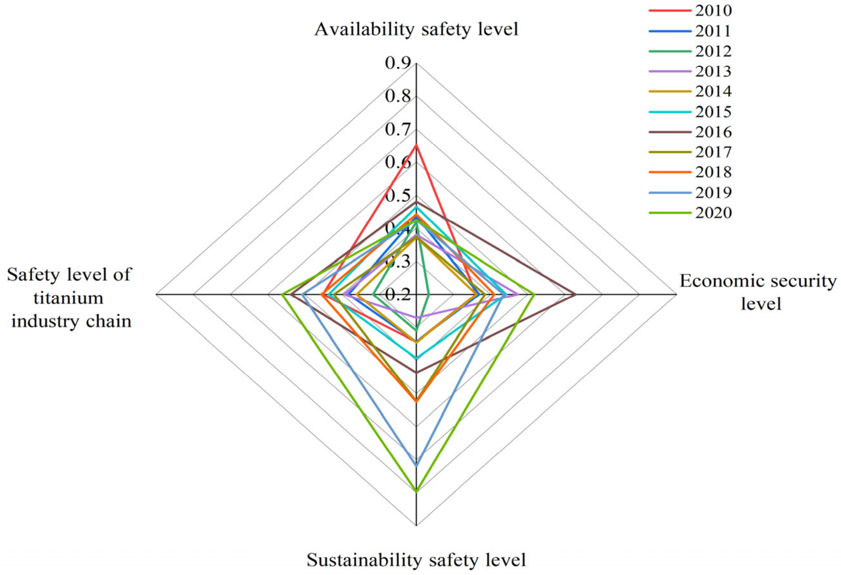

Figure 7. Radar chart of China's titanium industry chain security from 2010 to 2020.

4.2.3. Sensitivity Analysis

Sensitivity analysis is an analytical method that quantitatively describes the degree of influence of the model input variables on the output variables. A sensitivity analysis of the safety evaluation index system of the Ti industry chain helps identify the direction and degree of influence of different combinations of factors on the safety level of the Ti industry chain. Based on the security level of the Ti industry chain in China and the weight of each indicator from 2010 to 2020, assuming that the weight of each indicator did not change, it is classified according to the security dimension of the Ti industry chain.

Based on 2020, the combination of influencing factors was adjusted at the rate of change of −15, −10, −5, 5, 10, and 15%, and sensitivity analysis of the security dimension of the Ti industry chain was performed.

In general, the sensitivity of the Ti industry chain to changes in security availability is higher than that of economics and sustainability, as shown in Figure 8. For usability indicators, the sensitivity of positive changes in the security of the Ti industry chain is significantly higher than that of negative changes. In other words, compared with the negative impact of reducing the security and availability of the Ti industry chain, more attention should be paid to positive reinforcement. At a change level of 15%, the positive sensitivity was approximately nine times the negative sensitivity, and a small increase in the safety and availability in the Ti industry chain would have a greater positive impact on the safety level of the entire Ti industry chain.

For sustainability indicators, the sensitivity to negative changes in the safety level of the Ti industrial chain was significantly higher than that to positive changes. That is, compared to the positive strengthening of the safety and sustainability of the Ti industry chain, it is necessary to pay more attention to the negative factors of sustainability.

For the economic indicators, the positive and negative sensitivity changes in the safety level of the Ti industrial chain were small, and the sensitivity level was relatively stable.

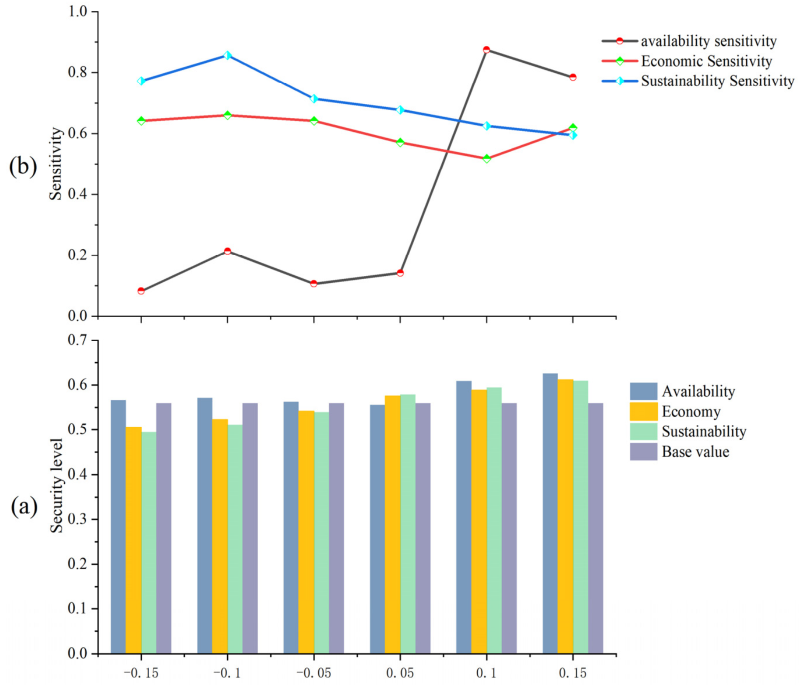

Figure 8. Changes in the level of security (**a**) and sensitivity analysis of dimensions (**b**).

4.3. Correlation Analysis of the Ti Industry Chain and Sensitivity Analysis

According to the grey correlation analysis, the indicators related to the changing trend of the safety level of China's Ti industry chain greater than 0.8 include availability indicators (titanium dioxide (TiO_2) self-sufficiency rate, TiO_2 external dependence), economic indicators (defense and military expenditure, GDP, TiO_2 trade deficit, Ti product net profit margin), and sustainability indicators (CR3, CR5, TiO_2 production capacity, Ti ingot production capacity, high-end industry share, Ti product gross margin, TiO_2 production capacity utilization rate, sponge Ti capacity utilization rate, China Innovation Index), as shown in Figure 9. Based on the 2020 data, assuming that the weight of each indicator remains unchanged, sensitivity analysis was performed for indicators with a correlation greater than 0.8 at −15, −10, −5, 10, and 15%, as shown in Figure 10.

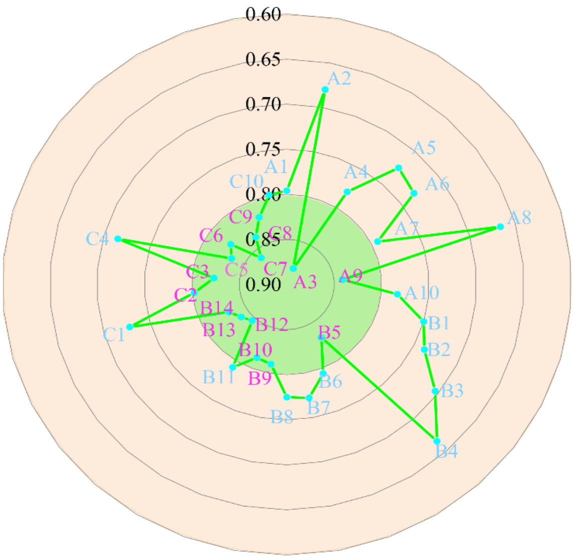

Figure 9. Correlation diagram between the safety level of the titanium industry chain and various influencing factors.

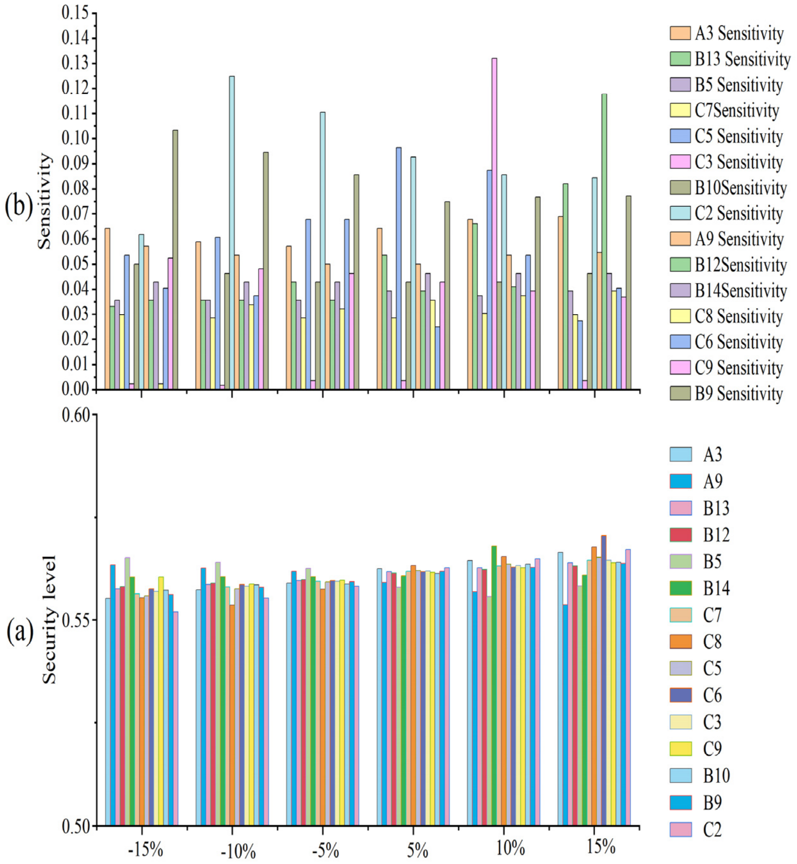

Figure 10. The changes in indicators arouse changes in the level of security of the titanium industry chain (**a**) and sensitivity analysis of indicators (**b**).

Overall, under the positive and negative 15, 10, and 5% variables, the change in the degree of correlation (greater than 0.8) made the change in the safety index of the Ti industry chain small. Among them, the indicators with high safety sensitivity in the Ti industry chain are CR5 and the China Innovation Index.

First, the self-sufficiency rate of TiO_2 in the ±15, 10, and 5% variables was caused by a change in the range of the Ti industry chain safety index from 0.0054 to 0.0058. The positive and negative sensitivity changes in the safety level of the Ti industry chain are small, and the sensitivity to positive changes is higher than that to negative changes; that is, instead of considering the negative impact of the decline in the self-sufficiency rate of Ti dioxide, the self-sufficiency rate of TiO_2 should be appropriately improved.

The change in the external dependence of TiO_2 under the variables of plus or minus 15, 10, and 5% caused changes in the safety index of the Ti industry chain between −0.0069 and 0.0028.

The positive and negative sense of the safety level of the Ti industry chain changes significantly, and under the 15% change, the positive sensitivity is approximately 2.5 times the negative sensitivity. In other words, while considering the positive impact of reducing the external dependence on TiO_2, the negative impact of excessive dependence on imports of TiO_2 should be strengthened.

Second, the changes in the safety index of the Ti industry chain caused by investment in national defense and GDP in the positive and negative 15, 10, and 5% variables were between −0.003 and 0.0033 and between −0.0025 and 0.0021, respectively. Relative to the GDP and defense expenditures, the positive and negative sensitivity changes in the safety level of the Ti industry chain are small, and the sensitivity level is relatively stable. The trade deficit in TiO_2 under the variables of plus or minus 15, 10, and 5% caused a change in the safety index of the Ti industry chain between −0.0049 and 0.0045. The positive and negative sense of the safety level of the Ti industry chain changes significantly when the amount of change is 5%, and the positive and negative sense of 10% is higher than the positive and negative sense of the change rate of 15%. In other words, it is crucial to carefully consider the effects of a 15% change in the trade deficit of TiO_2. Additionally, when examining the positive sense, a 5% increase should be regarded as approximately 1.5 times more impactful than a 10% decrease in the trade deficit. In essence, when considering the positive impact of the trade deficit of Ti dioxide, the negative impact of the increase in the trade deficit of TiO_2 should be considered.

The net profit margin of Ti products in the positive and negative 15, 10, and 5% variables caused the Ti industry chain safety index to change between −0.0001 and 0.0074. The safety level of the Ti industry chain changes significantly in the positive sensitivity under the 10% variable, and the positive sensitivity is higher than the negative sensitivity; in other words, the small increase in the net profit margin of Ti products under this variable has a relatively positive impact on the safety of the Ti industry chain.

Third, the industry concentrations CR3 and CR5 caused changes in the safety index of the Ti industry chain under positive and negative 15, 10, and 5% variables, between −0.0042 and 0.0039 and between −0.0077 and 0.0067, respectively. The change in CR3 in the industry concentration causes small positive and negative sensitivity changes in the safety level of the Ti industry chain, and the sensitivity level is relatively stable. The change in CR5 causes a large change in the positive and negative sense of the safety level of the Ti industry chain, while the sensitivity of the negative change in CR5 is higher than that of the positive change under the variables of 5 and 10%. In other words, compared with the improvement of CR5, more attention should be paid to the negative impact of CR5 decline.

Fourth, the production capacity of TiO_2 and Ti ingots caused by changes in the safety index of the Ti industry chain under the variables plus and minus 15, 10, and 5% are between −0.0048 and 0.0046, and −0.003 and 0.0099, respectively.

Relative to TiO_2 production capacity, the safety level of the Ti industry chain is equal in the positive and negative directions under the variables of 5 and 10%, that is, when the Ti ingot production capacity is reduced or increased by 10 or 5%, the impact of positive and negative changes equally considered. Under the 15% variable, the positive sensitivity was less than the negative sensitivity, and more consideration should be given to the impact of fewer negative changes on the safety of the Ti industry chain under this variable.

Relative to the Ti ingot capacity, the sensitivity under negative variables remained unchanged. The positive change under the 15% variable is approximately 3.3 times the negative sensitivity; that is, the small increase in Ti ingot production capacity at this time will have a significant positive impact on the safety of the Ti industry chain.

The proportion of high-end industries under the 15, 10, and 5% variables caused the Ti industry chain safety index to vary between −0.0036 and 0.0039.

The positive and negative sensitivity changes in the safety level of the Ti industry chain are small, and the sensitivity to positive changes is higher than negative changes and remains unchanged. In other words, within the scope of this study, the proportion of high-end industries should be increased.

The gross profit margin of Ti products changes in the safety index of the Ti industry chain under the variables of plus or minus 15, 10, and 5% and is between −0.0019 and 0.0033. For the gross profit margin of Ti products, the positive and negative sense of the safety level of the Ti industry chain changes greatly, and under the 15% variable, the positive sensitivity is approximately 17 times the negative sensitivity; that is, at the level of this change, a small increase in the gross profit margin of Ti products has a higher positive impact on the safety level of the Ti industry chain.

The capacity utilization rate of TiO_2 and the capacity utilization rate of sponge Ti under the variables of plus or minus 15, 10, and 5% caused the changes in the safety index of the Ti industry chain between −0.0034 and 0.0036 and between −0.0044 and 0.0031, respectively. Relative to the capacity utilization rate of Ti dioxide, the positive and negative sense of the safety level of the Ti industry chain changes greatly. Under the 5% variable, the negative sense of the safety level of the Ti industry chain is approximately 2.7 times the positive sensitivity; that is, compared with the improvement in the capacity utilization rate of Ti dioxide, more attention should be paid to the negative impact of the decline in the capacity utilization rate of Ti dioxide.

Relative to the capacity utilization rate of sponge Ti, the negative sensitivity of the safety level of the Ti industry chain is higher than the positive sensitivity; that is, at the same level of change, more attention should be paid to the negative impact of the decline in the capacity utilization rate of sponge Ti.

The China Innovation Index causes a change in the safety index of the Ti industry chain between -0.0087 and 0.0065 under positive and negative 15, 10, and 5% variables, respectively. The negative sense of the safety level of the Ti industry chain was higher than its positive sensitivity; that is, more attention should be paid to improving the innovation index in the Ti industry under the same level of change.

5. Conclusions and Policy Suggestions

5.1. Conclusions

By constructing a comprehensive evaluation system for the Ti industry, security was established, including availability, economics, and sustainability. The entropy weight-TOPSIS method was used to analyze the safety level of the Ti industry chain from 2010 to 2020, and the coupling degree and sensitivity of the Ti industry and each dimension layer were analyzed by coupling degree analysis and sensitivity. The grey correlation analysis method was used to analyze the factors with the highest correlation with the Ti industry chain, and the sensitivity analysis of the factors with high correlation in the Ti industry chain was analyzed.

The results show that during the evaluation period, the overall safety level of China’s Ti industry chain first declines and then rises, which is highly similar to the development status of China’s Ti industry, showing that the model we constructed has certain feasibility and can help China’s Ti industry structure and other aspects of policy formulation. According to the dimension layer, the safety availability level of the Ti industry chain was relatively weak and showed a downward trend. The coupling of the economic and safety levels is low in the years when the safety level of the Ti industry was low. According to the sensitivity analysis, the sensitivity of the Ti industry chain to changes in safety availability is higher than that of economy and sustainability. At a change level of 15%, the positive sensitivity is approximately nine times the negative sensitivity. That is, the safety availability of the Ti industry chain under the 15% variable is slightly improved, which has a greater positive impact on the safety level of the entire Ti industry chain.

According to the results of the gray correlation analysis, indicators with a correlation greater than 0.8 comprise those of availability (TiO_2 self-sufficiency rate, TiO_2 external dependence), economic (defense and military expenditure, GDP, TiO_2 trade deficit, TiO2 products), net profit margin, and sustainability (CR3, CR5, TiO_2 production capacity, Ti ingot production capacity, high-end industry ratio, TiO_2 product gross margin, TiO_2 capacity utilization rate, Ti sponge capacity utilization rate, and China Economic Innovation Index). Overall, under the variables of plus or minus 15, 10, and 5%, the change in a single indicator with a correlation degree greater than 0.8 causes a small change in the safety index of the Ti industry chain, and the indicators with higher sensitivity to the entire Ti industry chain are CR5 and the China Innovation Index.

Among them, under the change in CR5 at 5% and 10%, the sensitivity to negative change is greater than that to positive change, which means that it is necessary to pay more attention to the negative rather than the positive impact of the decline in industry concentration. Compared with the China Innovation Index, the negative sensitivity of the safety level of the Ti industry chain is higher than the positive sensitivity; that is, more attention should be paid to improving the innovation index in the Ti industry under the same level of change.

The advantage of this study is that the 34 indicators can reflect the safety level of the Ti industry, and a set of evaluation systems from the whole to the dimension of the indicators was constructed; however, the disadvantage is that the influence of non-directional factors at different stages is not considered. It is suggested that readers can evaluate the security of the Ti industry supply chain based on the security of the supply of high-end Ti products and Ti resources and different forms of changes to provide more opinions on the supply of Ti resources in China. The framework of this study is suitable for evaluating the safety level of the Ti industry, the impact of certain factors on the development of the Ti industry, and providing reference opinions on the formulation of Ti industry policies.

5.2. Polic Suggestions

As the safety availability level of the Ti industry chain was relatively weak and showed a downward trend, the economic level exerted a greater influence on the development of the Ti industry. The indicators with higher sensitivity to the entire Ti industry chain are CR5, the China Innovation Index, and the developmental status of the Ti industry. As a result, several policy recommendations have been proposed, including promoting the recycling of Ti resources.

To further improve safety in the Ti industry chain. The following policy recommendations are proposed based on an analysis of the industry chain in China's academic circles and the current situation of the Ti industry in China. Upstream in the Ti industry, it is necessary to accelerate research, improve the utilization rate and utilization level of Ti resources, and enhance the quality of raw Ti materials. The concentration of enterprise production has improved in the middle reaches of the Ti industry. A complete consumption structure exists downstream of the Ti industry.

The details are as follows:

(1) First, we consider the existing patented technologies in the Ti industry chain. Some developed countries have monopoly advantages over the Ti industry and cannot be surpassed in a short period, such as the preparation of high-end Ti materials and recycling of Ti waste. In the processing field, the Ti industry in China should adhere to bottom-line thinking, such as the production of high-end Ti materials, the production technology of high-grade sponge Ti, and other fields to focus on tackling key problems to maintain adequate stability and safety in the face of any form.

(2) The availability of Ti resources is important for consolidating the security of the Ti industry. Based on the distribution characteristics of Ti resources in China and related policies, the first task is to promote market-oriented reform in the upstream areas of the Ti industry chain, stimulate the vitality of upstream exploration and mining enterprises of Ti resources, and increase the strength of exploration and mining development through the reform of upstream mining rights, and opening and exit mechanisms to improve the self-sufficiency guarantee level of Ti resources in China. Second, the import channels of Ti resources must be broadened, and the impact of Ti raw materials, Ti product import concentrations, and geopolitical risks on the security of the Ti industry in China must be reduced. Simultaneously, research and development of Ti waste recycling technology is needed to improve the recycling rate of Ti waste in China.

(3) To adhere to long- and short-term safety relationships of Ti resources, from the perspective of import and export trades, China mainly exports low-grade Ti at low prices. Most of the total trade balance has been reduced in quantity, thereby reducing the availability of Ti resources in China. Therefore, the exploitation of Ti resources in China should be reasonably conducted such that the lean ore is mined by force and the rich ore is mined by fines. According to the distribution characteristics of Ti resources in China, the cost of domestic Ti resources, international Ti resource prices, geopolitical reforms, and other factors are comprehensively considered to achieve the best balance between self-sufficiency and import supplementation of Ti raw materials and products. For example, when the price of international Ti resources is reasonable, the import of

Ti resources should increase, the mineable life of Ti resources in China should increase, and the future security level of Ti resources in China should be improved.

(4) By carrying forward alliance thinking, attaching importance to industry alliances, and strengthening industry concentration, currently, the evolution of the industry chain is progressing toward a decentralized high-end industry. Enterprises on the same information platform can form strategic alliances to achieve complementary advantages, such as process docking, resource sharing, and cultural integration.

Author Contributions: Conceptualization, X.H. and W.W.; methodology, X.H.; software, X.H.; validation, X.H., W.W. and M.Q.; formal analysis, X.H.; investigation, W.W.; data curation, X.H.; writing—original draft preparation, X.H.; writing—review and editing, W.W.; project administration, C.Z. and S.Y.; funding acquisition, W.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Foundation of Guizhou Province [grant numbers QKHJC-ZK 2021-YB 261 and QKHJC 2019-1406], the National Natural Science Foundation of China [grant number 51874108], the Talent Projects of Guizhou University and the Education Department of Guizhou Province [grant number GDPY 2019-20, and QJHKYZ 2021-097].

Data Availability Statement: Data are contained within the article.

Acknowledgments: The author is grateful to senior engineers Qiang Liang and Jinze Li of Zunyi Titanium Co., Ltd. for their valuable discussions and advice.

Conflicts of Interest: The authors declare no conflict of interest.

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