information

MDPI

Article

Research on the R&D Strategies of Iron and Steel Enterprises Based on Semantic Topic Analysis of Patents

Hongxia Wang [1], Ming Li [2,*], Zhiru Wang [1,*] and Zitong Shan [1]

[1] School of Economics and Management, University of Science and Technology Beijing, Beijing 100083, China
[2] School of Urban Economics and Management, Beijing University of Civil Engineering and Architecture, Beijing 100044, China
* Correspondence: liming@bucea.edu.cn (M.L.); wangzhiru@ustb.edu.cn (Z.W.)

Abstract: R&D strategies play a decisive role in the promotion of enterprise innovation output and innovation ability. In order to thoroughly investigate the R&D strategies of iron and steel enterprises, an R&D strategy analysis framework based on R&D semantic topic analysis and outlier behavior detection was proposed. Additionally, empirical research on R&D layout and direction, R&D quality, and the achievement maintenance strategy of enterprises, from both macro and micro perspectives, was conducted. The feasibility of the R&D strategy analysis framework was verified. Additionally, the results show that, in terms of R&D topic layout strategy, most enterprises adopted a stable maintenance strategy after quickly completing the layout; regarding the R&D focus strategy, most enterprises focused on R&D fields and carried out strategic management; for R&D quality control strategy, some enterprises adopted a strategy of prolonging the duration of invention patents, and high-quality outputs with a long lifetime were developed rapidly. These research results have reference value for Chinese enterprises, to adjust their R&D strategies, and for the government, to formulate supporting policies.

Keywords: R&D strategy; LDA topic model; Grubbs analysis; survival analysis; iron and steel enterprises

Citation: Wang, H.; Li, M.; Wang, Z.; Shan, Z. Research on the R&D Strategies of Iron and Steel Enterprises Based on Semantic Topic Analysis of Patents. *Information* **2023**, *14*, 199. https://doi.org/10.3390/info14030199

Academic Editor: Haridimos Kondylakis

Received: 7 February 2023
Revised: 10 March 2023
Accepted: 20 March 2023
Published: 22 March 2023

1. Introduction

Technological research and development (R&D) is important for the development of the iron and steel industry (ISI), which is energy-intensive and emissions-intensive. As the largest steel producer and consumer, China has a responsibility to promote sustainable development of the ISI industry. Technological innovation is critical for the achievement of carbon neutral targets [1,2] and the raw material security of the ISI [3]. Previous studies found that the technical regression of the steel-making sub-process is the main factor that impedes environmental total factor productivity (ETFP) growth [4]. Technological improvements and the R&D of ultra-low carbon technologies and hydrogen-based steel-making technologies are important for the short-term and long-term development of ISI [5].

High-quality technological innovation outputs rely on R&D strategies; the layout and direction of R&D in the early stages have huge impacts on enterprise value [6]. Previous studies conducted sufficient research on R&D strategy selection at the macro level. For instance, the existing studies found that enterprises can obtain access to technological innovation from external acquisitions, internal R&D, or a combination of both [7–14]. These three different ways have different impacts on enterprises' innovation performance [15–19], and the selection of R&D strategies for different enterprises are influenced by both internal and external factors [20–22]. Some studies also paid attention to specific R&D strategies [23–26], such as the R&D fields (exploratory R&D, exploitative R&D, or both) on which enterprises should focus.

However, the existing literature has paid insufficient attention to microscopic analysis of the R&D process and rarely detailed the contents of the R&D topic, R&D topic selection behavior, and R&D achievement maintenance strategies of enterprises in specific R&D processes. These specific R&D strategies have direct impacts on both the technological innovation outputs of iron and steel enterprises and the sustainable development of the iron and steel industry. Therefore, it is necessary to investigate iron and steel enterprises' R&D strategies thoroughly from a micro level. In order to conduct in-depth analysis of R&D strategies, this paper proposes a research framework based on semantic topic analysis and R&D outlier behavior analysis. Then, we conducted an investigation of the R&D topic layout strategies, R&D topic focus strategies, and R&D quality control strategies of Chinese iron and steel enterprises. The R&D strategy analysis framework proposed in this paper can be used to conduct real-time and dynamic analysis of the R&D strategy of an industry and competitors.

The remainder of this article is organized as follows: The related literature is reviewed in Section 2. The methods and data used in this paper are introduced in Section 3. Then, the results and discussion are presented in Section 4. Finally, we offer concluding remarks and address some limitations in Section 5.

2. Literature Review

2.1. R&D Strategies at the Macro Level

Enterprises can obtain access to technological innovations in three different ways, including external technology acquisition (i.e., buying), internal independent R&D (i.e., making), and a combination of external acquisition and internal R&D (i.e., buying–making) [7,8]. Different R&D strategies have different effects on innovation performance. Additionally, R&D strategies will influence the success of innovations. Some scholars believe that external technology procurement cannot promote enterprise innovation as expected [9,10]. Some even believe that the procurement of external technology has negative effects on the enterprises' own innovation [11]. Chen and Yuan [12] found that the contribution of internal R&D is larger than outsourcing for Chinese high-tech firms. Tsai and Wang [13] found that internal independent R&D has a positive effect on innovation performance. Others believe that external knowledge procurement and internal R&D are complementary innovation activities [14]. External technology acquisition (e.g., machine and equipment purchase) or the combination of external technology acquisition and internal R&D can ensure the success of process and product innovations [15]. The combination of technology acquisition and internal R&D has a longer and greater effect on innovation performance compared with the other two forms [7].

However, research works on the complementarity or substitutability of internal R&D and external R&D have not reached a unanimous conclusion [16]. Some researchers believed that both internal R&D capabilities and sources of external knowledge (e.g., knowledge from value chain partners and technology service providers) affect innovation outputs. Firms with stronger internal R&D and more R&D cooperation with value chain partners have better innovation performance [17]. The level of internal R&D investment also has an impact on the complementarity and substitutability between internal R&D and external R&D strategies. R&D alliances or R&D acquisitions are complementary to internal R&D when a firm has high levels of internal R&D investment [18]. In addition, decisions about the selection of products, processes, and organizational innovations have an impact on a firm's productivity. Organizational innovation and process innovation have a larger effect than product innovation. Cooperation with suppliers or clients promotes product or process innovations. The quality standard certifications of foreign markets also have positive impacts on a firm's innovation performance [19].

Additionally, there are many factors that affect a firm's decision of whether to cooperate with enterprises in the supply chain (e.g., suppliers, competitors, and customers) or not. Teece, Pisano, and Shuen [20] believed that, against the background of rapid technological development, enterprises should focus on internal technological R&D, as well as the improvement of organizational and management capabilities. Companies with different technological capabilities tend to adopt different innovation strategies. Firms with greater technological capabilities prefer cooperative R&D to internal independent R&D [21]. The brand differentiation gap between a firm and its competitors also has a significant impact on their selection of cooperative innovation strategies. A cooperative relationship tends to be chosen when the gap between two firms is large, or when the R&D cost is mainly borne by the competitor [22].

2.2. Specific Strategies of R&D Fields

Whether a firm should specialize in exploratory or exploitative R&D or pursue both depends on the R&D strategies adopted by intra-industry peers and changes across industries. If a firm's R&D strategy is similar to its competitor's, its innovation performance will decrease [23]. In addition, new emerging science and technologies (NESTs) have tremendous innovation potential and enormous uncertainties [24].

Technologies in the IT industry progress more rapidly and focus more on product development than other sectors [25]. Additionally, companies usually approach innovation in three different ways, which can be categorized as need seekers, market readers, or technology drivers [26]. These three innovation models have similar goals for innovation performance but have different features. Among them, need seekers (e.g., Apple Inc.) make great efforts to find and address customer's future or unstated needs. Market readers (e.g., Samsung) focus on incremental innovations to existing products. Technology drivers (e.g., Google) pay more attention to breakthrough innovations, in addition to incremental change. Jaruzelski, Staack, and Goehle's report also showed that need seekers' innovation strategies are highly aligned with their business strategy, and they are the most consistently successful compared with the other two models [26].

3. Methods and Data

3.1. Methods

The research framework of specific R&D strategies is shown in Figure 1. First, the corresponding text and statistical information were extracted from the description item information and legal status information of each patent's basic filing data. The basic patent data included all the patents filed by the 72 largest Chinese iron and steel enterprises at the State Intellectual Property Office of China. Additionally, the top 20 enterprises, in terms of the number of patents and the number of patent topics, were selected as industry representatives for the case study. The criteria used to select the sample companies are explained in Data Section 3.2. After removing duplicate data, the professional vocabulary of the iron and steel industry was collected and the text data of patent application files were segmented using Jieba software; nonsense words (e.g., "of", "on") were weeded out.

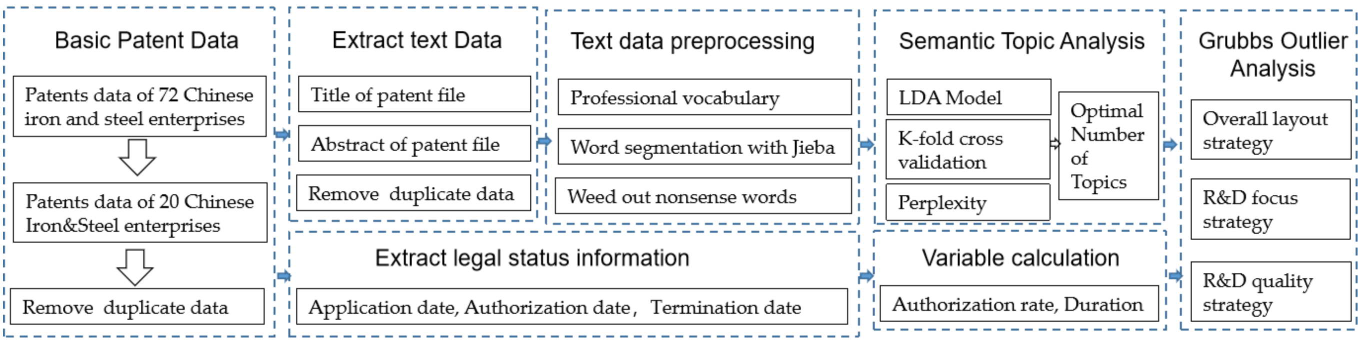


Figure 1. The research framework.

Second, a semantic topic analysis was carried out, to investigate the number of R&D topics and R&D topic layout strategies. Specifically, the LDA model was used to recognize R&D topics (detailed explanation presented in Section 3.1.1), and the perplexity value and K-fold cross validation were used to determine the optimal number of R&D topics, as explained in Section 3.1.2. In addition, variables such as the authorization rate and the duration of patents were calculated to investigate the R&D quality control strategies.

Third, the Grubbs algorithm (detailed calculation presented in Section 3.1.3) was used to extract outliers of R&D topics with a relatively high number of patent applications and long patent survival times. An outlier analysis from the perspective of R&D topic and life cycle was conducive to determining the R&D topic focus strategy and R&D quality control strategy for the whole R&D process.

3.1.1. LDA Topic Model

After text data preprocessing, the words that contributed to the topic mining were obtained. Then, the latent dirichlet allocation (LDA) model proposed by Blei et al. [27] was used for topic recognition. From the perspective of semantics, the document–topic distribution matrix and topic–vocabulary distribution matrix of each patent document were obtained, representing each patent document and selecting a certain topic with a certain probability and with each topic selecting a certain word with a certain probability, so as to realize the semantic analysis of the text. At the same time, the LDA model solves the problem of the "polysemy of one word" or "many words having the same meaning" that traditional text mining algorithms cannot solve. Additionally, it has been used in different fields, including filtering noise patents [28], performing technology assessments of R&D in the block-chain field [29], predicting the research topics of anthropogenic marine debris (AMD) [30], and the topic evolution of mental models [31].

The process of LDA model includes two parts. The first step is to determine the probability of topic $p\left(\vec{z}\right)$. The second step is to determine the probability of words in the topic $p(\vec{w}|\vec{z})$. Therefore, we can derive Equation (1):

$$p\left(\vec{w},\ \vec{z}\right) = p\left(\vec{w}|\vec{z}\right)p\left(\vec{z}\right) \tag{1}$$

When the probability of words is known, the potential probability of topic after each word $p(\vec{z}|\vec{w})$ can be calculated according to Equation (2):

$$p\left(\vec{z}|\vec{w}\right) = \frac{p\left(\vec{w},\vec{z}\right)}{p\left(\vec{w}\right)} = \frac{p\left(\vec{w},\vec{z}\right)}{\sum_z p\left(\vec{w},\vec{z}\right)} \tag{2}$$

According to Gibbs sampling and expectation, we can derive the document–topic distribution matrix θ_{mat} and the topic–vocabulary distribution matrix φ_{mat}.

$\theta_{mat} = \left[\overrightarrow{\theta_1}\ \overrightarrow{\theta_2}\ \ldots\ \overrightarrow{\theta_m}\right]$, where the mth document and the kth topic can be calculated using Equation (3).

$$\theta_{m,k} = \frac{n_{m,k} + \alpha_k}{\sum_{i=1}^{K} n_{m,i} + \alpha_i} = \frac{n_{m,k} + \alpha}{\sum_{i=1}^{K} n_{m,i} + K\alpha} \tag{3}$$

$\varphi_{mat} = \left[\overrightarrow{\varphi_1}\ \overrightarrow{\varphi_2} \ldots\ \overrightarrow{\varphi_m}\right]$, where the kth topic and the wth word can be calculated using Equation (4).

$$\varphi_{k,w} = \frac{n_{k,w} + \beta_w}{\sum_{i=1}^{V} n_{k,i} + \beta_i} = \frac{n_{k,w} + \beta}{\sum_{i=1}^{V} n_{k,i} + V\beta} \tag{4}$$

3.1.2. Perplexity and K-Fold Cross-Validation

In this paper, the maximum probability topic corresponding to the document in the document–topic probability matrix was taken as its topic, and on this basis, the enterprise R&D strategy was explored. The LDA model has to specify the number of topics in advance and cannot determine the optimal number of topics on its own. Blei et al. [27] proposed calculating the perplexity value corresponding to the number of different topics; the number of topics with the minimum value of perplexity is the optimal value. The calculation of perplexity is shown in Equation (5).

$$b^{H(q)} = b^{-\frac{1}{N}\sum_{i=1}^{N}\log_b q(x_i)} \quad (5)$$

where $H(q)$ represents the entropy of the probability distribution, and base, b, can be either 2 or e; x_i is the text to be tested; and N is the size of the text set.

If base b is e, the perplexity can be calculated using Equation (6).

$$perplexity = \exp\{-\frac{\sum_{d=1}^{M}\log p(w_d)}{\sum_{d=1}^{M} N_d}\} = \exp\{-\frac{\sum_{d=1}^{M}\sum_{w_i\in d}\log\{\sum_{z\in d} p(z|d) * p(w_i|z)\}}{\sum_{d=1}^{M} N_d}\} \quad (6)$$

where $\sum_{w_i d}\log\{\sum_{z\in d}(p(z|d) * p(w_i|z))\}$ equals $\log p(w_d)$, w_d stands for all the words in document d, N_d is the total number of words (including repeated words) contained in the document of section d, and z represents the topic.

In order to ensure reliability and accuracy, K-fold cross-validation was used for cross-verification; the k value was 10; and the number of topics ranged from 10 to 500. In order to reduce the computational complexity and maintain the accuracy of the algorithm, the number of topics was set in advance during the operation of the LDA model; the operation was performed by adding ten topics in sequence. Additionally, the corresponding perplexity value was calculated to determine the topic quantity, K1, corresponding to the minimum value. The topics within the 20 intervals (K1 − 20, K1 + 20) before and after the K1 value were cross-verified to calculate the perplexity value and find the mean, so as to finally determine the optimal number of topics K.

The number of topics in the patent texts of 20 representative iron and steel enterprises and the corresponding perplexity values are shown in Figure 2. The horizontal axis is the number of topics, and the vertical axis is the corresponding perplexity value. It is clear that the perplexity value decreased rapidly with the increasing number of topics. Then, the perplexity value slowly became smooth and finally began to increase, which means that each enterprise reached the lowest point. Additionally, the optimal number of topics could be determined from the lowest point.

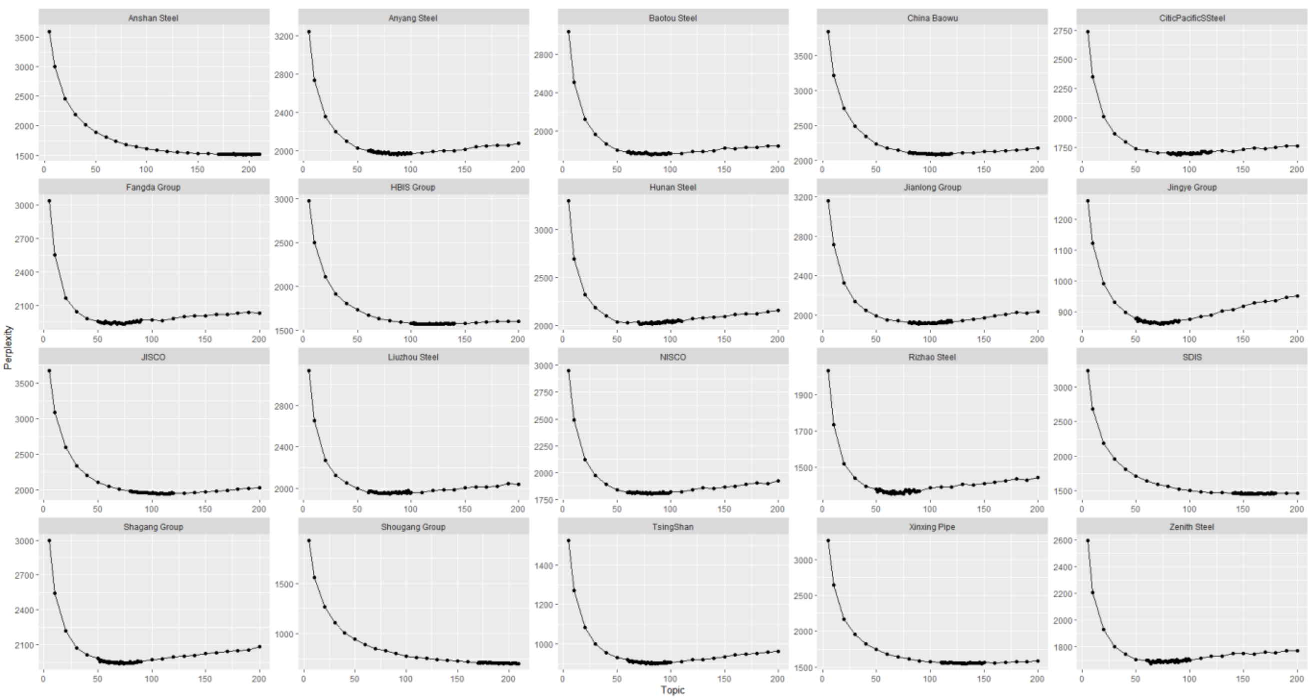


Figure 2. The topics of the patent texts and the corresponding perplexity values.

3.1.3. The Grubbs Algorithm for Outlier Detection

The Grubbs value, G_n, can be calculated using Equation (7).

$$G_n = \frac{|x_{out} - \overline{x}|}{s} \tag{7}$$

where s stands for the standard deviation. $GP(n)$ is the threshold value of Grubbs test. When $G_n > GP(n)$, it is judged as an outlier; otherwise, no outlier is found.

3.2. Data

This study used all the published patent application data of iron and steel enterprises to explore their research and development strategies. In order to ensure the stability and reliability of the research results, this paper referred to the 2021 global crude steel production ranking of steelmakers published by MetalBulletin, an industry research institution in the UK. In 2021, a total of 133 steel enterprises around the world produced more than two million tons of crude steel, of which 72 were Chinese enterprises. In this study, the top 20 enterprises in terms of the number of patents and the number of patent topics were selected as industry representatives. The list of 20 iron and steel enterprises and their abbreviated names are shown in Table 1. The total number of patent applications of these 20 enterprises accounted for 93.6% of the total number of patent applications of the 72 iron and steel enterprises.

Table 1. List of iron and steel enterprises and their abbreviated names.

No.	Name	Abbreviated Name
1	Anyang Iron and Steel Group Corporation	Anyang Steel
2	Ansteel Group	Anshan Steel
3	Baotou Steel Group	Baotou Steel
4	Beijing Jianlong Heavy Industry Group Co., Ltd.	Jianlong Group
5	Liuzhou Steel Group	Liuzhou Steel
6	HBIS Group	HBIS Group
7	Hunan Steel Group	Hunan Steel
8	Shagang Group	Shagang Group
9	Jingye Group	Jingye Group
10	Jiuquan Iron Steel Group	JISCO
11	Fangda Group	Fangda Group
12	Nanjing Iron and Steel	NISCO
13	TsingShan Holding Group	TsingShan
14	Rizhao Steel Holding Group	Rizhao Steel
15	Shandong Iron and Steel Group Co., Ltd.	SDIS
16	Shougang Group	Shougang Group
17	Xinxing Ductile Iron Pipe Co., Ltd.	Xinxing Pipe
18	China Baowu Steel Group Corporation	China Baowu
19	Zenith Steel Group Company Limited	Zenith Steel
20	Citic Pacific Special Steel Group Co., Ltd.	CiticPacificSSteel

The patent data were obtained from the State Intellectual Property Office of China. The specific search method was as follows: First, the search term was entered in the "Applicant" field. The search term included the name of the enterprise and its subsidiary, with the application period from 1985 to September 2022. In the second step, all patent applicants were matched accurately, and 132,515 pieces of patent data were retrieved after removing some duplicate data, including 54,510 pieces of invention patent data, 73,973 pieces of utility model patent data, and 4032 pieces of design patent data. Among the invention patents, there were 20,785 patents granted and 33,725 patents that had been applied for but not authorized. Patent data contained two parts: one was the description of the patent, such as the application number, applicant (patent), name, invention (design) person, abstract, sovereignty, and other information; the other part was the legal status, which contained the registration and filing information of the patent, from application to expiration, including the application date, public date, substantive examination date, authorization date, license filing situation, decision of application rejecting, correction of the invention patent application, termination of patent rights, etc. In the text analysis part, the patent name, abstract, and description were combined and analyzed, and other information was extracted from the legal status information.

4. Results and Discussion

4.1. Overall R&D Topic Layout Strategy

The number of invention patent applications and the number of R&D topics represent the scope and direction of the R&D layout, while the authorization rate reflects the quality of R&D to some extent. Therefore, the dynamic changes in these three indicators can be used to investigate the overall R&D layout and quality strategy of enterprises.

4.1.1. The Distribution of Patents and Topics

Figure 3 shows the distribution of the number of patents applied for and the patent topics of sample enterprises from 1985 to 2022. In Figure 3, the horizontal axis represents the enterprises, and the first vertical axis represents the number of invention patents granted, the number of invention patent applications that were not granted (i.e., invention patent applying), the number of utility model patents, and the number of design patents. The second vertical axis represents the number of patent topics.

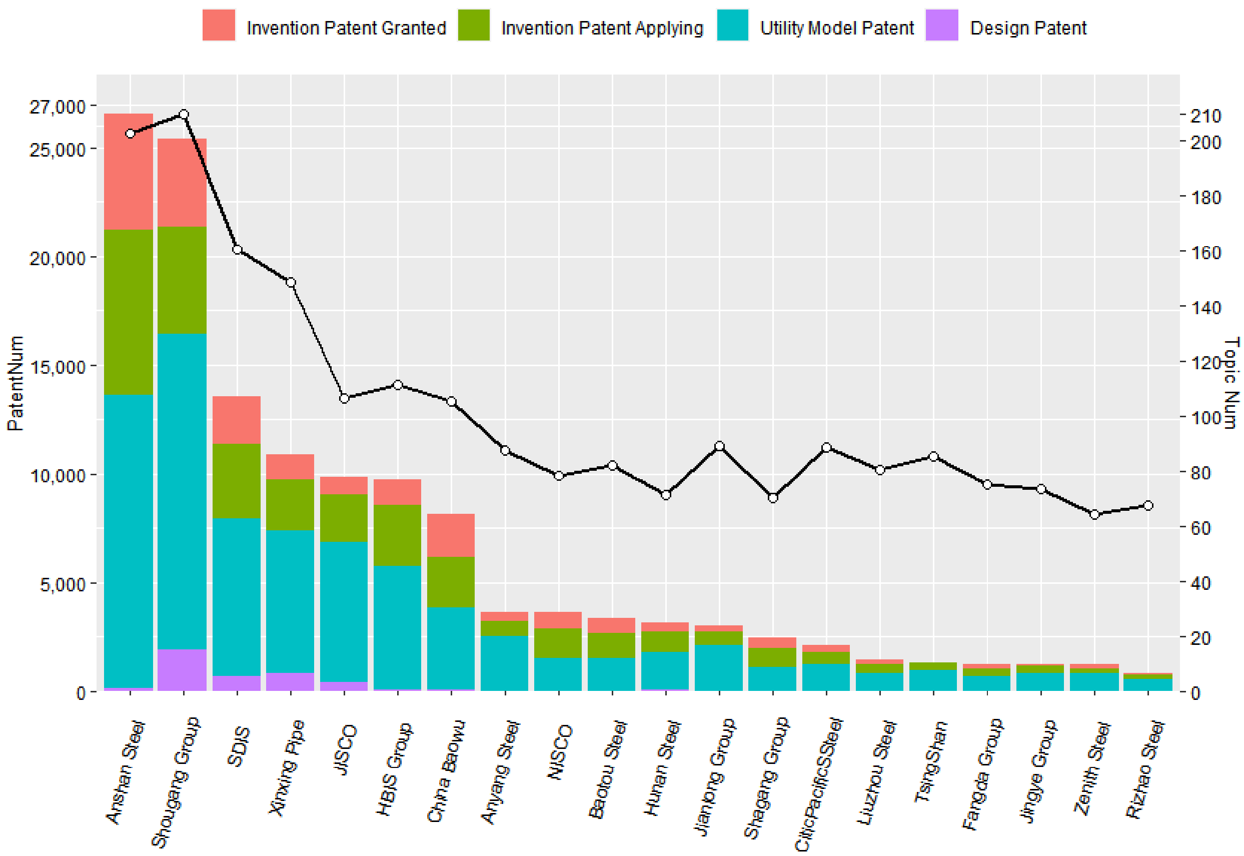


Figure 3. Number of patents and number of topics. Note: invention patent applying represents an invention patent applied but not granted; invention patent granted represents a granted invention patent. The line refers to the topic numbers of patents.

From the perspective of enterprises, Anshan Steel, Shougang Group, Shandong Iron and Steel (SDIS), Xinxing Pipe, Jiuquan Iron Steel Group (JISCO), Hebei Iron and Steel Group (HBIS Group), and China Baowu Steel Group Corporation (China Baowu) had clear advantages in the total number of patent applications and the number of patent topics. Among them, the total number of patents for Anshan Steel reached 26,600, and the number of patent topics amounted to 202. Shougang Group's total patent count was slightly lower than Anshan Steel's, at 25,400, but it surpassed Anshan Steel in the number of patent topics, at 209. Shandong Iron and Steel and Xinxing Pipe, ranked third and fourth, having a large gap from the top two companies regarding the total number of patents, 13,500 and 10,900, respectively, about half that of Anshan Steel. From the perspective of patent types, the number of utility model patents in most enterprises was higher than that of invention patents. The number of appearance design patents was the lowest, which is related to the product characteristics of iron and steel enterprises.

4.1.2. Time Trends in the R&D Topic Coverage

To some extent, the number of patent R&D topics reflected the coverage of enterprise R&D topics. The variation in the number of patent topics (R&D topics) of sample enterprises from 1985 to 2022 is shown in Figure 4. Notably, the data for 2022 are accurate as of September 2022. The horizontal axis is the year, and the vertical axis is the number of patent applications and R&D topics of the enterprises, respectively.

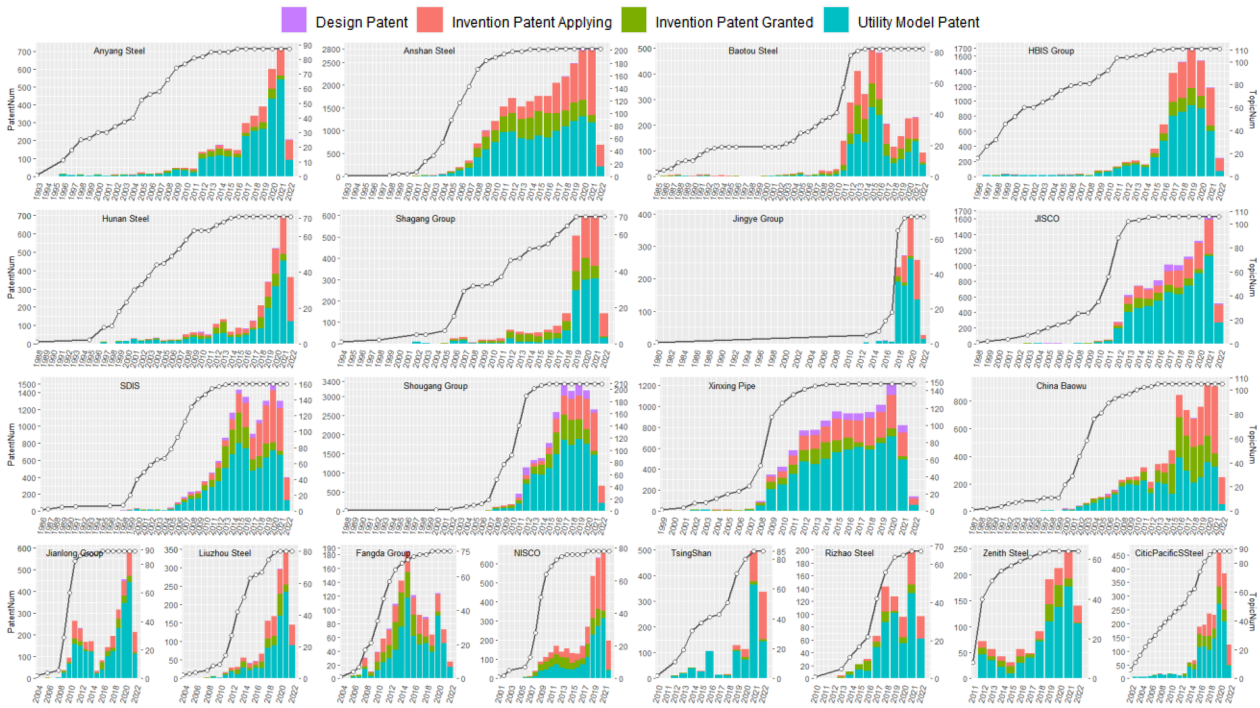


Figure 4. Number of patents and topics during 1985–2022. Note: invention patent applying stands for an invention patent applied but not granted, and invention patent granted represents a granted invention patent. The line refers to the topic number of patents.

As shown in Figure 4, Anshan Steel and Shougang Group had the most extensive R&D theme coverage, with more than 200 topics. SDIS, Xinxing Pipe, JISCO, HBIS Group, and China Baowu's R&D theme coverage ranked the second, with more than 100 themes. Second, in terms of the time of R&D theme layout, most enterprises completed the layout of all themes around 2012, when the topic number curve reached its peak. Jingye Group, Shagang Group, Rizhao Steel, and Fangda Group completed their layout of R&D themes in 2018. Finally, from the perspective of strategic dynamic adjustment, the research and development theme layout was investigated. Most enterprises adopted the strategy of stable maintenance after rapidly completing the layout, while small enterprises such as TsingShan, Citic Pacific Special Steel, Liuzhou Steel, and Rizhao Steel were in the stage of catch-up and expansion.

4.1.3. Time Trend of the Invention Patent Grant Rate

Compared with utility model and design patents, invention patents often better reflect the R&D level of enterprises. Additionally, the grant rate of invention patents can reflect R&D quality to some extent. Therefore, the following analysis focused on invention patents. The time trend of the number of invention patent applications and the authorization rate is shown in Figure 5. Except for individual enterprises, the total number of invention patent applications of the sample enterprises exhibited an increasing trend year-by-year, indicating that iron and steel enterprises paid increasing attention to their R&D level.

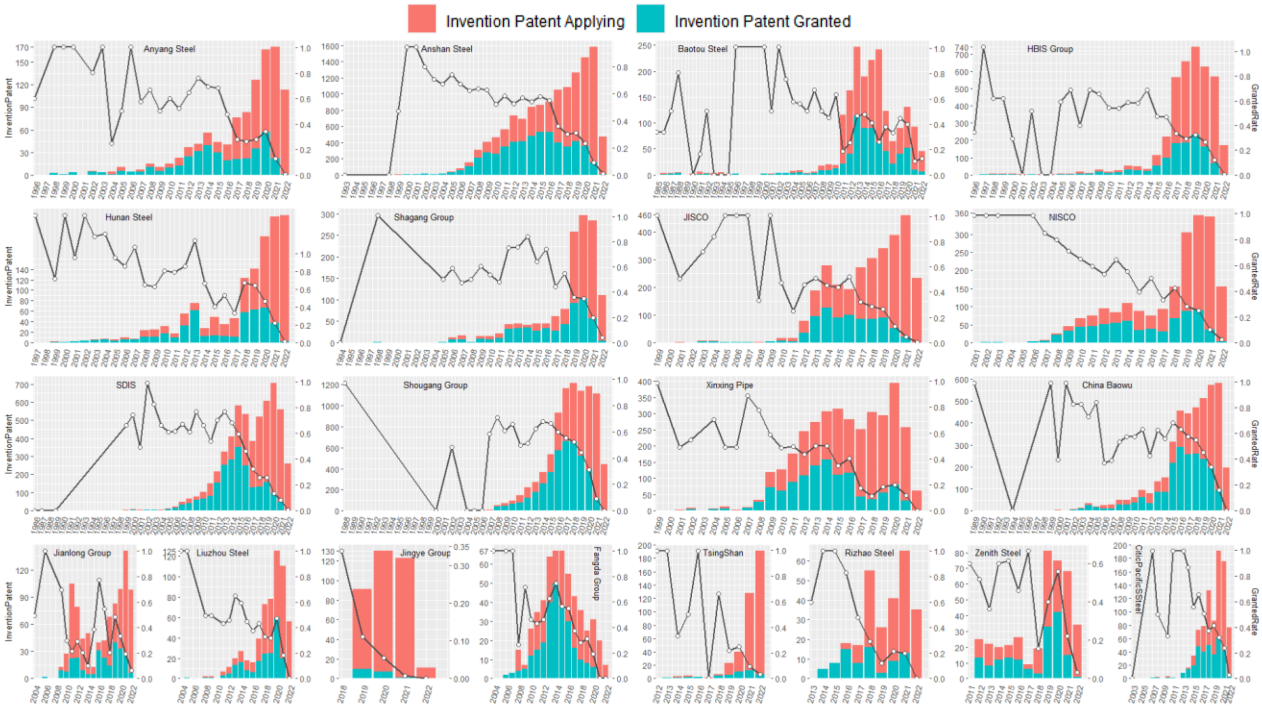


Figure 5. Number of invention patents and grant rate during 1985–2022. Note: invention patent applying stands for an invention patent applied but not granted, and invention patent granted represents a granted invention patent. The line refers to the grant rate of invention patents.

As shown in Figure 5, the grant rate of most enterprises showed a certain volatility. It can be roughly divided into three stages. From 1985 to 2010, the total amount of invention patent applications was low, but the grant rate was high. From 2011 to 2016, the total amount of invention patent applications and the grant rate were both high. Enterprises made strategic improvements in the quality of R&D (i.e., the grant rate of invention patents increased). The relatively low grant rate in 2017–2022 was related to lags in patent licensing.

A comparison between enterprises indicated that the grant rates of AnshanSteel, China Baowu, Xinxing Pipe, and Shougang Group between 2011 and 2016 were relatively high and stable, especially the grant rate of Anshan Steel and China Baowu, staying above 50%. Notably, the grant rates of Nanjing Iron and Steel (NISCO), Shandong Iron and Steel (SDIS), Fangda Group, and Liuzhou Steel showed a downward trend in the second stage, indicating that their research and development quality management level should be improved.

The above analysis shows that enterprises can quickly expand and enter the competition in terms of the number of patent applications and coverage of topics, but can further improve in terms of specific R&D layout strategy and R&D quality strategy.

4.2. R&D Topic Focus Strategy

It is not sufficient to analyze the R&D strategy of iron and steel enterprises only from the perspective of the overall application volume, grant rate, and the number of patent topics owned by enterprises. Enterprises usually adopt different strategies for different topics when conducting R&D controls. Therefore, it is necessary to conduct an in-depth analysis from the level of enterprise R&D topics, to further explore their R&D strategies. Outlier analysis can be used to find points whose behavior or characteristics are inconsistent with those of other sample points. Outlier analysis from the perspective of the R&D topic and life cycle is conducive to determining the R&D direction strategy in the whole R&D process. The Grubbs test is a stable and reliable outlier test method. In this study, the p value was set at 5%, to extract the total number of applications contained in the different topics in the sample enterprises and the outlier points of the application volume of a single topic in its whole life cycle, to analyze the R&D strategy.

4.2.1. R&D Focused Field

Outliers are usually inconsistent with the behavior or characteristics of other sample points. The research and development strategies of enterprises can be analyzed by combining outliers at the enterprise and topics levels. For example, the outlier points for the total number of invention patent applications for different themes of an enterprise represent a higher number of invention applications for these themes compared with the other invention patents of the enterprise. These themes are usually the aspects to which the enterprise pays more attention and are also the focus of their research and development.

In this study, outliers were extracted for analysis from the perspective of the total number of invention patent applications, the total number of authorizations, and the authorization rate in different enterprise topics; the corresponding meanings of topics were extracted by matching using a topic–word matrix. The results are shown in Tables 2 and 3. The outliers in Tables 2 and 3 are all upper outliers. These topics were larger on the patent application scale than other topics, and could be regarded as the main research and development field of the enterprise.

Table 2. Topic numbers and the corresponding number of invention patent applications.

No.	Anyang Steel		Anshan Steel		Baotou Steel		Jianlong Group		Liuzhou Steel		HBIS Group		Hunan Steel		Shagang Group		Jingye Group		JISCO	
	(a)	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**
1	61	108	14	893	11	190	12	142	41	63	6	925	61	344	48	210	53	36	85	317
2	19	65	198	611	73	131	63	67	42	34	17	323	22	137	53	129			90	224
3	50	62	125	378	17	94	53	48	11	27	27	264	23	56	54	75			64	175
4	4	53	73	347	78	94	55	38	13	27	38	164	52	48	28	65			26	169
5	79	48	181	324	49	92	8	26	77	24	8	122	16	46	40	59			59	166
6	84	43	183	310	19	78	36	26	59	22	7	100	1	44	46	57			55	117
7	38	36	34	281	44	75	71	26	52	19	67	92	7	44					40	101
8	85	36	148	257	33	68	13	25	5	17	28	82							33	100
9	39	31	191	238	20	66	57	22			64	71							96	79
10	24	29	70	215	24	63	1	21			4	64							67	72
11	52	28	79	205							72	62							20	71
12	27	27	140	190							98	57							93	66
13	29	25									110	55							47	62
14	16	23									9	52							66	58
15	80	21																	46	49
16	58	19																		
17	87	18																		
18	46	16																		

Note: (a) refers to the topic number of the outliers; (b) refers to the number of invention patent applications within the subject (Appsum).

In terms of the number of invention patent applications, Shougang Group, Anshan Steel, Hebei Iron and Steel (HBIS), and Anyang Steel had widely ranging main fields, with 26, 12, 14, and 18 focused fields, respectively. However, the R&D scale of Anyang Steel's single focused field was far smaller than that of the top three enterprises, and the highest number of invention patent applications was 108 items. Shougang Group, Anshan Steel, and Hebei Iron and Steel had 10, 12, and 3 topics with R&D scales greater than 190 items, respectively.

Table 3. Topic numbers and the corresponding number of invention patent applications (continued.).

No.	Fangda Group		NISCO		TsingShan		Rizhao Steel		SDIS		Shougang Group		Xinxing Pipe		China Baowu		Zenith Steel		Citic Pacific Steel	
	(a)	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**	**(a)**	**(b)**
1	44	59	7	364	27	33	19	44	31	519	166	617	63	205	21	546	43	100	5	295
2	36	38	41	167	71	29	44	39	119	366	181	424	14	130	71	176	61	38	20	62
3	4	33	38	115	1	24	4	31	125	280	129	400	26	117	25	150	9	17	7	39
4			1	94	80	24	24	22	89	212	62	387	138	102	59	140	50	17	82	36
5			36	93	30	23	18	11	17	127	74	284	83	79	93	136	31	15	25	26
6			51	86	46	22	41	11	134	118	73	275	7	78	66	121			43	24
7			74	76	49	19			83	115	52	230	32	78	17	116			50	24
8			35	65	15	14			78	114	31	218	99	65					27	20
9			57	61	18	14			6	105	20	215							42	20
10			66	52	13	11			84	103	187	190							6	16
11			72	43					66	102	105	188							80	15
12			17	40					45	97	21	183							11	13
13									5	90	55	179								
14									79	78	6	154								
15									51	75	104	145								
16									126	68	202	135								
17											179	133								
18											208	131								
19											188	121								
20											97	120								
21											33	102								
22											144	99								
23											143	98								
24											7	97								
25											191	93								
26											149	89								

Note: (a) refers to the topic number of the outliers; (b) refers to the number of invention patent applications within the subject (Appsum).

Analyzing the topic content, we found that the research and development of Shougang Group mainly focused on “hot rolling”, “cold rolling”, “finishing rolling”, “desulfurization, dephosphorization, decarbonization”, “energy recovery”, “intelligence”, “rolling control method”, “control circuit”, “model optimization”, “dust removal”, “monitoring”, “continuous casting”, “reliability”, “heating system”, “blast furnace ironmaking”, “energy storage”, “heat conduction”, etc.

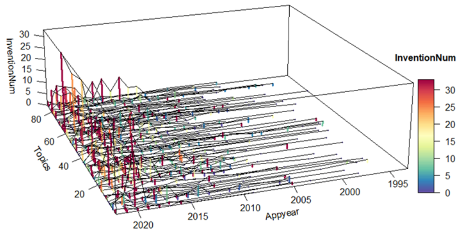
Anshan Steel’s research and development mainly focused on “toughness”, ”smelting”, “final rolling temperature”, “optimization”, “evaluation”, “raw materials”, “mixing”, “utilization”, “solution”, “recovery”, “utilization”, “thickness control method”, ”monitoring”, “magnetic separation”, “flotation”, “sewage treatment method”, “annealing”, and “heat recovery”, among other fields.

Hebei Iron and Steel’s research and development mainly concentrated on “plate”, “production method”, “steel”, “optimization”, “parameters”, “heat treatment”, “galvanized”, “rolling”, “control system”, “improve the qualified rate”, “stainless steel”, etc.

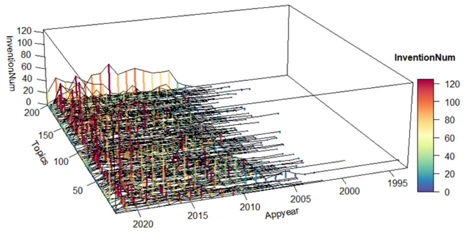
Anyang Steel’s research and development mainly concentrated on the “silicon steel”, “technology”, “production” and “additive”, “catalyst”, “tapping”, “quality”, “purification”, “efficiency”, “monitor”, “graphitization”, “performance”, “improve”, “furnace”, “process” “mining”, “construction”, “rectification”, etc.

4.2.2. Time Trends in the Focused Fields

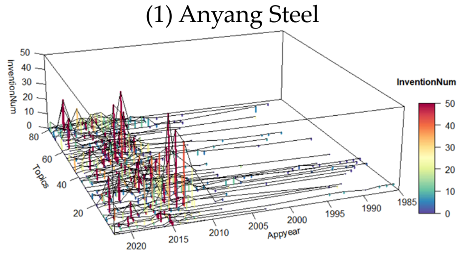
Three-dimensional graphs of the number of invention patent applications for each topic in the different years are shown in Figure 6. The three axes are the year of invention patent applications (Appyear), the number of topics (Topics), and the number of invention patent applications (InventionNum).



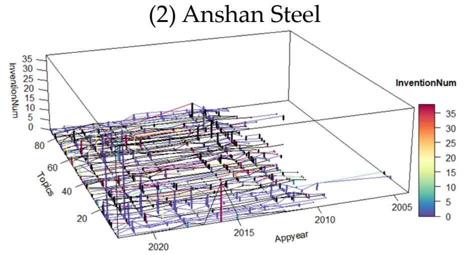
(1) Anyang Steel



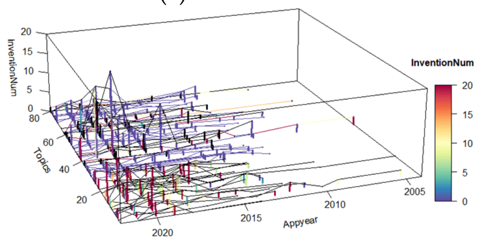
(2) Anshan Steel



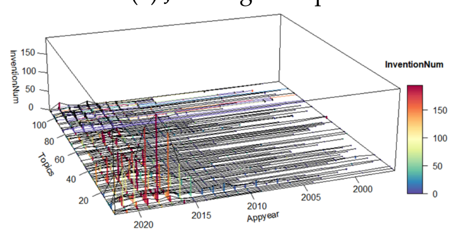
(3) Baotou Steel



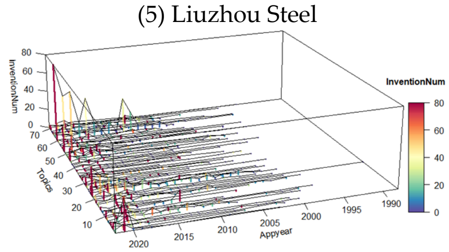
(4) Jianlong Group



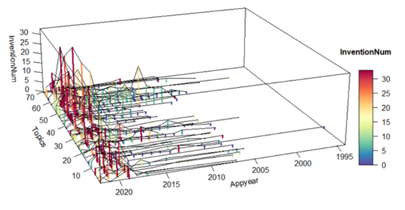
(5) Liuzhou Steel



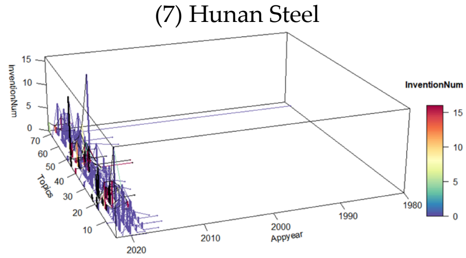
(6) HBIS Group



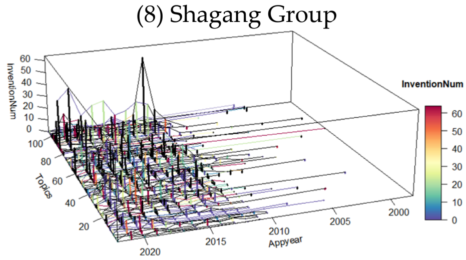
(7) Hunan Steel



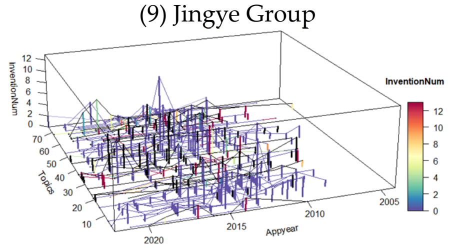
(8) Shagang Group



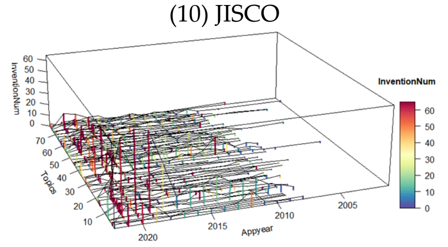
(9) Jingye Group



(10) JISCO



(11) Fangda Group



(12) NISCO

Figure 6. *Cont.*

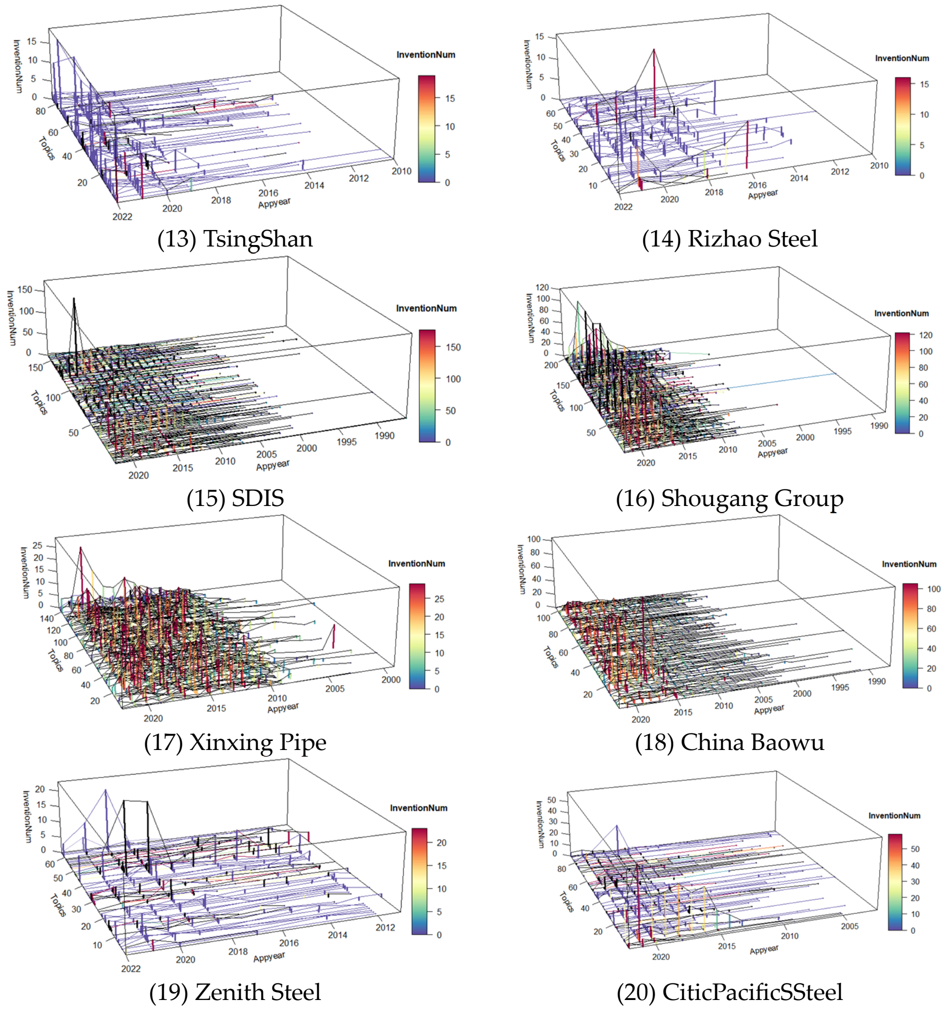


Figure 6. Time trend of the invention patent application volume of different topics.

The overall time trend shows that, before the financial crisis in 2008, the number of invention patent applications of most enterprises was small, which means that the steel enterprises adopted the strategy of the strategic contraction of R&D investment in the face of the crisis. After 2010, the number of invention patent applications for the various themes began to increase. In 2015, the number of invention patent applications began to peak for most enterprises.

The peak of invention patent applications of Anshan Steel, Shougang Group, Xinxing Pipe, and China Baowu was more intensive. With the passage of time, the patent application volume of the different R&D themes showed a continuous increase. This indicates that these enterprises adopted expansion strategies in R&D investment in a number of focused fields. Other enterprises had obvious peaks in some individual themes, which shows that they have adopted strategic research and development in key individual fields, such as China Baotou, Hebei Iron and Steel, Nanjing Iron and Steel (NISCO), etc.

4.3. R&D Quality Control Strategy

The Chinese government had provided incentive policies and corresponding subsidies for patent applications and authorizations, which were fully cancelled at the end of June 2021. Some scholars believed that this would lead to enterprise's ignoring patent quality; they apply for patents in order to earn patent subsidies or stay in line with certain preferential policies. However, the maintenance of patent rights requires a certain maintenance cost, and the duration of patents reflects the quality or value of the patents, which is an effective evaluation method. Therefore, it was necessary to further investigate R&D strategies from the perspective of the maintenance of invention patents.

4.3.1. Overall Analysis of Invention Patent Lifetime

The duration of the granted invention patents held by iron and steel enterprises was calculated, and a KM survival curve was drawn, as shown in Figure 7. The horizontal axis in Figure 7 shows the number of days of survival, and the vertical axis shows the survival rate. Overall, different enterprises adopted different strategies regarding the maintenance time of their invention patents, which can be roughly divided into three groups.

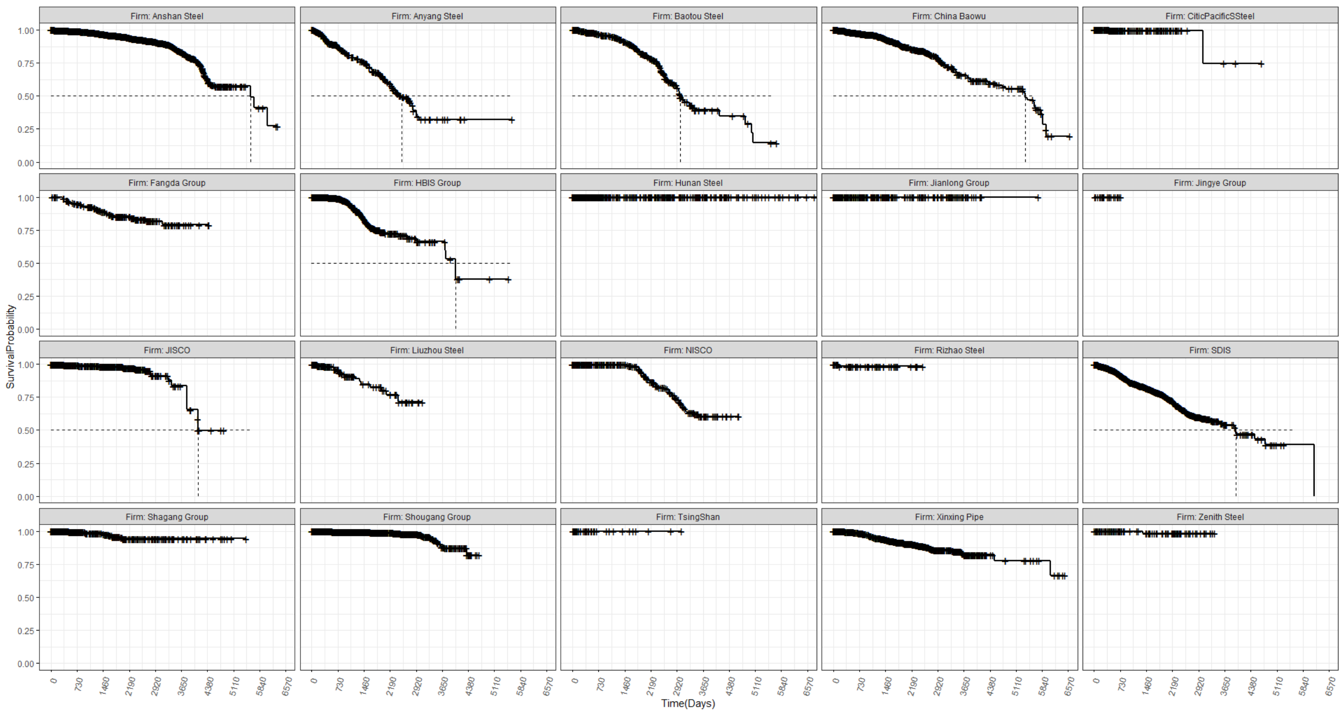


Figure 7. Overall survival rate of the invention patents.

The expiry rate of the granted invention patents held by the first group of enterprises was low. For example, the KM curves of Beijing Jianlong Heavy Industry Co., LTD. (Jianlong Group), Hunan Steel Group (Hunan Steel), Jiangsu Shagang Group (Shagang Group), Jingye Group, TsingShan Holding Group (TsingShan), Rizhao Steel Holding Group (Rizhao Steel), and Zenith Steel Group Company Limited (Zenith Steel) were almost horizontal, indicating the low patent expiry rate of these companies.

By observing the patent survival days of these seven enterprises, it can be seen that the KM lines of Beijing Jianlong Heavy Industry, Hunan Steel, and Jiangsu Shagang Group reached 5735 days, 7877 days, and 5476 days, respectively. Hunan Steel Group had the longest maintenance time. Comparatively, the KM curves of Jingye Group, TsingShan Holdings Group, Rizhao Steel, and Zenith Steel were shorter. The longest durations of their invention patents were 749 days, 3047 days, 2508 days, and 3376 days, respectively. In addition, the R&D histories of these four companies were relatively short, no more than 12 years. Jingye Group began to apply for invention patents in 2018. TsingShan Holding Group began to apply for invention patents in 2012, but most applications were after 2018. Rizhao Steel began to apply for invention patents in 2013, but most applications were after 2016. Zenith Steel began to apply for invention patents in 2011.

The second group held more than 50% of the authorized invention patents that had not expired. The KM curves of the Guangxi Liuzhou Steel Group (Liuzhou Steel), Fangda Group, Nanjing Iron and Steel (NISCO), Shougang Group, Xinxing Ductile Iron Pipe Co., Ltd. (Xinxing Pipe), and Citic Pacific Special Steel Group Co., Ltd. (CiticPacificSSteel) exhibited no intersections with the median survival time line, indicating that more than 50% of the patents authorized by these enterprises have not expired. Among them, the KM lines of Xinxing Pipe and Shougang Group were longer, indicating that their patents had a longer life, the longest were 6477 days and 4692 days, respectively. These two companies adopted the strategy of long-term maintenance.

In the third group, most of the authorized invention patents held by enterprises were invalid but generally maintained for a long time. The KM curves of Anyang Steel, Anshan Steel, Baotou Steel, Hebei Iron and Steel (HBIS), Jiuquan Iron Steel Group (JISCO), Shandong Iron and Steel Group Co., Ltd. (SDIS), and China Baowu exhibited intersections with the median survival time line. Starting from the median survival time line, the survival times of China Baowu and Anshan Steel were longer, with the longest survival times being up to 6617 days and 6344 days, respectively. In addition, compared with Anshan Steel, the end of the KM curve for China Baowu was denser, indicating that China Baowu held more high-quality invention patents. The longest survival times of China Baowu, Shandong Iron and Steel, Hebei Iron and Steel, Anyang Steel, and Jiuquan Iron Steel Group (JISCO) were 5714 days, 6158 days, 5511 days, 5602 days, and 4839 days, respectively.

4.3.2. Comparative Analysis of the Lifetime of Expired and Unexpired Inventions

It was difficult to accurately determine the control situation of the lifetime of expired and unexpired invention patents from the KM curve of all invention patents. Therefore, the invention patents held by each enterprise were further divided into groups according to whether they had become invalid or not. The KM curves of the expired invention patents and the proportion of the unexpired invention patents in different time periods were drawn, as shown in Figure 8. The horizontal axis represents the survival time in the number of days, and the vertical axis represents the survival rate of the expired invention patent and the survival distribution ratio of the unexpired invention patent.

The median survival time of Shougang Group was the longest, reaching 2190 days, followed by Anshan Steel, China Baowu, and Baotou Steel. The enterprises can be divided into four groups according to the relationship between the duration proportion curve of unexpired invention patents (referred to as the unexpired curve) and the life curve of expired invention patents (referred to as the expired curve).

The first group of firms did not have expired invention patents, so there was only one curve, including Jianlong Group, Hunan Steel, Jingye Group, and TsingShan. Among these four enterprises, Jianlong Group and Hunan Steel's invention patent survival periods were longer. The two curves of the second group of enterprises were close to each other, indicating that these enterprises had implemented a balanced R&D quality strategy. Regarding Anyang Steel and Baotou Steel, for example, the survival times of the unexpired invention patents were longer than those of the expired invention patents, which indicates that these two enterprises had implemented an achievement maintenance strategy for some patents.

In the third group, the survival curve of the unexpired invention patents was higher than the survival curve of the expired invention patents, and the survival time corresponding to 50% of the unexpired invention patents was longer than the median survival time of the expired invention patents, which proves that these enterprises had implemented a corresponding extension strategy in terms of the maintenance of R&D achievements, including Fangda Group, Rizhao Steel, Shandong Iron and Steel, and Xinxing Pipe.

In the fourth group, the survival curve of the unexpired invention patents was lower than the survival curve of the expired invention patents; these enterprises need to appropriately adopt the strategy of prolonging the life of patents, including Anshan Steel, Liuzhou Steel, Hebei Iron and Steel, Shagang Group, Jiuquan Iron Steel Group (JISCO), Nanjing Iron and Steel (NISCO), Shougang Group, China Baowu, Zenith Steel, and Citic Pacific Special Steel Group.

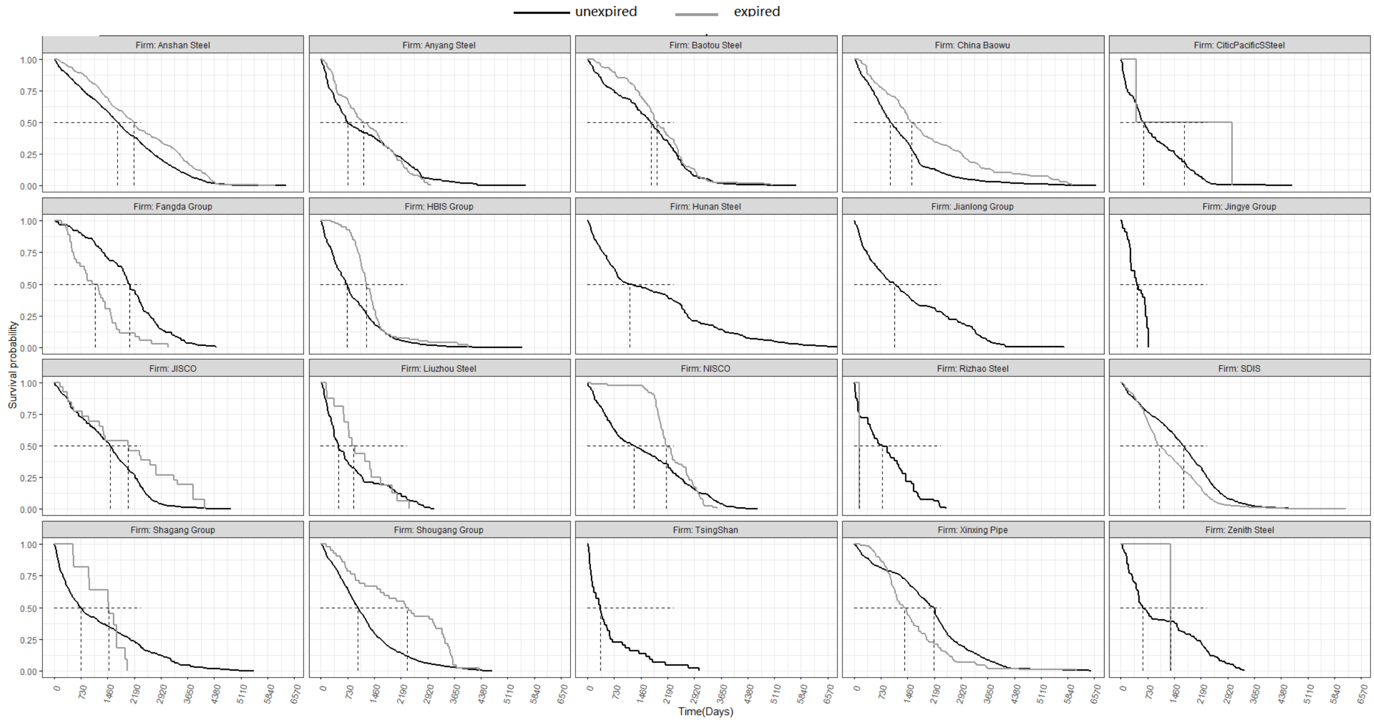


Figure 8. Lifetime of expired and unexpired invention patents. Note: The dark line represents the unexpired invention patents, and the light line represents the expired invention patents. In the calculation of the KM survival curve, deleted data were removed from the denominator each time. If all data were deleted data, then the plotted survival curve was a horizontal line with a survival rate of 1. When processing unexpired data as deleted data, their distribution has difficulty reflecting the data and misunderstandings can easily occur. Therefore, the unexpired patents were also treated as expired patents, i.e., all the current unexpired patents were assumed to have immediately expired, so as to view their distribution for comparative analysis.

4.3.3. The Lifetime of Each Topic of Invention Patent

Section 4.3.2 shows that some iron and steel enterprises adopted the strategy of extending the duration of invention patents, from the perspective of the enterprise as a whole. The following is an in-depth study of their R&D achievement maintenance strategies at the R&D topic level. KM curves of all topics held by the iron and steel enterprises were drawn and log-rank tests were conducted, as shown in Figure 9. The horizontal axis represents the number of days of survival, and the vertical axis represents the survival rate. Except for Jianlong Group, Hunan Steel, Jingye Group, TsingShan Holding Group, Zenith Steel, and Citic Pacific Special Steel Group, the *p*-values of other enterprises were less than 5%, indicating that they had implemented different duration strategies for different themes.

In order to further explore which R&D topics had life-extension strategies, this study first calculated the median life-span of the expired and unexpired invention patents, focusing on the different topics of iron and steel enterprises, and then extracted outliers for analysis, as shown in Tables 4 and 5. Xinxing Pipe No. 71 had a median survival of up to 6080 days. Five enterprises, HBIS, Shagang Group, Shandong Iron and Steel (SDIS), Shougang Group, and China Baowu, exhibited a median survival of more than 4000 days. This shows that these steel enterprises adopted a life extension strategy.

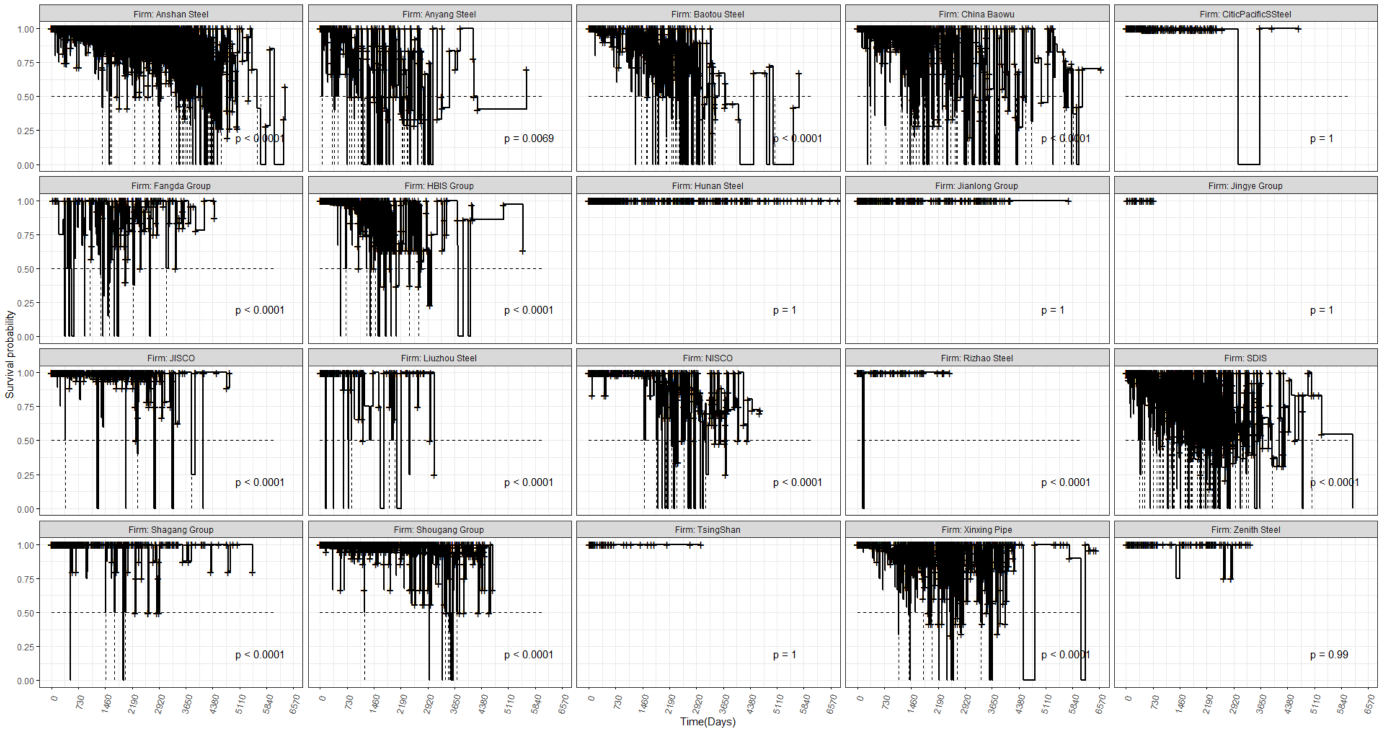


Figure 9. KM curves of different themes over the years.

Table 4. Outlier of the median duration of invention patents by topic.

Type	No.	Anyang Steel		HBIS Group		Shagang Group		Fangda Group		TsingShan	
		a	b	a	b	a	b	a	b	a	b
Unexpired patents	1	40	3810	86	3551	17	4853			4	2123
	2			33	3432	5	3645			59	1704
	3					60	3435			49	1230
	4									10	1148
Expired patents	1			98	4021			38	3118		
	2			42	3760						
	3										

Note: (a) refers to the number of topics; (b) refers to the time (days) of the outlier of the invention patent median duration within the topic. Enterprises with no outlier detected are not listed.

Table 5. Outlier of the median duration of invention patents by topic (continued).

Type	No.	Rizhao Steel		SDIS		Shougang Group		Xinxing Pipe		China Baowu	
		a	b	a	b	a	b	a	b	a	b
Unexpired patents	1	20	2354			75	4118			47	4531
	2					178	3043				
Expired patents	1			37	5042			71	6080	28	5427
	2			64	4791			5	3582	93	5076
	3			127	4497						

Note: (a) refers to the number of topics; (b) refers to the time (days) of the outlier of the invention patent median duration within the topic. Enterprises with no outlier detected are not listed.

5. Conclusions

This study proposed an enterprise R&D strategy analysis framework, based on a combination of semantic topic analysis for patents and outlier behavior. The framework first extracted semantic topics for invention patents held by enterprises using the LDA model and calculated the corresponding perplexity value, to determine the optimal number of topics. Then, combined with the Grubbs outlier test, the number of invention patent applications, the number of invention patents granted, the grant rate, and a KM survival curve were calculated. On this basis, from the perspective of patents and patent topics, the R&D layout, focus, and quality strategy, as well as the main fields and the follow-up patent maintenance strategies, were analyzed. Through empirical analysis of the patent data of 20 large iron and steel enterprises from 1985 to September 2022, the validity and feasibility of the R&D strategy analysis framework were verified; the following conclusions were drawn:

First, in terms of the R&D direction and layout strategy, Chinese iron and steel enterprises can quickly implement cutting-edge technologies, focus on their own main field, carry out R&D investment, and maintain a stable R&D investment strategy when the external environment changes. Second, in terms of the R&D focus strategy, most enterprises have a focus on their main field and performed strategic management. Third, in terms of R&D quality strategy and R&D achievement maintenance strategy, most enterprises focused on strategic extension of the life of some invention patents within a theme, but some enterprises still had a gap and need to extend the life of unexpired invention patents.

The results of this paper may have some beneficial applications in enterprise R&D strategy and government support policy. While paying attention to the market as market readers, Chinese enterprises, especially start-ups, should focus more on their own main R&D fields, to carry out in-depth technological innovations, i.e., adopting the strategies of technology drivers by paying more attention to breakthrough innovations, in addition to incremental change [26]. In the case of setbacks or external influences, they should improve the quality of their own research and development or adopt prudent research and development investment strategies, to help them overcome difficulties. In addition, enterprises should further strengthen the research and development of high-quality and long-lifetime technologies. Enterprises should focus their R&D on sintering processes, because among the five main processes in iron and steel manufacturing (sintering, coking, ironmaking, steelmaking, and steel rolling [32]), sintering is the highest emitting process for sulfur dioxide, nitrogen oxide, and particulate matter [33]. In addition, iron and steel enterprises should emphasize the R&D of green technologies, including energy-saving technologies (e.g., electric arc furnace (EAF) with scrap) [34,35]; blast furnace–basic oxygen furnace technology and converter negative energy steelmaking technology [36]; carbon capture and storage (CCS) and hydrogen-based direct reduction (DR) technology [37,38]; potentially transformative technologies [39]; technologies for generating electricity using sensible coke heating and material substitution technologies for blast furnace slag, instead of cement doping to produce concrete [40]; and technologies for steel slag mineralization and carbon fixation in coordination with solid waste disposal [41].

In terms of supporting and encouraging policies for enterprise innovation, the Chinese government should consider the overall grant rate of enterprises and the maintenance of subsequent R&D achievements, and precisely support the themes with a high grant rate or long-term R&D achievements, so as to constantly promote enterprises to innovate in cutting-edge technologies. In addition, because innovation can be spurred by environmental regulation in the short term [42], the Chinese government could formulate and optimize environmental regulation policies to promote the R&D of green technologies.

This study also has some limitations. First, we did not explore the technical value of any specific R&D fields. We could investigate this further in future studies. Second, the influential factors on iron and steel enterprises' R&D strategies were not analyzed; these would be interesting to explore in future studies.

Author Contributions: Conceptualization, H.W. and M.L.; Data curation, Z.S.; Formal analysis, H.W. and M.L.; Funding acquisition, H.W., M.L. and Z.W.; Methodology, H.W. and M.L.; Visualization, M.L. and Z.S.; Writing—original draft, H.W. and M.L.; Writing—review and editing, H.W. and Z.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (71903013, 72101028, 72274012, and 72073009), the Fundamental Research Funds for the Central Universities (FRF-BR-19-004B, FRF-BR-20-03A), the Fundamental Research Funds for Beijing University of Civil Engineering and Architecture (X20042).

Data Availability Statement: Data are available upon request.

Acknowledgments: The authors would also like to thank the anonymous reviewers, whose comments and suggestions helped us to improve the paper. We would like to acknowledge the experts who provided suggestions.

Conflicts of Interest: The authors declare that they have no conflict of interest.

References

1. Lin, B.; Wu, R. Designing energy policy based on dynamic change in energy and carbon dioxide emission performance of China's iron and steel industry. *J. Clean. Prod.* **2020**, *256*, 120412. [CrossRef]
2. Li, W.; Zhang, S.; Lu, C. Research on the driving factors and carbon emission reduction pathways of China's iron and steel industry under the vision of carbon neutrality. *J. Clean. Prod.* **2022**, *357*, 131990. [CrossRef]
3. Yu, X.; Tan, C. China's pathway to carbon neutrality for the iron and steel industry. *Glob. Environ. Chang.* **2022**, *76*, 102574. [CrossRef]
4. Zhu, L.; He, F. A Multi-stage Malmquist-Luenberger Index to Measure Environmental Productivity in China's Iron and Steel Industry. *Appl. Math. Model.* **2022**, *103*, 162–175. [CrossRef]
5. Ren, L.; Zhou, S.; Peng, T.; Ou, X. A review of CO_2 emissions reduction technologies and low-carbon development in the iron and steel industry focusing on China. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110846. [CrossRef]
6. Weeds, H. Strategic delay in a real options model of R&D competition. *Rev. Econ. Stud.* **2002**, *69*, 729–747.
7. Claudio, C.C.; Cristina, B.S.; Teresa, G.M. R&D strategies and firm innovative performance: A panel data analysis. *Int. J. Innov. Manag.* **2010**, *14*, 1013–1045.
8. Gunday, G.; Ulusoy, G.; Kilic, K.; Alpkan, L. Effects of innovation types on firm performance. *Int. J. Prod. Econ.* **2011**, *133*, 662–676. [CrossRef]
9. Schmiedeberg, C. Complementarities of innovation activities: An empirical analysis of the German manufacturing sector. *Res. Policy* **2008**, *37*, 1492–1503. [CrossRef]
10. Santamaría, L.; Nieto, M.J.; Barge-Gil, A. Beyond formal R&D: Taking advantage of other sources of innovation in low- and medium-technology industries. *Res. Policy* **2009**, *38*, 507–517.
11. Pérez-Luño, A.; Valle-Cabrera, R. How does the combination of R&D and types of knowledge matter for patent propensity? *J. Eng. Technol. Manag.* **2011**, *28*, 33–48.
12. Chen, Y.; Yuan, Y. The innovation strategy of firms: Empirical evidence from the Chinese high-tech industry. *J. Technol. Manag. China* **2007**, *2*, 145–153. [CrossRef]
13. Tsai, K.; Wang, J. External technology sourcing and innovation performance in LMT sectors: An analysis based on the Taiwanese Technological Innovation Survey. *Res. Policy* **2009**, *38*, 518–526. [CrossRef]
14. Cassiman, B.; Veugelers, R. In Search of Complementarity in Innovation Strategy: Internal R&D and External Knowledge Acquisition. *Manag. Sci.* **2006**, *52*, 68–82.
15. Goedhuys, M.; Veugelers, R. Innovation strategies, process and product innovations and growth: Firm-level evidence from Brazil. *Struct. Chang. Econ. Dyn.* **2012**, *23*, 516–529. [CrossRef]
16. Love, J.H.; Roper, S.; Vahter, P. Dynamic complementarities in innovation strategies. *Res. Policy* **2014**, *43*, 1774–1784. [CrossRef]
17. Chen, Y.; Vanhaverbeke, W.; Du, J. The interaction between internal R&D and different types of external knowledge sourcing: An empirical study of Chinese innovative firms. *R&D Manag.* **2016**, *46*, 1006–1023.
18. Hagedoorn, J.; Wang, N. Is there complementarity or substitutability between internal and external R&D strategies? *Res. Policy* **2012**, *41*, 1072–1083.
19. Wadho, W.; Chaudhry, A. Innovation strategies and productivity growth in developing countries: Firm-level evidence from Pakistani manufacturers. *J. Asian Econ.* **2022**, *81*, 101484. [CrossRef]
20. Teece, D.J.; Pisano, G.; Shuen, A. Chapter 6—Dynamic Capabilities and Strategic Management. In *Knowledge and Strategy*; Zack, M.H., Ed.; Butterworth-Heinemann: Boston, MA, USA, 1999; pp. 77–115.
21. Wu, Y.; Gu, F.; Ji, Y.; Guo, J.; Fan, Y. Technological capability, eco-innovation performance, and cooperative R&D strategy in new energy vehicle industry: Evidence from listed companies in China. *J. Clean. Prod.* **2020**, *261*, 121157.
22. Li, Y.; Huang, L.; Tong, Y. Cooperation with competitor or not? The strategic choice of a focal firm's green innovation strategy. *Comput. Ind. Eng.* **2021**, *157*, 107301. [CrossRef]
23. Mavroudi, E.; Kesidou, E.; Pandza, K. Effects of ambidextrous and specialized R&D strategies on firm performance: The contingent role of industry orientation. *J. Bus. Res.* **2023**, *154*, 113353.
24. Robinson, D.K.R.; Huang, L.; Guo, Y.; Porter, A.L. Forecasting Innovation Pathways (FIP) for new and emerging science and technologies. *Technol. Forecast. Soc. Chang.* **2013**, *80*, 267–285. [CrossRef]

25. Babkin, A.V.; Lipatnikov, V.S.; Muraveva, S.V. Assessing the Impact of Innovation Strategies and R&D Costs on the Performance of IT Companies. *Procedia—Soc. Behav. Sci.* **2015**, *207*, 749–758.
26. Jaruzelski, B.; Staack, V.; Goehle, A.B. Global Innovation 1000: Proven Paths to Innovation Success. Tech & Innovation. 2014. Available online: https://www.strategy-business.com/article/00295 (accessed on 19 March 2023).
27. Blei, D.M.; Ng, A.Y.; Jordan, M.I. Latent dirichlet allocation. *J. Mach. Learn. Res.* **2003**, *3*, 993–1022.
28. Yoon, J.; Jeong, B.; Kim, M.; Lee, C. An information entropy and latent Dirichlet allocation approach to noise patent filtering. *Adv. Eng. Inform.* **2021**, *47*, 101243. [CrossRef]
29. Zhang, H.; Daim, T.; Zhang, Y.P. Integrating patent analysis into technology roadmapping: A latent dirichlet allocation based technology assessment and roadmapping in the field of Blockchain. *Technol. Forecast. Soc. Chang.* **2021**, *167*, 120729. [CrossRef]
30. Tomojiri, D.; Takaya, K.; Ise, T. Temporal trends and spatial distribution of research topics in anthropogenic marine debris study: Topic modelling using latent Dirichlet allocation. *Mar. Pollut. Bull.* **2022**, *182*, 113917. [CrossRef]
31. Ma, J.; Wang, L.; Zhang, Y.-R.; Yuan, W.; Guo, W. An integrated latent Dirichlet allocation and Word2vec method for generating the topic evolution of mental models from global to local. *Expert Syst. Appl.* **2023**, *212*, 118695. [CrossRef]
32. Wang, Y.; Wen, Z.; Cao, X.; Zheng, Z.; Xu, J. Environmental efficiency evaluation of China's iron and steel industry: A process-level data envelopment analysis. *Sci. Total Environ.* **2020**, *707*, 135903. [CrossRef]
33. Liu, J.; Wang, S.; Yi, H.; Tang, X.; Li, Z.; Yu, Q.; Zhao, S.; Gao, F.; Zhou, Y.; Wang, Y. Air pollutant emission and reduction potentials from the sintering process of the iron and steel industry in China in 2017. *Environ. Pollut.* **2022**, *307*, 119512. [CrossRef]
34. Wang, X.; Yu, B.; An, R.; Sun, F.; Xu, S. An integrated analysis of China's iron and steel industry towards carbon neutrality. *Appl. Energy* **2022**, *322*, 119453. [CrossRef]
35. Zhang, S.; Yi, B.; Guo, F.; Zhu, P. Exploring selected pathways to low and zero CO_2 emissions in China's iron and steel industry and their impacts on resources and energy. *J. Clean. Prod.* **2022**, *340*, 130813. [CrossRef]
36. Liu, X.; Peng, R.; Bai, C.; Chi, Y.; Li, H.; Guo, P. Technological roadmap towards optimal decarbonization development of China's iron and steel industry. *Sci. Total Environ.* **2022**, *850*, 157701. [CrossRef]
37. Ren, M.; Lu, P.; Liu, X.; Hossain, M.; Fang, Y.; Hanaoka, T.; O'Gallachoir, B.; Glynn, J.; Dai, H. Decarbonizing China's iron and steel industry from the supply and demand sides for carbon neutrality. *Appl. Energy* **2021**, *298*, 117209. [CrossRef]
38. Shen, J.; Zhang, Q.; Xu, L.; Tian, S.; Wang, P. Future CO_2 emission trends and radical decarbonization path of iron and steel industry in China. *J. Clean. Prod.* **2021**, *326*, 129354. [CrossRef]
39. Kim, J.; Sovacool, B.K.; Bazilian, M.; Griffiths, S.; Lee, J.; Yang, M.; Lee, J. Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Res. Soc. Sci.* **2022**, *89*, 102565. [CrossRef]
40. Xue, R.; Wang, S.; Gao, G.; Liu, D.; Long, W.; Zhang, R. Evaluation of symbiotic technology-based energy conservation and emission reduction benefits in iron and steel industry: Case study of Henan, China. *J. Clean. Prod.* **2022**, *338*, 130616. [CrossRef]
41. Yang, Y.; Xu, W.; Wang, Y.; Shen, J.; Wang, Y.; Geng, Z.; Wang, Q.; Zhu, T. Progress of CCUS technology in the iron and steel industry and the suggestion of the integrated application schemes for China. *Chem. Eng. J.* **2022**, *450*, 138438. [CrossRef]
42. Wang, X.; Zhang, T.; Nathwani, J.; Yang, F.; Shao, Q. Environmental regulation, technology innovation, and low carbon development: Revisiting the EKC Hypothesis, Porter Hypothesis, and Jevons' Paradox in China's iron & steel industry. *Technol. Forecast. Soc. Chang.* **2022**, *176*, 121471.