Impact of Gas Control Policy on the Gas Accidents in Coal Mine

Authors:

Wei Ke, Kai Wang

Date Submitted: 2021-05-25

Keywords: intervention degree, delphi method, control policy, gas accident, coal mine

Abstract:

Coal mine gas accidents pose a serious threat to the safety of coal mines in China. To prevent such accidents, the Chinese government and relevant agencies have issued a number of related control policies, though the effect of these policies on gas accidents is still lacking. In this study, the relevant data of coal mine gas accidents in China from 2003 to 2018 are sorted and analyzed. The analysis results show that the number of coal mine accidents and deaths has decreased significantly. However, gas accidents account for the highest proportion of deaths and pose the largest threat, compared with other types of accidents. Subsequently, the developmental stages of China's gas control policies are summarized; they are the independent development stage, the promotion stage and the consolidation stage. A method of calculating the intervention degree of the gas control policies is proposed. The results show that the policy intervention degree is the highest, and the number of accidents is the fastest in the stage of promotion. It is concluded that gas control policies have obvious inhibitory effects on the occurrence of gas accidents, and these policies are fundamental in preventing coal mine gas accidents.

Record Type: Published Article

Submitted To: LAPSE (Living Archive for Process Systems Engineering)

Citation (overall record, always the latest version):	LAPSE:2021.0406
Citation (this specific file, latest version):	LAPSE:2021.0406-1
Citation (this specific file, this version):	LAPSE:2021.0406-1v1

DOI of Published Version: https://doi.org/10.3390/pr8111405

processes

MDPI

Article

Impact of Gas Control Policy on the Gas Accidents in Coal Mine

Wei Ke and Kai Wang *

School of Emergency Management and Safety Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China; onlykw@163.com

* Correspondence: kaiwang@cumtb.edu.cn

Received: 8 October 2020; Accepted: 2 November 2020; Published: 4 November 2020

Abstract: Coal mine gas accidents pose a serious threat to the safety of coal mines in China. To prevent such accidents, the Chinese government and relevant agencies have issued a number of related control policies, though the effect of these policies on gas accidents is still lacking. In this study, the relevant data of coal mine gas accidents in China from 2003 to 2018 are sorted and analyzed. The analysis results show that the number of coal mine accidents and deaths has decreased significantly. However, gas accidents account for the highest proportion of deaths and pose the largest threat, compared with other types of accidents. Subsequently, the developmental stages of China's gas control policies are summarized; they are the independent development stage, the promotion stage and the consolidation stage. A method of calculating the intervention degree of the gas control policies is proposed. The results show that the policy intervention degree is the highest, and the number of accidents is the fastest in the stage of promotion. It is concluded that gas control policies have obvious inhibitory effects on the occurrence of gas accidents, and these policies are fundamental in preventing coal mine gas accidents.

Keywords: coal mine; gas accident; control policy; delphi method; intervention degree

1. Introduction

Coal plays an important role in the supply of energy worldwide for producing heat, electricity and other valuable industrial materials over the past few centuries. To date, coal still represents approximately 27.6% of the total primary energy supply in the world [1] According to statistics, in 2018, the total coal consumption in the world was 3.772 billion tons of oil equivalent. Among them, the United States used 317 million tons, and India used 452 million tons. China ranked first in all countries with 1.907 billion tons of coal consumption (BP, 2019). China is currently the world's largest consumer of coal, as well as the largest emitter of energy-related carbon dioxide (CO_2). Nearly 80% of China's annual energy-related CO_2 emissions are from the combustion of coal and coal-derived products [2,3]. With the rapid development of China's economy, China has become a major energy producer and consumer in the world. However, the discrepancy between its economic and environmental states has become increasingly prominent [4,5]. China's resource conditions, which are relatively rich coal, poor oil, less gas and uranium, lead to coal being China's main energy source, which will not change in the short term [6–8]. According to a BP report, coal accounted for 58% of China's primary energy consumption in 2018 [9], and it is an irreplaceable and stable main energy source in the short term. China's coal resource endowments and long-term high demands have led to an increase in mining intensity and a decrease in the amount of shallow resources [10]. Most mines are gradually entering a state of deep resource exploitation [11]. Deep resource exploitation in kilometer-deep wells has gradually become a new normal for resource exploitation, and the mining depth has extended at a speed of 10~25 m per year [12].

Coal mine gas accidents are mainly coal and gas outbursts and gas explosions. A gas outburst accident refers to an accident caused by a geological disaster as a result of the formation of a coal seam under the action of ground stress and the gravitational force released by the gas, which causes the weak coal seam to break through the line of resistance and instantly release a large amount of gas and coal. The main reason for this is mining caused by stress concentration, when the load exceeds the strength limit of coal and rock, resulting in shear damage [13]. If the concentration of gas in the air reaches an explosive concentration, an explosion can occur in the presence of an open flame. A gas explosion will produce a high-temperature, high-pressure shock wave and release toxic gas. With continuous increases in mining depth, the geological conditions of resources become more complex. The geostress level increases and the geotemperature rises, which makes it more difficult to exploit resources and worsens the working environment. The gas pressure in coal seams also increases. The intensity and frequency of coal mine gas accidents obviously increase with increasing depth, and the coal mine safety situation deteriorates further [14].

To achieve favorable levels of accident prevention and control, the statistics of 362 major coal mine accidents in China between 2000 and 2016 were collected and a human factor analysis and classification system for China's mines (HFACS-CM) was established [15]. Based on these statistical methods, 106 coal dust explosion accidents that occurred in China between the years of 1949 and 2007 were investigated, so as to review the overall situation and provide quantitative information on coal dust explosions [16]. Fatal gas accidents in Chinese coal mines were quantitatively analyzed using data from 2006 to 2010 [17] and a cause classification framework based on the 24Model for accident causation [18] A method to assess the risk value of unsafe behavior was presented, based on the analysis of fatal injuries in underground coal mines [19]. The frequency of major gas explosion accidents between the years 1980 and 2010 was reviewed [20] and the safety fractal analysis method was described and used to guide investigators in exploring the elements [21]. By illuminating unsafe behaviors and their distribution characteristics in a systematic fashion, the mine safety professionals was provided with valuable information to reduce the number of gas explosions [22]. In previous studies, the data statistics, data analysis and other means have been used to analyze the occurrence of various types of accidents and provide pertinent suggestions.

More and more studies have focused on the investigation of the policy influencing security. The evidence on the impact of EU policies on global food security was reviewed, focusing on several EU policy areas [23]. A one-sector integrated assessment framework was combined with a series of well-proposed energy security metrics to extensively explore the unidirectional consistency between climate policy and energy security from a national perspective [24]. The innovative concept of food security policy was described, presenting a theoretical microeconomic model of food security [25]. An analysis on institutionalization, standardization and normalization concepts was performed to clarify the management focus and objective use of institutionalization, standardization and normalization of safety production [26]. These studies have analyzed the relevant policies in various fields of safety production, but there are still some deficiencies in the research on gas control policies. In the present study, the correlations between gas accidents and relevant control policies are analyzed comprehensively. The main contents of this work are arranged as follows. The background and analysis method are introduced in Sections 2 and 3, respectively. The results of the gas accident analysis are in Section 4, and the influence of policy on gas accidents is in Section 5. The last section presents the main conclusions.

2. Background

According to the Coal Mine Accident Analysis Reports from the State Administration of Coal Mine Safety (SACMS) over the years [27–34], the number of accidents and death toll were obtained. As shown in Figure 1, the number of accidents decreased from 4143 to 224 for coal mines in China from 2003 to 2018, and the associated deaths decreased from 6434 to 333 during the same period. A number of 25,588 coal mine accidents have occurred since the year 2003, resulting in 42,439 deaths. Among these accidents, there were 1843 major accidents and 8252 deaths, accounting for 7.20% of the total accidents

and 19.44% of the total deaths, respectively; 336 tremendous accidents and 5219 deaths, accounting for 1.31% of the total accidents and 12.30% of the total deaths, respectively; and 55 extraordinarily serious accidents and 3282 deaths, accounting for 0.21% of the total accidents and 7.73% of the total number of deaths, respectively.

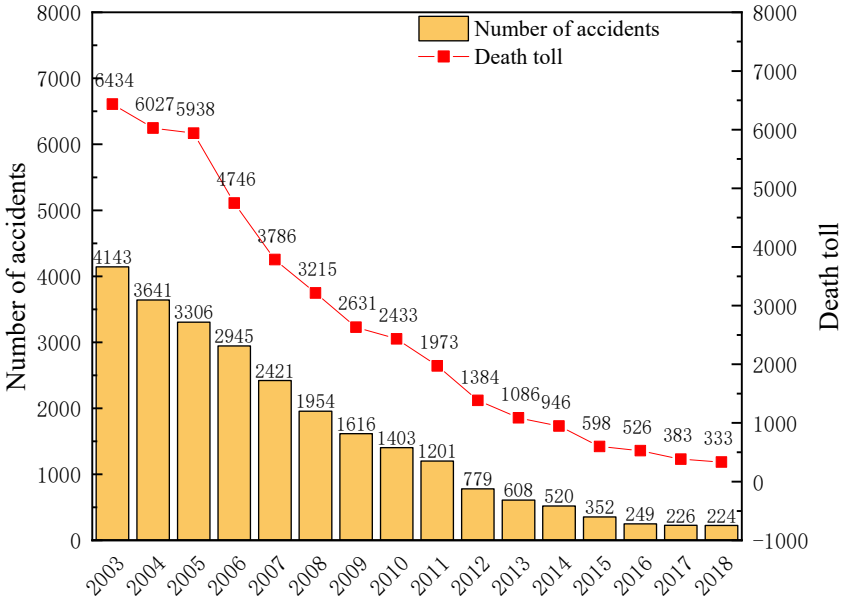

Figure 1. Changes in the number of coal mine accidents and deaths in China from 2003 to 2018.

From 2003 to 2018, the total number of coal mine accidents in China exhibited a downward trend. The descent was very surprising, which corresponded to decreases of 94.59% and 94.82%, respectively. The curve of the fatality rate also fell rapidly. As shown in Figure 2, it decreased from 3.724 in 2003 and 0.093 in 2018. There are two reasons for the rapid decline of the curve illustrated in Figure 2. On the one hand, with the improvement of the mechanization and intelligence of coal mining, more and more workers were gradually replaced by automated machinery and equipment, and the number of workers in the work place was reduced. On the other hand, relevant agencies issued a series of gas control policies, which played a key guiding role in coal mine safety production. Overall, the safety production of coal mines in China is improving.

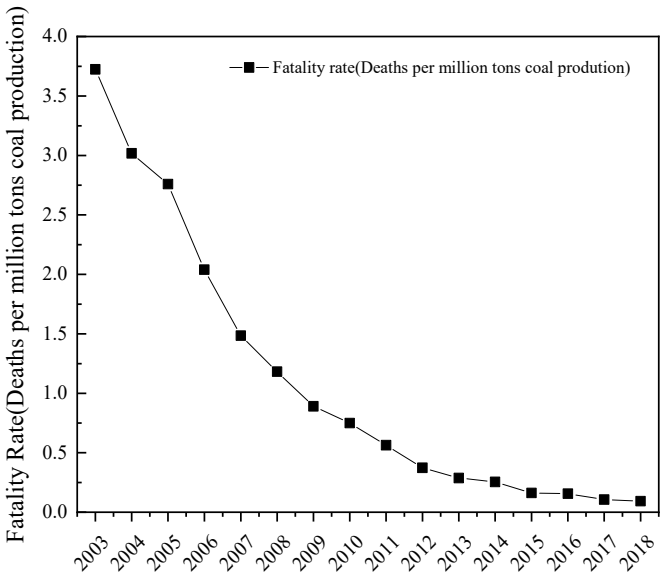

Figure 2. Changes in the fatality rates in coal mines from 2003 to 2018.

In terms of gas accidents, from 2003 to 2018, there were 2984 gas accidents in China, with 12,807 deaths (Table 1), accounting for 11.66% and 30.18% of the total number of coal mine accidents, respectively. The specific data analysis is presented in Section 4.

Table 1. Statistics of gas accidents from 2003 to 2018.

Year	Gas Accidents				Major Gas Accidents		Tremendous and Above Gas Accidents	
	Quantity	Proportion	Deaths	Proportion	Number of Accidents	Deaths	Number of Accidents	Deaths
2003	584	14.10%	2118	32.92%	173	785	33	766
2004	492	13.51%	1900	31.52%	134	596	32	867
2005	414	12.52%	2171	36.56%	115	505	41	1331
2006	327	11.10%	1319	27.79%	126	591	26	490
2007	272	11.24%	1084	28.63%	83	413	22	460
2008	182	9.31%	778	24.20%	63	290	18	352
2009	157	9.72%	755	28.70%	57	260	11	374
2010	145	10.33%	623	25.61%	57	299	11	220
2011	119	9.91%	533	27.01%	43	233	12	207
2012	72	9.24%	350	25.29%	29	144	7	159
2013	59	9.70%	348	32.04%	20	119	10	192
2014	47	9.04%	266	28.12%	18	74	10	162
2015	45	12.78%	171	28.60%	20	94	3	42
2016	26	10.44%	226	42.97%	12	54	8	161
2017	25	11.06%	103	26.89%	13	54	3	32
2018	18	8.04%	62	18.62%	8	36	1	13

3. Methodology

Many researchers have analyzed industrial accidents, based on the frequency of accidents occurring in fixed intervals, and have used various sources of accident data to study security in mining [35–38]. Accident statistics and analysis is the basis of objective management of safety work. Without the correct conclusion of accident statistics and analysis, objective management cannot be carried out. In order to reduce casualties, we should focus on reducing repetitive accidents and preventing major accidents. Statistical analysis of accidents can help us to understand the development trend of accidents, quantify the severity of accidents and excavate the root causes of accidents, which plays an important and positive role in preventing accidents. In this paper, a similar method is used to study the occurrence law of coal mine gas accidents.

To quantitatively analyze the impact of policies, many scholars use the Delphi method to rank the importance of policies and assign relevant weighted scores [39–42]. The advantage of the Delphi method is that the opinions are anonymous, so it is more likely to express unpopular opinions, all of which have the same weight, avoiding the problem of domination by important people. At the same time, experts do not have to gather in a certain place at a certain time, which is more convenient and widely representative. This paper uses this method to rank the importance of gas prevention policies, provide the corresponding weight of the degree of influence and analyze the relationships between gas accidents and relevant prevention policies.

4. Results

To analyze the occurrence law of gas accidents more comprehensively, the time of occurrence, accident grade, region, accident type, mine ownership, number of mines and their relationships with China's economic development are studied in this section.

4.1. Distribution of Accident Intervals

From 2003 to 2018, through a series of effective control measures, the number of gas accidents and deaths in China showed a decreasing trend year by year (Figure 3). From 2003 to 2018, the number of accidents decreased from 584 to 18, a decrease of 96.92%, and the number of deaths decreased from 2118 to 62, with a decrease of 97.07%. A control effect is obvious.

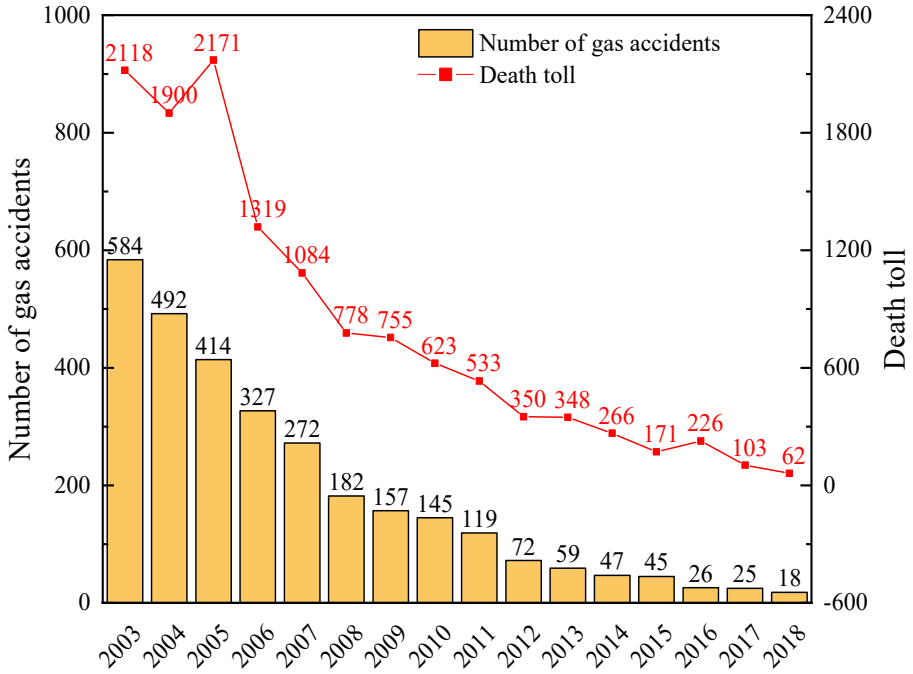

Figure 3. Changes in incidents of and deaths from coal mine gas accidents in China from 2003 to 2018.

4.2. Analysis by Grade

According to the number of casualties and direct economic losses caused by production safety accidents, accidents are generally classified into the following grades:

1. An extraordinarily serious accident refers to an accident that causes more than 30 deaths, more than 100 serious injuries (including acute industrial poisoning, the same as below) or direct economic losses of more than 100 million yuan;
2. A tremendous accident refers to an accident that causes the deaths of more than 10 people and fewer than 30 people, serious injuries of more than 50 people and fewer than 100 people or direct economic losses of more than 50 million yuan and less than 100 million yuan;
3. A major accident refers to an accident that causes the deaths of more than 3 persons and fewer than 10 persons, serious injuries of more than 10 persons and fewer than 50 persons or direct economic losses of more than 10 million yuan and less than 50 million yuan.
4. A general accident refers to an accident that causes the deaths of fewer than 3 persons, serious injuries of fewer than 10 persons or direct economic losses of less than 10 million yuan.

From 2003 to 2018, there were 971 major gas accidents that caused 4547 deaths in China, accounting for 52.69% of the total major coal mine accidents and 55.10% of the total deaths, respectively. There were

248 tremendous and above gas accidents that caused 5828 deaths, accounting for 63.42% and 68.56% of the total tremendous or more severe accidents, respectively (Figures 4 and 5). Gas accidents account for more than 50% of all major or more severe accidents in coal mines. Thus, gas accidents are considered as the first killer of coal mines.

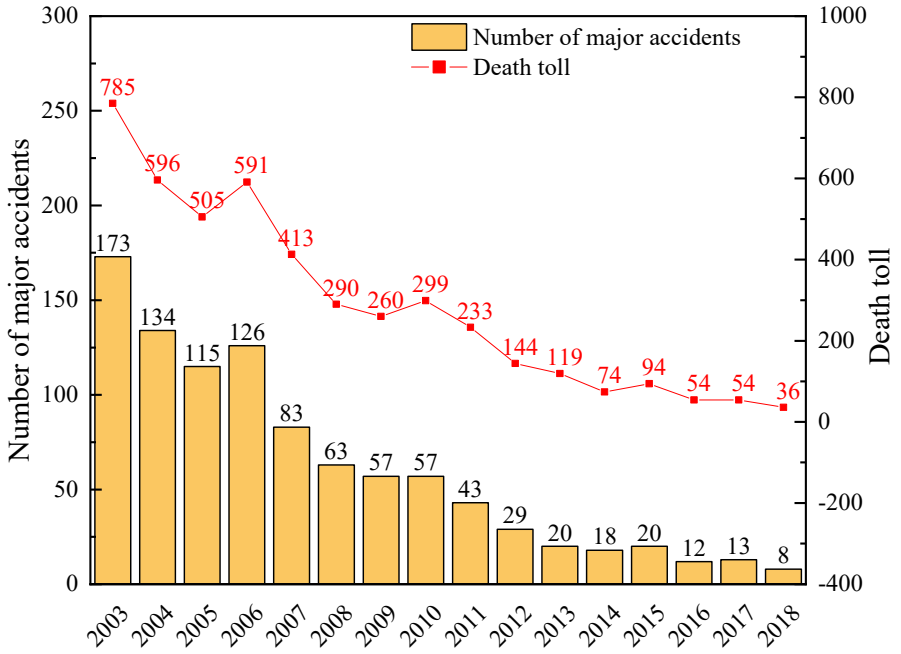

Figure 4. Changes in the number of major gas accidents and deaths.

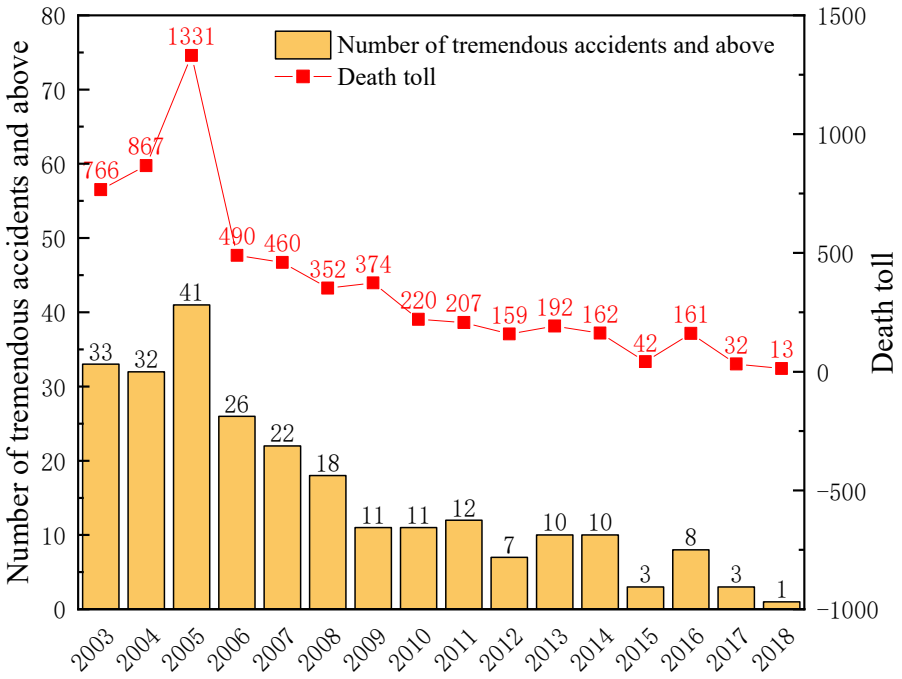

Figure 5. Changes in the number of tremendous gas accidents and deaths.

As seen from Figure 4, the number of major gas accidents and deaths decreased from 173 and 785, respectively, in 2003 to 8 and 36, respectively, in 2018, which corresponded to decreases of 95.37% and 95.41%, respectively. As seen from Figure 5, the number of tremendous and above gas accidents and deaths decreased from 33 and 766, respectively, in 2003 to 1 and 13, respectively, in 2018,

which corresponded to decreases of 96.97% and 98.30%, respectively. Thus, in the past 15 years, the occurrence of gas accidents has been significantly curbed.

4.3. Analysis by Region

From 2008 to 2013, the provinces with the most gas accidents were Hunan and Guizhou, with more than 45 cases each, followed by Yunnan and Sichuan, with 38 and 26 gas accidents, respectively, and Chongqing, Shanxi and Henan, with more than 10 gas accidents each (Figure 6).

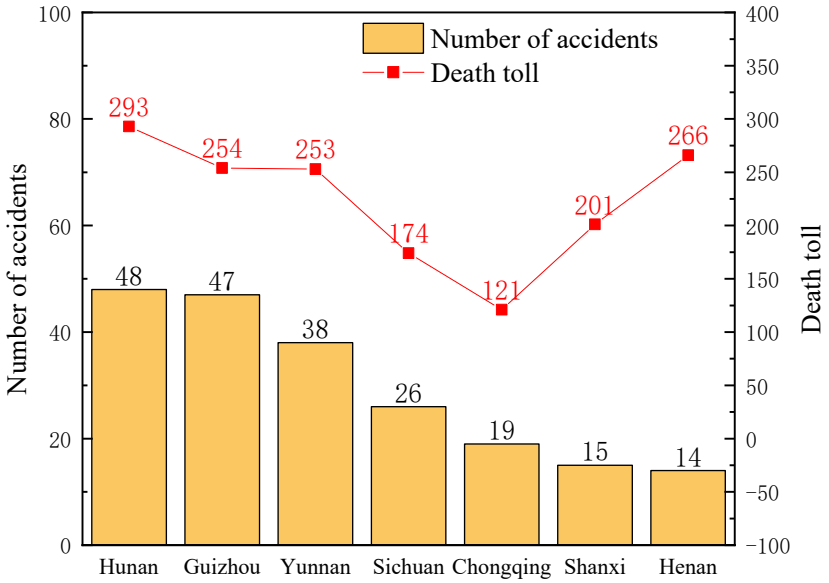

Figure 6. Statistics of gas accidents in different provinces from 2008 to 2013.

As seen from the above chart, gas accidents occurred frequently in Hunan and Guizhou. The reason for this is that the coal occurrence conditions and geological structure conditions in Hunan and Guizhou are complex, the gas content is high and the technical content of mines is low; the accidents mainly occurred in township coal mines. From 2008 to 2013, the fatality rate of accidents in the Henan province was relatively high, which was mainly due to the high frequency of major and above accidents. Eight of the accidents were extraordinarily serious gas accidents, accounting for 57.1% of all accidents, and the highest death toll in a single case was 19. The main reasons for these results were the deep mining of coal seams in the Henan province, high gas content in this area, confusion in management and illegal operations.

From 2013 to 2017, the number of gas accidents and deaths in all provinces decreased significantly (Figure 7). In terms of the number of accidents, there were more than 10 gas accidents in each of 8 provinces. Most of the accidents were in Guizhou and Hunan, which had 27 accidents each, while Chongqing had 17 accidents, Sichuan and Shanxi had 15 accidents each and Yunnan, Heilongjiang and Hubei had more than 10 accidents each. In terms of the number of deaths, only one province, Guizhou, had more than 100 deaths. There were 7 provinces with 50–100 deaths each: Chongqing, Jilin, Hunan, Heilongjiang, Sichuan, Shanxi and Yunnan. According to the statistics, the coal mine safety situation in most provinces is continuing to improve, and the number of accidents and deaths has decreased significantly.

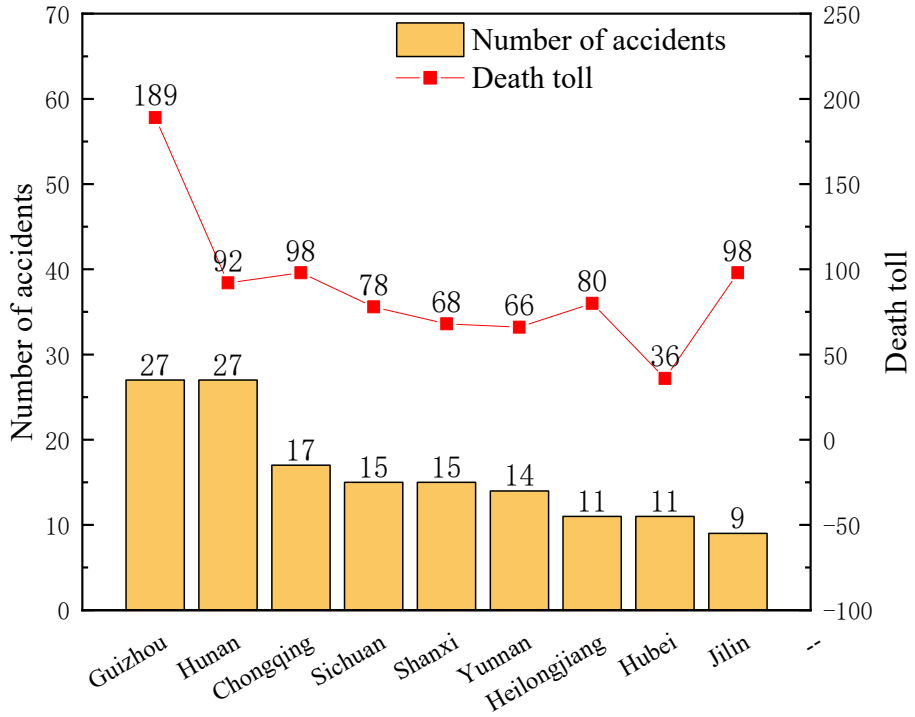

Figure 7. Statistics of gas accidents in different provinces from 2013 to 2017.

We can see that in Guizhou, Hunan, Sichuan and other areas with more complex geological structures, the possibility of gas disasters will increase. This prediction is mainly based on the fact that gas disasters, especially coal and gas outburst accidents, are usually related to the geological structure of the coalfield. A closer proximity to the geological structure belt corresponds to an increase in abnormal gas occurrences and higher levels of concentrated tectonic stress. Geological structure not only controls the formation of gas occurrence areas, but also affects gas enrichment and migration, which is also the main cause of coal and gas outbursts.

4.4. Analysis by Accident Type

Gas accidents are mainly caused by gas explosions, coal and gas outbursts and gas asphyxia. Due to limited data collection, this section only analyzes data from 2008 to 2018. From 2008 to 2018, a total of 341 major gas accidents occurred; 149 gas explosion accidents occurred with 757 deaths, accounting for 43.70% and 45.33% of the total number of major gas accidents and deaths, respectively, and 122 coal and gas outburst accidents occurred with 617 deaths, accounting for 35.78% and 36.95% of the total number of major gas accidents and deaths, respectively. There were 64 gas asphyxia and poisoning accidents and 264 deaths, accounting for 18.77% and 15.81% of the total number of major gas accidents and deaths, respectively (Figure 8).

From 2008 to 2018, 52 gas explosion accidents occurred with 1181 deaths, accounting for 55.91% and 62.29% of the total number of tremendous and more severe gas accidents, respectively, and 34 coal and gas outburst accidents occurred with 605 deaths, accounting for 35.56% and 31.91% of the total number of tremendous and more severe gas accidents, respectively. Three gas asphyxia and poisoning accidents occurred with 51 deaths, accounting for 3.23% and 2.69% of the total number of tremendous and more severe gas accidents, respectively (Figure 9).

According to the above data, of all types of disasters, gas explosion accidents were predominant; the number of occurrences was the highest with gas explosion accidents, followed by coal and gas outburst accidents. From 2008 to 2018, the frequencies of the various types of gas accidents fluctuated by year, but there was a significant overall trend showing a decline (Figures 10 and 11).

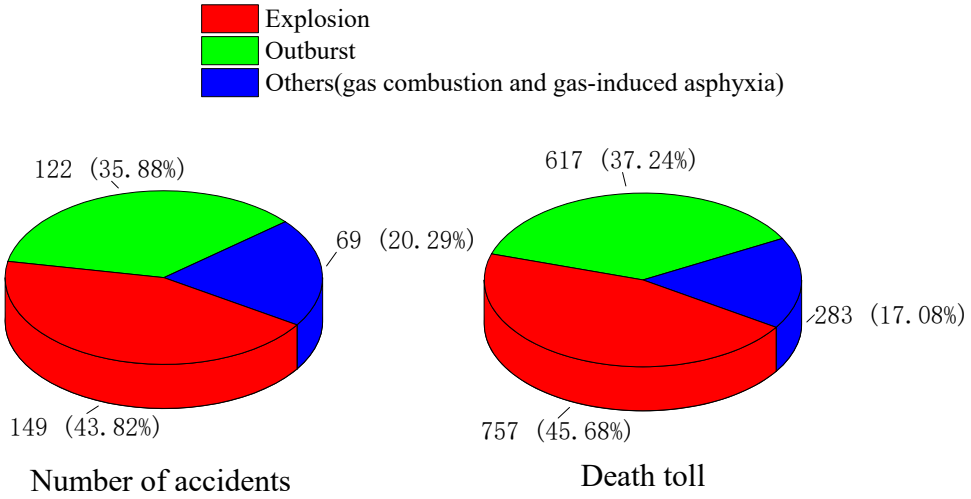

Figure 8. Proportion of various types of accidents in major gas accidents from 2008 to 2018.

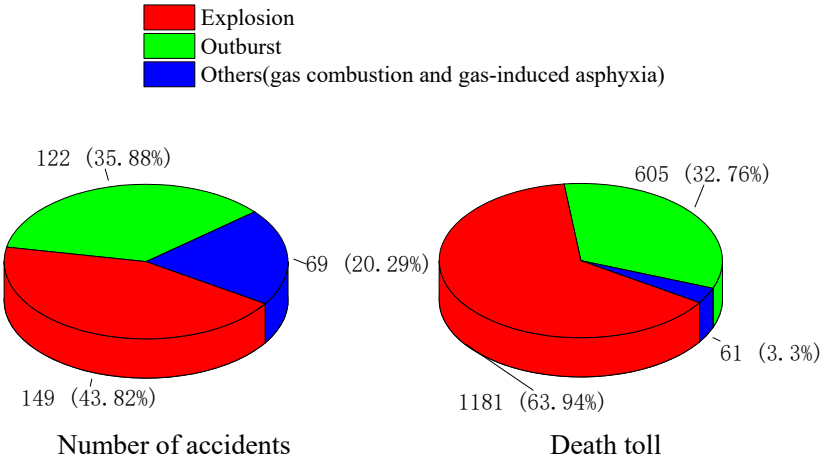

Figure 9. Proportion of various types of accidents in tremendous and above gas accidents from 2008 to 2018.

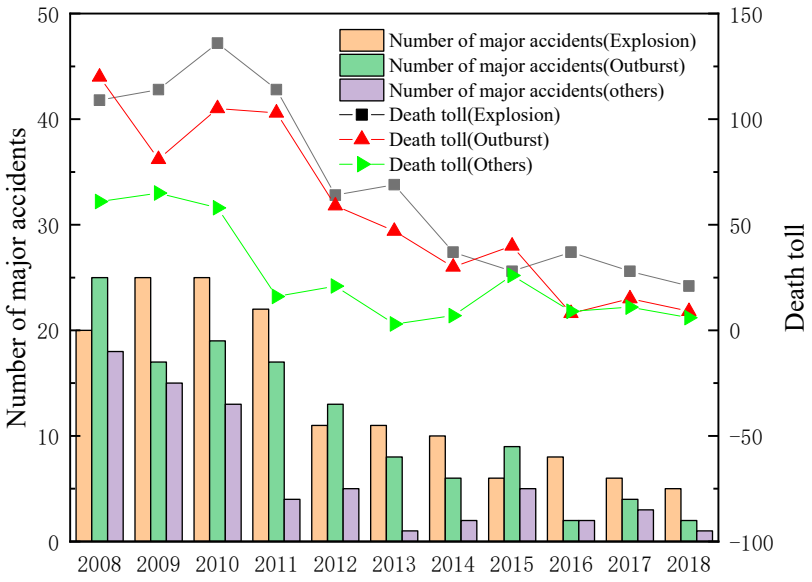

Figure 10. Variations of the different types of accidents in major gas accidents from 2008 to 2018.

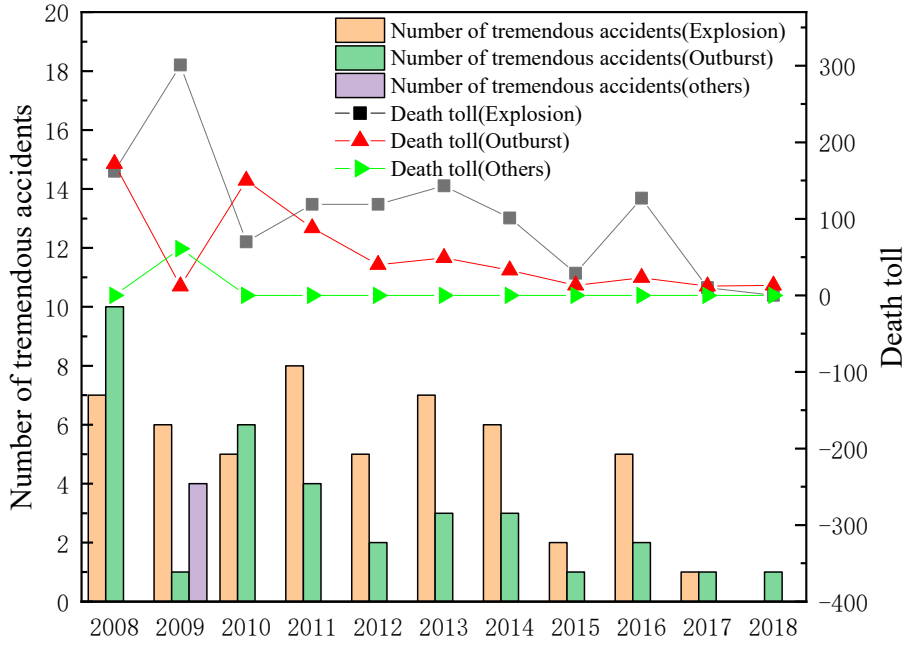

Figure 11. Variations of the different types of accidents in tremendous and more severe gas accidents from 2008 to 2018.

4.5. Analysis by Coal Mine Ownership

According to the ownership system, coal mines in China can be classified into national strategic mines (NSM), provincial national mines (PNM) and township mines (TM). Due to limited data collection, this section only analyzes data from 2013 to 2018. From 2013 to 2018, 153 major gas accidents occurred in China with 1387 deaths. The number of accidents in TM was the largest, with 107 accidents and 982 deaths, accounting for 69.3% and 70.8% of the total accidents and total deaths, respectively. In addition, there were 36 accidents and 324 deaths in NSM, accounting for 25.53% and 23.36% of the total accidents and total deaths, respectively. There were 10 accidents and 81 deaths in PNM, accounting for 6.54% and 5.84% of the total accidents and total deaths, respectively (Figure 12).

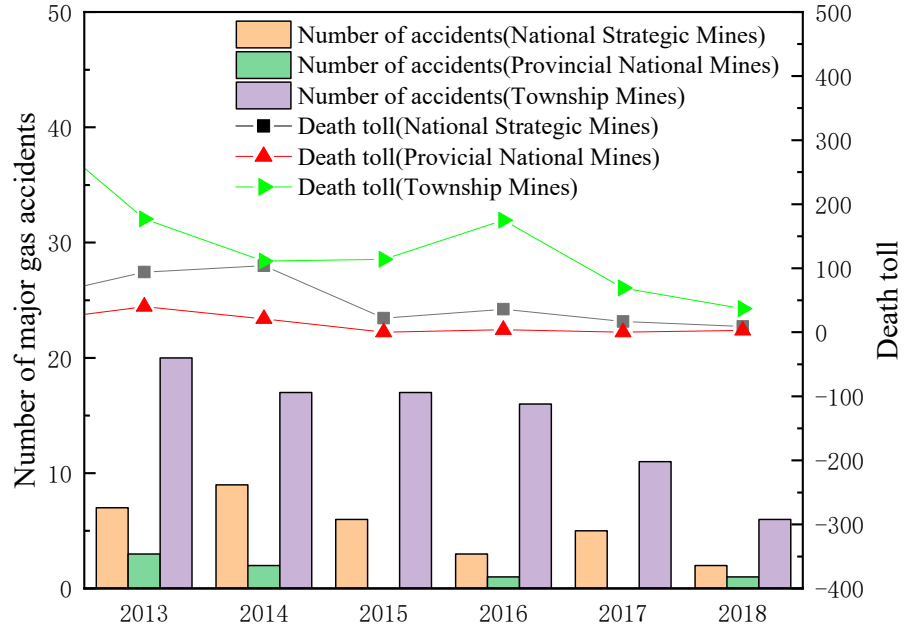

Figure 12. Changes in gas accidents in coal mines with different ownerships from 2012 to 2018.

The number of gas accidents and deaths in TM were obviously higher than those in NSM and PNM. The main reason is that with increases in coal seam mining depths, gas disasters become more serious. Compared with the national mines, which have relatively good safety technical task forces, TM are obviously weak in technology, management and equipment, which leads to a higher probability of an accident.

4.6. Analysis by Mine Quantity

Due to limited data collection, this section only analyzes data from 2012 to 2018. Figure 13 shows the changing trend of the number of coal mines and the number of coal mine gas accidents from 2012 to 2018. With continuous adjustments and optimization processes in the industrial structure of China's coal industry, efforts in eliminating the backward production capacity and resolving the excess production capacity have achieved tangible results. The merging and reorganization of enterprises and the integration of technological innovations have been carried out in an orderly manner, resulting in a gradual decline in the number of coal mines in China. Large-scale modern coal mines have gradually become the main sources of coal production. Industrial concentration has increased, backward production capacity has gradually been eliminated and the ratio of high-quality production capacity has been improved. In particular, the shutdown and elimination of a number of small coal mines that had serious disasters, a lack of safe production conditions, outdated technology and equipment, poor gas prevention and control abilities and frequent accidents played an important role in reducing coal mine accidents in China.

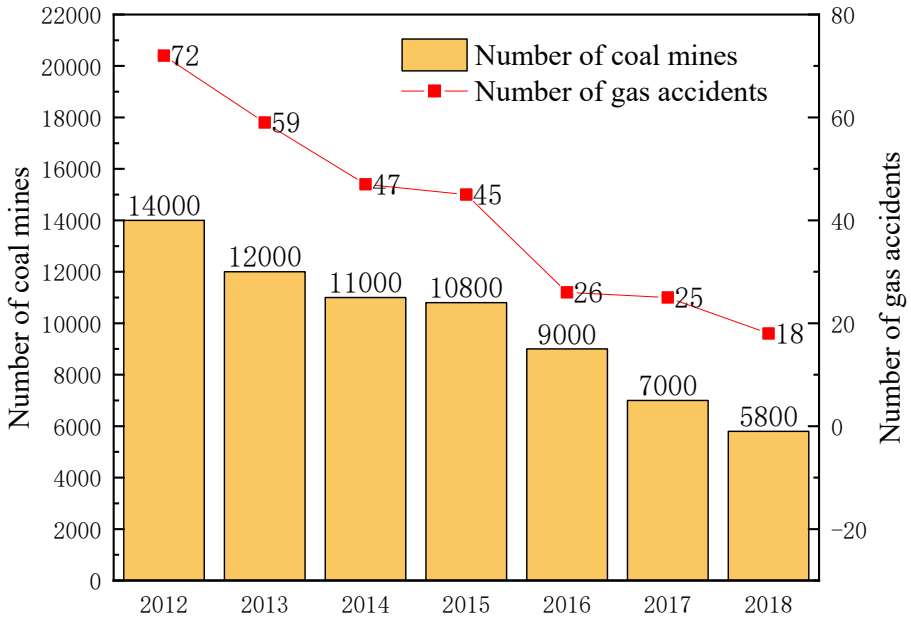

Figure 13. Changes in the number of gas accidents and coal mines.

4.7. Analysis by Economic Development

Coal, which is China's main source of energy, has always occupied a large proportion of the primary energy production and consumption structure. Coal production and consumption not only meet the needs of human life and production, but also promote the development of the coal industry. With the development of the economy and changes in industrial structure, coal production will also change. There is a close relationship between economic development and coal production, which affects the safety of coal mines.

As seen from Figure 14, with an increase in GDP, the number of coal mine gas accidents decreased year by year. The growth rate of the GDP and the declining rate of the number of coal mine gas accidents are drawn on the same map in Figure 15.

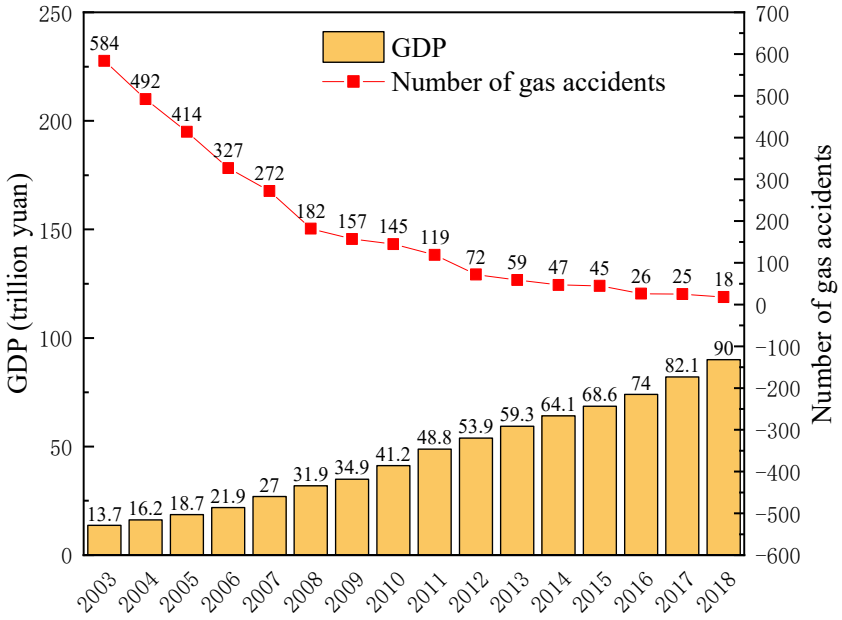

Figure 14. Changes in the number of gas accidents and GDP.

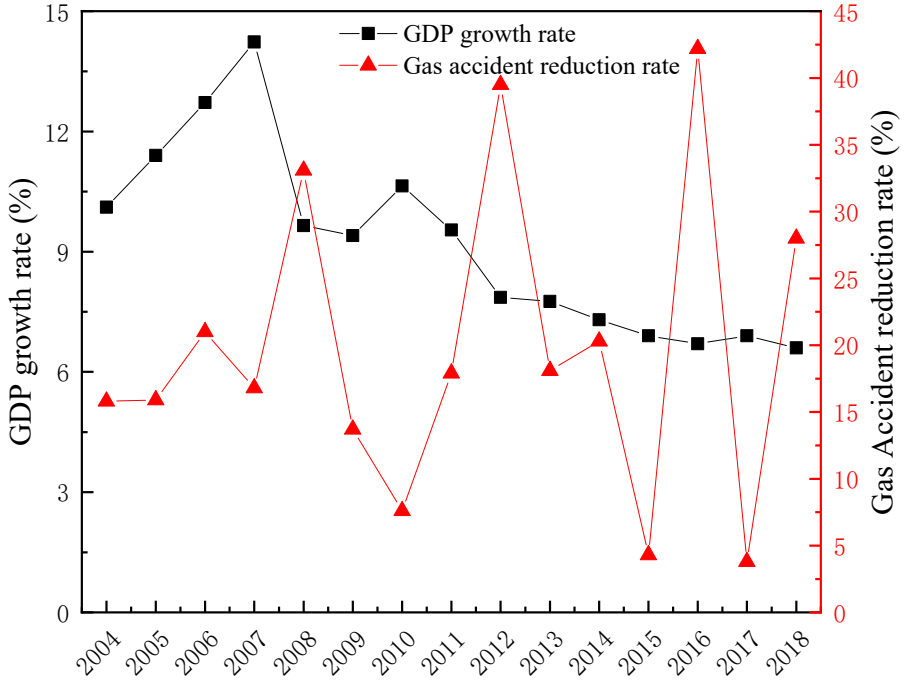

Figure 15. Changes in the growth rate of the GDP and the decline in the number of gas accidents.

As seen from the chart, during 2003~2007, the GDP and economic growth increased each year, and the number of coal mine gas accidents decreased, but the decline ratio fluctuated little.

From 2008 to 2018, the overall growth rate of the GDP slowed, but the decline rate of the number of coal mine gas accidents fluctuated greatly. For example, from 2007 to 2008, the number of gas accidents decreased from 16.8% to 33.1%. This result shows that the number of gas disasters in 2008 was significantly curbed and decreased significantly. However, from 2008 to 2010, the decline rate of the number of gas accidents elicited a large drop, from 33.1% to 7.6%, indicating that the number declined during this period and that the rate of decline slowed. Nevertheless, these trends are not obvious.

5. Discussion

From the above analysis results, great progress has been made in the safety production and gas prevention of coal mines in China. TM accidents are the most prominent. The main types of TM accidents are gas explosions and coal and gas outbursts. The causes of these accidents include geological conditions, technology, equipment, management and other aspects. In this paper, the impact of national policies related to coal mine gas accidents on the occurrence of accidents is discussed.

5.1. Analysis of Gas Control Policies

Research on gas control policies has a certain cross-disciplinary nature, and the definitions of related concepts need to be improved eventually. Therefore, this paper only gives a definition for the scope of discussion: principles, plans, laws, regulations, standards, norms, resolutions, decisions and notifications related to gas prevention and control formulated by the state or departments and the inspection and control of safety in production. Important speeches made by leaders of relevant parties and state and departments are referred to as coal mine gas control policies and policies in a broad sense.

5.1.1. Stage of Gas Control Policy

Coal mine gas prevention and control work is the top priority of coal mine safety production. The Chinese government has attached great importance to this work and has issued a series of policies and measures to promote coal mine gas prevention and control. Generally, there is a time lag between the promulgation of a policy and its effect on the prevention and control of gas accidents. Therefore, this paper collects and collates the relevant policies of gas prevention and control from 2000 to 2018. In Figure 16, the developmental stages of gas control policies and the number of annual promulgation policies are given.

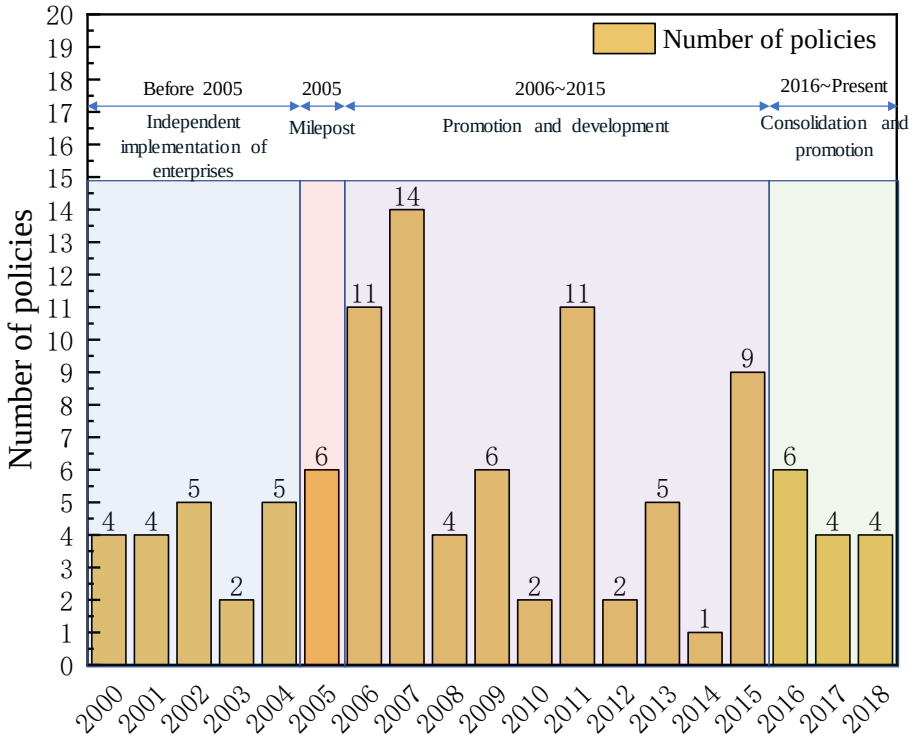

Figure 16. Development stage and quantity distribution of gas control policies.

In the past 20 years, the policy system of gas prevention and control has been continuously improved, and the development process has been divided into the following periods or stages:

1. Before 2005, the work on gas prevention and control mainly relied on the independent development of coal mine enterprises. At the national level, there is a lack of systematic and normative policy guidance. Most of the policies related to gas prevention and control are contained in comprehensive policies, and there is a lack of targeted policies for gas prevention and control;
2. In 2005, China's coal mine gas prevention and control mechanism was formally formed, which is an important milestone in promoting the work. After the establishment of the Inter-ministerial Coordination Leading Group for Coal Mine Gas Prevention, a series of targeted policies for gas prevention, such as Opinions on the Implementation of Coal Mine Gas Control and Utilization, have been issued, and the related organizations and functions of gas prevention and control have been further improved;
3. The period from 2006 to 2015 was the promotion and development stage for gas prevention and control. At the national level, we should vigorously promote the rapid development of gas prevention and control, establish and improve the gas prevention and control system, organize major technical tackles, achieve breakthroughs, publish gas control and utilization policies intensively, further expand the policy coverage, continuously refine policy contents and further improve operability and pertinence;
4. The period including and following 2016 was the consolidation and promotion stage for gas prevention and control. In 2016, the state started a structural reform on the coal industry's supply side and issued a series of industry policies. At this stage, the gas prevention and control system had been improved, the technology had been further improved and serious gas accidents had been effectively controlled.

5.1.2. Effectiveness of Gas Control Policy

From 2003 to 2018, remarkable achievements were made in the prevention and control of coal mine gas in China. The total number of gas accidents and deaths dropped dramatically. Gas accidents were effectively curbed, and major and more severe gas accidents were essentially eliminated. The important source of these positive results is the promulgation of a series of gas control policies and measures by the Chinese government and relevant departments.

By sorting out a series of gas control policies and related accident data in the past 15 years, the preliminary assumption of the intervention degree of gas control policies is proposed, and the relationships between occurrence trends and policy interventions on the degree of gas accidents in China are analyzed.

At present, there are many studies that have conducted quantitative assessments of economic security policies in China and in other countries, and the scope of these studies has gradually extended to include assessments of climate protection policies and safety production policies, but there are few quantitative studies on gas control policies. To deeply analyze the correlation between gas prevention and control policies and gas accident control, the idea of the degree of policy intervention is proposed. By ranking the degrees of the importance and influence of policies and considering the number and degree of the influence of policies, a quantitative evaluation of policy intervention degree is made.

5.1.3. Policy Data Sources

To conduct a more comprehensive analysis of the role of policies in accident prevention and control, this paper collects and collates relevant policies issued since 2000, mainly from the official websites and databases of the National Development and Reform Commission, the Ministry of Finance, the Ministry of Emergency Management, the National Coal Mine Safety Supervision Bureau and other ministries, as well as the compilation of relevant important documents and yearbooks.

5.1.4. Analysis of Policy Intervention Degree

Policy Classification

As shown in Figure 17, the policies are sorted on the basis of time. According to the different publishing institutions and forms of the policies, while considering the different influences of different policies, the gas control policies were divided into five categories: laws and regulations, leaders' speeches and instructions, targeted inspection and remediation actions, treatment of the persons responsible for accidents and accident notifications.

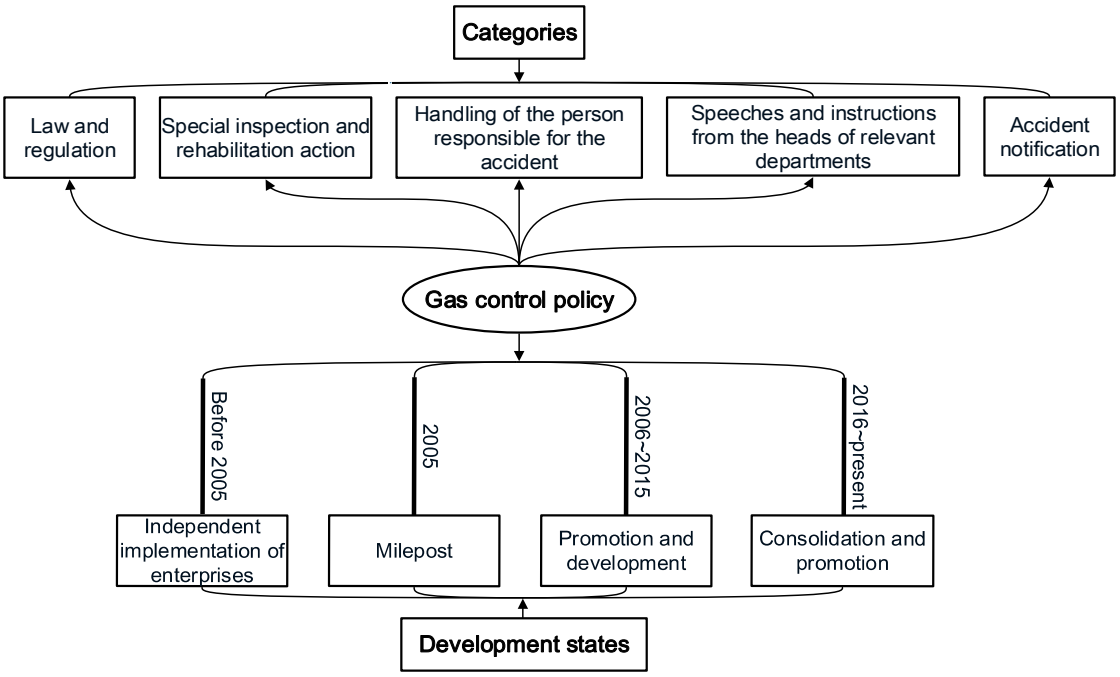

Figure 17. Classification and development stage of gas control policy.

Ranking and Quantitative Assignment

This paper qualitatively ranks the degrees of influence of the above five types of gas control policies. The order of influence from large to small is as follows: P1 is laws and regulations, P2 is leaders' speeches and instructions, P3 is the handling of accident liabilities, P4 is special inspection and remediation actions and P5 is accident notifications. The weights of 5, 4, 3, 2 and 1 were given to these five kinds of policies, respectively.

Considering the timeliness of policies, to determine the objective effectiveness cycles of different policies and analyze the cumulative effects of policies, it was assumed that the objective effectiveness of policies was obvious and stable in the years of their effectiveness cycles, but weak in the years beyond their effectiveness cycles. The policy effectiveness cycles were roughly divided into three levels: the period of effectiveness of P1 was 5 years, those of both P2 and P4 were 3 years and those of both P3 and P5 were 1 year. By synthesizing factors such as the number of policies and the weight of the degree of influence, we can obtain the degree of policy intervention. The concrete calculation model is as follows:

$$Ai = Pi \times Vi \tag{1}$$

where Ai is the policy intervention degree, Pi is the number of policies and Vi represents the weight of the degree of influence.

The annual and cumulative policy intervention degree were calculated by the above formula, and the results are shown in Figure 18.

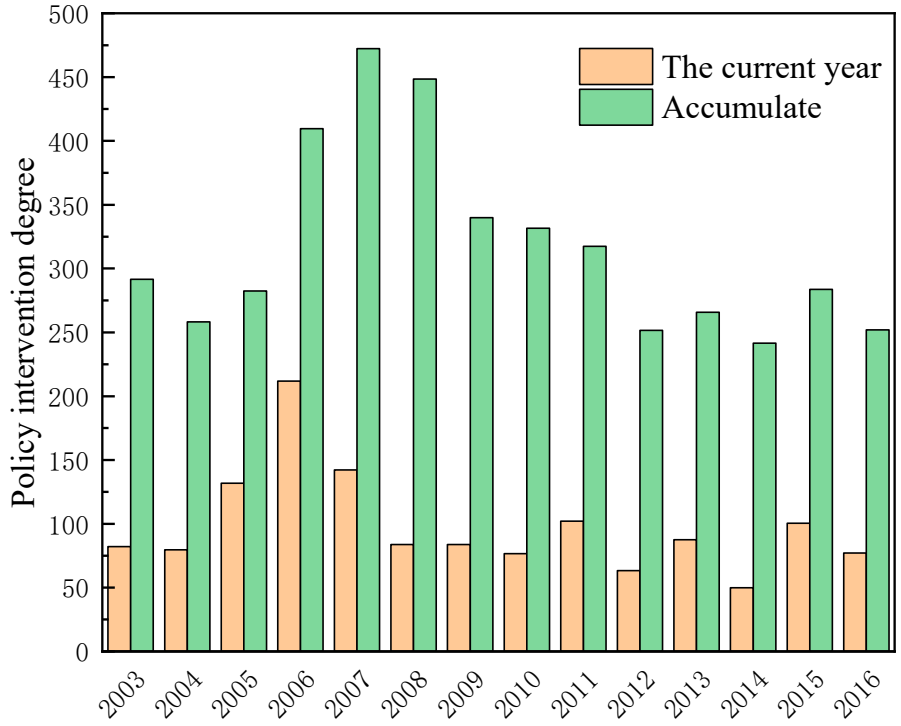

Figure 18. Histogram of the intervention degree of China's gas control policy from 2003 to 2016.

Figure 18 shows the histogram of the intervention degree of China's gas control policy from 2003 to 2016. From 2003 to 2004, the degree of policy intervention in that year was relatively low, with little fluctuation. The degree of policy intervention increased significantly from 2005 to 2007, and the degree of policy intervention in that year was greater than in other years, which directly led to a relatively high degree of cumulative policy intervention from 2006 to 2008. After 2007, the degree of policy intervention that year remained relatively stable. This shows that before 2005, the frequent occurrence of coal mine gas accidents and the large number of deaths aroused the vigilance of relevant agencies, and prompt measures were taken to issue a series of targeted control policies, which played a positive role in the prevention and control of coal mine gas accidents.

5.2. Analysis of the Relation between Gas Accidents and Policy Intervention Degree

The implementation of a policy has a timeliness effect on the prevention and control of gas accidents. Therefore, the trend charts of the number of deaths and accidents in China were compared with the trend charts of the cumulative intervention degree of gas prevention and control policies, as shown in Figure 19.

From the graph, we can see that the corresponding relationship between coal mine gas accidents and the intervention degree of gas prevention and control policies in China has a certain regularity, and the following analysis additionally considers the evolution processes of the policies.

From 2003 to 2005, targeted policies for gas control and utilization were issued sequentially, and due to the periodic cumulative effect of policy effectiveness, the intervention degree of gas prevention and control policies increased rapidly. The number of deaths and accidents was negatively correlated with the degree of policy intervention, indicating that at this stage, the gas prevention and control policies were gradually improved and strengthened. The degree of policy intervention has played an active role in ensuring the safe production of coal mines.

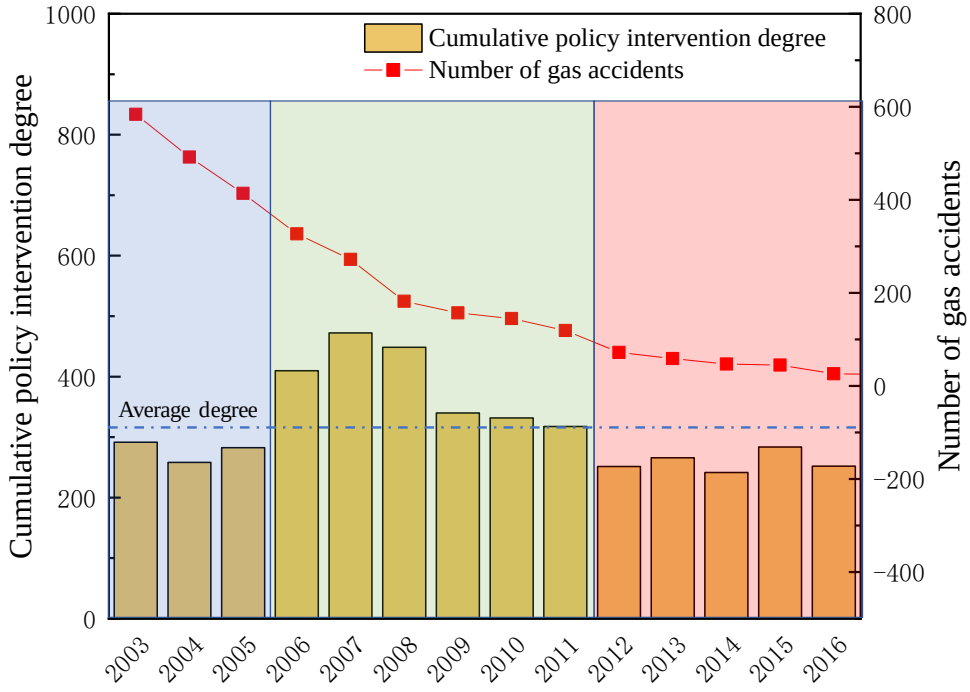

Figure 19. Trend comparison of gas accidents and the policy intervention degree from 2003 to 2016.

After many extraordinarily serious gas accidents in 2004 and 2005, from 2006 to 2011, the state attached great importance to the safety of coal production, especially to the control of gas disasters, and actively explored the comprehensive utilization of gas in promoting sustainable development of the coal industry. The competent authorities for gas prevention and control work have been stable, and policies for gas control and utilization have been issued intensively. More than 40 policies have been issued. The coverage of the policies has been further expanded, involving economic policies such as finance, taxation, price, technology and equipment. The contents of the policies have been continuously refined, and the operability and pertinence of the policies have been further improved. The intervention degree has reached the highest level since 2003. At the same time, the number of deaths and accidents has declined rapidly, and the efforts for gas disaster control have achieved remarkable results.

From 2012 to 2016, the policy system of gas control and utilization was gradually formed and continuously improved. The intervention degree of gas control policies remained stable, effectively guaranteeing the efforts for gas prevention and control continued despite major changes in industrial structure. The number of gas accidents continued to decline steadily, and the number of deaths showed a declining trend, but stopped declining in 2016. Up to 20 gas accidents and 215 deaths occurred in coal mines, accounting for 60.6% and 74.4% of the total number of coal mine accidents and deaths, respectively. Gas accidents are still the focus of preventing and curbing serious and extraordinarily serious accidents.

6. Conclusions

After years of management, the level of safety production in China's coal industry has been significantly improved, especially the occurrence of gas accidents, which has been significantly curbed. However, the total number of coal mine accidents in China is still large, and the fatality rate is still far greater than those of developed countries. Gas accidents are still the first killer of coal mines. Through this study, the main conclusions are as follows:

1. Among all types of accidents in coal mines, gas accidents pose the greatest threat to safety in production, accounting for 11.66% of accidents and 30.18% of deaths.
2. Among the gas accidents, gas explosion and coal and gas outburst accidents are the most serious. Complex areas, in terms of geological structure, have the highest frequency of occurrence, and the township coal mines are the main mines in the ownership system.
3. The development of China's coal mine gas control policy has gone through three stages: the independent development stage of enterprises before 2005, the promotion stage from 2006 to 2015 and the consolidation and promotion stage from 2016 to present, with 2005 being a milestone in the development of gas control policy.
4. With continuous improvements in the gas control policy system, gas accidents have been greatly curbed. Gas control policies are an important aspect in guaranteeing coal mine safety in production and are the main drivers of gas prevention and control work.
5. Gas control policies are active and effective in the prevention and control of coal mine gas accidents, indicating that the comprehensive implementation of safety policies is an important measure to ensure the safety of production activities, having important guidance for high-risk industries, production activities with frequent accidents and areas with significantly unsound policies.

Author Contributions: Conceptualization, W.K.; Methodology, W.K.; Validation, K.W.; Formal Analysis, W.K. and K.W.; Investigation, W.K.; Resources, K.W.; Writing—Original Draft Preparation, W.K.; Writing—Review & Editing, K.W.; Visualization, W.K.; Supervision, K.W.; Project Administration, W.K. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support provided by the Major Consulting Project of the Chinese Academy of Engineering (No. 2017-ZD-03) and the National Science Foundation of China (No. 51904311). Comments by all anonymous reviewers are highly appreciated.

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

References

1. Zhao, W.; Cheng, Y.; Pan, Z.; Wang, K.; Liu, S. Gas diffusion in coal particles: A review of mathematical models and their applications. *Fuel* **2019**, *252*, 77–100. [CrossRef]
2. Andrews-Speed, P.; Yang, M.; Shen, L.; Cao, S. The regulation of China's township and village coal mines: A study of complexity and ineffectiveness. *J. Clean. Prod.* **2003**, *11*, 185–196. [CrossRef]
3. Lin, J.; Fridley, D.; Lu, H.; Price, L.; Zhou, N. Has coal use peaked in China: Near-term trends in China's coal consumption. *Energy Policy* **2018**, *123*, 208–214. [CrossRef]
4. Cattaneo, C.; Manera, M.; Scarpa, E. Industrial coal demand in China: A provincial analysis. *Resour. Energy Econ.* **2011**, *33*, 12–35. [CrossRef]
5. Liu, H.; Cheng, Y. The elimination of coal and gas outburst disasters by long distance lower protective seam mining combined with stress-relief gas extraction in the Huaibei coal mine area. *J. Nat. Gas Sci. Eng.* **2015**, *27*, 346–353. [CrossRef]
6. Guo, H.; Yuan, L.; Cheng, Y.; Wang, K.; Xu, C. Experimental investigation on coal pore and fracture characteristics based on fractal theory. *Powder Technol.* **2019**, *346*, 341–349. [CrossRef]
7. Wang, K.; Du, F.; Wang, G. The influence of methane and CO_2 adsorption on the functional groups of coals: Insights from a Fourier transform infrared investigation. *J. Nat. Gas Sci. Eng.* **2017**, *45*, 358–367. [CrossRef]
8. Wang, K.; Du, F.; Wang, G. Investigation of gas pressure and temperature effects on the permeability and steady-state time of chinese anthracite coal: An experimental study. *J. Nat. Gas Sci. Eng.* **2017**, *40*, 179–188. [CrossRef]
9. Dudley, B. BP Statistical Review of World Energy Statistical Review of World. *Bp* **2019**, *68*, 64.
10. Yuan, L. Control of coal and gas outbursts in Huainan mines in China: A review. *J. Rock Mech. Geotech. Eng.* **2016**, *8*, 559–567. [CrossRef]
11. Yu, J.; Zheng, M.; Li, J.; Wu, X.; Guo, Q. Resource potential, exploration prospects, and favorable direction for natural gas in deep formations in China. *J. Nat. Gas Geosci.* **2018**, *3*, 311–320. [CrossRef]
12. Xie, H.; Gao, F.; Ju, Y.; Gao, M.; Zhang, R.; Gao, Y.; Liu, J.; Xie, L.Z. Quantitative definition and inves- tigation of deep mining. *J. China Coal. Soc.* **2015**, *40*, 1–10. (In Chinese)

13. Gao, M.; Zhang, S.; Li, J.; Wang, H. The dynamic failure mechanism of coal and gas outbursts and response mechanism of support structure. *Therm. Sci.* **2019**, *23*, S867–S875. [CrossRef]
14. Ranjith, P.G.; Zhao, J.; Ju, M.; De Silva, R.V.S.; Rathnaweera, T.D.; Bandara, A.K.M.S. Opportunities and Challenges in Deep Mining: A Brief Review. *Engineering* **2017**, *3*, 546–551. [CrossRef]
15. Liu, R.; Cheng, W.; Yu, Y.; Xu, Q. Human factors analysis of major coal mine accidents in China based on the HFACS-CM model and AHP method. *Int. J. Ind. Ergon.* **2018**, *68*, 270–279. [CrossRef]
16. Zheng, Y.P.; Feng, C.G.; Jing, G.X.; Qian, X.M.; Li, X.J.; Liu, Z.Y.; Huang, P. A statistical analysis of coal mine accidents caused by coal dust explosions in China. *J. Loss Prev. Process Ind.* **2009**, *22*, 528–532. [CrossRef]
17. Wang, L.; Cheng, Y.P.; Liu, H.Y. An analysis of fatal gas accidents in Chinese coal mines. *Saf. Sci.* **2014**, *62*, 107–113. [CrossRef]
18. Fu, G.; Cao, J.; Wang, X. Relationship Analysis of Causal Factors in Coal and Gas Outburst Accidents Based on the 24Model. *Energy Procedia* **2017**, *107*, 314–320. [CrossRef]
19. Meng, X.; Liu, Q.; Luo, X.; Zhou, X. Risk assessment of the unsafe behaviours of humans in fatal gas explosion accidents in China's underground coal mines. *J. Clean. Prod.* **2019**, *210*, 970–976. [CrossRef]
20. Chen, H.; Qi, H.; Feng, Q. Characteristics of direct causes and human factors in major gas explosion accidents in Chinese coal mines: Case study spanning the years 1980–2010. *J. Loss Prev. Process Ind.* **2013**, *26*, 38–44. [CrossRef]
21. Accou, B.; Reniers, G. Developing a method to improve safety management systems based on accident investigations: The SAfety FRactal ANalysis. *Saf. Sci.* **2019**, *115*, 285–293. [CrossRef]
22. Yin, W.; Fu, G.; Yang, C.; Jiang, Z.; Zhu, K.; Gao, Y. Fatal gas explosion accidents on Chinese coal mines and the characteristics of unsafe behaviors: 2000–2014. *Saf. Sci.* **2017**, *92*, 173–179. [CrossRef]
23. Bureau, J.C.; Swinnen, J. EU policies and global food security. *Glob. Food Secur.* **2018**, *16*, 106–115. [CrossRef]
24. Duan, H.; Wang, S. Potential impacts of China's climate policies on energy security. *Environ. Impact Assess. Rev.* **2018**, *71*, 94–101. [CrossRef]
25. Boratyńska, K.; Huseynov, R.T. An innovative approach to food security policy in developing countries. *J. Innov. Knowl.* **2017**, *2*, 39–44. [CrossRef]
26. Wang, Y.; Zhang, Y. Comparison and analysis of institutionalization, standardization and normalization of enterprise safety production. *Procedia Eng.* **2012**, *43*, 574–577. [CrossRef]
27. SACMS. *Chinese Coal Mine Accidents Report, 2003–2007*; State Administration of Coal Mine Safety: Beijing, China, 2008.
28. SACMS. *Chinese Coal Mine Accidents Report, 2008–2012*; State Administration of Coal Mine Safety: Beijing, China, 2013.
29. SACMS. *Chinese Coal Mine Accidents Report, 2013*; State Administration of Coal Mine Safety: Beijing, China, 2014.
30. SACMS. *Chinese Coal Mine Accidents Report, 2014*; State Administration of Coal Mine Safety: Beijing, China, 2015.
31. SACMS. *Chinese Coal Mine Accidents Report, 2015*; State Administration of Coal Mine Safety: Beijing, China, 2016.
32. SACMS. *Chinese Coal Mine Accidents Report, 2016*; State Administration of Coal Mine Safety: Beijing, China, 2017.
33. SACMS. *Chinese Coal Mine Accidents Report, 2017*; State Administration of Coal Mine Safety: Beijing, China, 2018.
34. SACMS. *Chinese Coal Mine Accidents Report, 2018*; State Administration of Coal Mine Safety: Beijing, China, 2019.
35. Bartholomew, D.J.; Cox, D.R.; Lewis, P.A.W. The Statistical Analysis of Series of Events. *J. R. Stat. Soc. Ser. A* **1966**, *129*, 587. [CrossRef]
36. Fearnhead, P.; Liu, Z. Efficient Online Inference for Multiple Changepoint Problems. In Proceedings of the 2006 IEEE Nonlinear Statistical Signal Processing Workshop, Cambridge, UK, 13–15 September 2006; pp. 5–8. [CrossRef]
37. Maguire, B.A.; Pearson, E.S.; Wynn, A.H.A. The time intervals between industrial accidents. *Biometrika* **1952**, *39*, 168–180. [CrossRef]
38. Zhang, C.W.; Xie, M.; Liu, J.Y.; Goh, T.N. A control chart for the Gamma distribution as a model of time between events. *Int. J. Prod. Res.* **2007**, *45*, 5649–5666. [CrossRef]
39. Foth, T.; Efstathiou, N.; Vanderspank-Wright, B.; Ufholz, L.A.; Dütthorn, N.; Zimansky, M.; Humphrey-Murto, S. The use of Delphi and Nominal Group Technique in nursing education: A review. *Int. J. Nurs. Stud.* **2016**, *60*, 112–120. [CrossRef]
40. Keeney, S.; Hasson, F.; McKenna, H.P. A critical review of the Delphi technique as a research methodology for nursing. *Int. J. Nurs. Stud.* **2001**, *38*, 195–200. [CrossRef]

41. Trevelyan, E.G.; Robinson, N. Delphi methodology in health research: How to do it? *Eur. J. Integr. Med.* **2015**, *7*, 423–428. [CrossRef]
42. Wright, G.; Rowe, G. The Delphi technique as aforecasting tool: Issues and analysis. *Int. J. Forecast.* **1999**, *15*, 353–375.