sustainability

MDPI

Article

An Analysis of Hazardous Chemical Accidents in China between 2006 and 2017

Laijun Zhao [1,2,3], Ying Qian [4], Qing-Mi Hu [3,*], Ran Jiang [3], Meiting Li [2] and Xulei Wang [5]

1 Sino-US Global Logistics Institute, Shanghai Jiao Tong University, Shanghai 200030, China; ljzhao70@sjtu.edu.cn
2 China Institute for Urban Governance, Shanghai Jiao Tong University, Shanghai 200030, China; lmtjiayou@sjtu.edu.cn
3 Antai College of Economics and Management, Shanghai Jiao Tong University, Shanghai 200030, China; rjiang@sjtu.edu.cn
4 School of Management, Shanghai University, Shanghai 200444, China; qian.ying@t.shu.edu.cn
5 College of Economics and Management, Qingdao Agriculture University, Qingdao 266109, China; 200501035@qau.edu.cn
* Correspondence: qingmihu@sjtu.edu.cn

Received: 12 July 2018; Accepted: 14 August 2018; Published: 18 August 2018

check for updates

Abstract: From the perspective of characteristics and causes, probability and forecast, and safety management evaluation, this paper analyzes 3974 hazardous chemical casualty accidents that occurred between 2006 and 2017 in China. The trends, monthly and hourly distributions, lifecycles, chemical and accident types, and the direct and indirect causes of casualty accidents are analyzed first. To estimate the probability of casualty accidents, the Poisson regression model is employed. The time series model is developed to forecast the number of casualty accidents. The safety management of hazardous chemicals is evaluated based on an inverted U-shaped curve that fits the relationship between the number of casualty accidents and petrochemical industry outputs. Moreover, measures for improving the safety management of hazardous chemicals are provided based on the analysis, forecast, and evaluation. The results show that the probability of 200–600 casualty accidents occurring per year in China is 59.10%. Sixteen of thirty provinces are identified as having better safety management with regard to hazardous chemicals.

Keywords: hazardous chemical accidents; safety management evaluation; poisson regression analysis; Kuznets curve; time series model

1. Introduction

With the rapid economic development in China, there are surging demands for hazardous chemicals for use in manufacturing and everyday life. Such chemicals pose considerable risks to safety and the environment, despite their benefits. Based on the accident statistics, 3974 hazardous chemical casualty accidents occurred in the 12-year period from 2006 to 2017, resulting in a total of 5203 deaths. Thus, on average, there is almost one casualty accident per day and more than one death each day. Since 2013, major accidents, which are defined as more than or equal to 3 deaths based on the Chinese classification standard "Production Safety Accident Investigation and Handling Rules" [1], and catastrophic accidents have occurred continuously. On 22 November 2013, an explosion caused by an oil pipeline leakage in Sinopec killed 62 and injured 136 people. On 1 March 2014, two tankers loaded with methanol crashed in a highway tunnel in Shanxi Province and the resulting explosion killed 40 people. On 12 August 2015, in Tianjin, catastrophic explosions occurred at midnight in warehouses where significant amounts of toxic chemicals were stored, killing 178 people, injuring 677 people, and resulting in a severe biochemical crisis [2] These hazardous chemical accidents (HCAs) have a huge impact on environmental health, safety, and sustainability. The management of hazardous chemicals poses serious challenges to central and local government departments. There is an urgent need to learn from past HCAs and improve safety management.

Research on the characteristics of HCAs has attracted much attention from scholars [3,4]. A common method is to use statistical techniques to analyze the characteristics, causes, and consequences of HCAs based on historical data. Hobeika et al. [5] investigated 570 HCAs that occurred in Pennsylvania in 1986–1987. They analyzed the causes of the accidents, the types of hazardous chemicals, and the types of cargo involved. Shorten et al. [6] analyzed the HCA data from 1987–1999 in Chester County, Pennsylvania, and found that the majority of the chemical leakage accidents occurred at noon on weekdays. Mannan et al. [7] provided a thorough analysis of injuries caused by chemicals including lost work days, industry groups involved, and parts of the body injured, to propose policy recommendations for reducing injuries due to chemicals. Darbra [8] conducted an analysis of 225 HCAs that occurred during production, storage and transportation. The results showed that external events and mechanical failure ranked highest as the causes of HCAs. Bubbico et al. [9] investigated the transportation of hazardous chemicals through the tunnels and found that for rail transportation, the risk does not increase going through tunnels, but for road transport, the risk of accidents is higher going through tunnels. Cox et al. [10] examined HCA cases associated with hazardous waste treatment and found that inadvertent heating is the major cause of these HCAs. Dakkoune et al. [11] analyzed the causes and consequences of 169 accidental events involving French chemical industries, and showed that operator error is the major cause of accidental events. Models are also used to assess the risks of hazardous chemicals [12]. Papazoglou et al. [13] developed a generic accident sequence model based on event trees and assessed the safety for sites producing and storing explosives based on quantitative risk assessment approach. Raemdonck et al. [14] proposed a framework to assess the risks of hazardous chemical transportation based on different transportation modes. Verslycke et al. [15] developed the chemistry scoring index to rank hazards to human health, safety, and the environment for chemicals used in oil and gas operations. Heo et al. [16] identified potential chemical hazard in Korea by spatial analysis of several chemical factories and accidents, and classified areas with different chemical hazard occurrences based on the estimated hazard levels. In addition, some studies have addressed the emergency response planning in case of chemical accidents [17,18]. Hosseinnia et al. [19] developed a multi-plant emergency response decision tool for chemical clusters in case of major accidents to determine plant emergency levels and respective response strategies.

In China, although research on HCAs began only recently, it has already achieved many new findings [20–22]. Currently, statistical analysis of HCAs focuses on the types of hazardous chemicals involved and the types of accidents [23,24], the time of day when HCAs occur [25], and the lifecycle phase of hazardous chemicals (production, storage, transportation, sales, utilization, and disposal) at which accidents occur [26,27]. Duan et al. [28] investigated the number of HCAs, the accident sites, and the firm size using the data from HCAs that occurred from 2000 to 2006. Zhang and Zheng [29] studied the time and spatial distribution of HCAs, the types of accidents, the fatality to injury ratios, and the causes of accidents based on the HCA data from 2006 to 2010. However, the above studies have usually only addressed several characteristics of HCAs, and a comprehensive analysis of characteristics and causes of HCAs appears to be lacking. To overcome this limitation, Zhao et al. [30,31] summarized the characteristics and causes of HCAs based on detailed statistical analysis.

Considering that the characteristics of HCAs are changing dramatically in an era of rapid economic development, continued research in this area is of great importance. Inspired by Zhao et al. [30,31], this study comprehensively analyzes the characteristics and causes of hazardous chemical casualty accidents in China between 2006 and 2017. Moreover, the use of models such as the Poisson regression model and the time series model in HCA research is scarce, relative to the use of statistical analysis. Thus, to better prepare for accident prevention and improve the response capacity, the Poisson regression model is applied to estimate the probability of hazardous chemical casualty accidents, and the time series model is employed to forecast the number of hazardous chemical casualty accidents.

Additionally, the safety management level of hazardous chemicals of each province is evaluated based on an inverted U-shaped curve that fits the relationship between the number of casualty accidents and petrochemical industry outputs, which has not been investigated previously.

2. Data and Methods

2.1. Data Sources

The data used in this study are mainly from the State Work Accident Briefing (SWAB) system and the State Administration of Work Safety (SAWS) [32]. SAWS is the most commonly used source for HCAs, as it reports all industrial accidents occurring in China. HCA reports published on the websites of National Registration Center for Chemicals [33], China Safety Production [34], Safety culture [35], Safety Management [36], and Guo Yin safety [37] are also gathered. More than 9000 cases (HCA cases do not include accidents occurring in Hong Kong, Macao and Taiwan; Tibet has no HCAs) were collected with detailed accident information, including time, location, enterprise information, casualty, and primary causes. These cases cover the majority of the HCAs and all of the casualty accidents that occurred from 2006 to 2017 and can therefore be used to analyze the characteristics and trends of casualty accidents in China. 3974 casualty accidents (defined as more than or equal to 1 causality) are identified as our base data. To evaluate the safety management level of each province, the output of the petrochemical industry for each province needs to be considered. These data are collected from the National Bureau of Statistics of the People's Republic of China.

2.2. Methods

Based on the obtained data, hazardous chemical casualty accidents are analyzed from the perspective of characteristics and causes, probability and forecast, and safety management evaluation. The corresponding measures are proposed to improve safety management levels. Statistical analysis is applied to investigate the characteristics and causes of casualty accidents. The probability of casualty accidents is estimated using a Poisson regression. A time series analysis is used to predict the number of casualty accidents in 2018 and the Kuznets curve is adopted to assess the safety management of hazardous chemicals in 30 Chinese provinces.

2.2.1. The Estimation of the Probability of HCA Occurrence Using Poisson Regression

Typically, Count data modeling techniques are used to analyze accident frequency. The common and convenient assumption is that accidents are Poisson-distributed in accident count analysis [38]. Nicholson and Wong [39] showed that the Poisson distribution is appropriate for the analysis of accidents at individual sites. Considering that HCA data are random, discrete, non-negative integers by nature, and that the occurrence probability of HCAs is very small in individual regions, a Poisson regression model can be used to estimate the probability of casualty accident occurrence in our study.

y denotes the number of casualty accidents that occurred. It is assumed that Y is independently distributed and that the Poisson distribution of Y, given by $\lambda(\lambda > 0)$, is:

$$\Pr(Y = y|\lambda) = \frac{e^{-\lambda}\lambda^{y}}{y!}, y = 0, 1, 2, \cdots \quad (1)$$

The Poisson distribution can be extended to a regression model based on each value of λ. The number of casualty accidents occurring in i location in a certain time period, y_i, conforms to the Poisson distribution with λ_i:

$$\lambda_i = E(y_i|X) = \exp\left(X'\beta'\right) = \prod_{j=1}^{k} \exp\left(\beta_j x_{ji}\right) \quad (2)$$

where $X = (x_{1i}, x_{2i}, \cdots, x_{ki})^T$ are covariates and β is the vector of estimated regression coefficients. β_j represents the expected change in the log of the mean per unit change in the predictor x_j. It can be computed using maximum likelihood estimation.

2.2.2. The Prediction of the Number of HCAs Using a Time Series Analysis

A prediction of the number of accidents is critical for the government and enterprises to prepare for accident prevention and to handle accidents effectively. Additionally, this prediction can increase awareness and improve the response capacity to reduce the impact of accidents. However, HCA forecast and modeling for planning and policy-making may entail a high degree of complexity, especially in the preliminary stage of concept formulation and model selection. This is because the factors that affect HCAs not only involve technological and equipment factors, but also human, environmental and management factors. Moreover, these factors dynamically evolve over time, and may lead to irregular and strongly nonlinear observations of HCAs. For example, many HCA phenomena entail strong behavioral and cognitive aspects that are difficult to isolate. To deal with the time dependencies and better reveal the underlying mechanism of HCA occurrence, time series models such as the autoregressive moving average (ARMA) model and autoregressive integrated moving average (ARIMA) model can be employed. These models are used to predict the number of HCAs in this study.

The ARMA model can be described as follows:

$$y_t = \phi_1 y_{t-1} + \phi_2 y_{t-2} + \ldots + \phi_p y_{t-p} + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \cdots - \theta_q a_{t-q} \tag{3}$$

where y_t is the predicted number of casualty accidents at time t; ϕ and θ are regression parameters; a_t is the random disturbance item at time t, and p and q are the number of orders. After implementing the d-th order difference, model ARMA (p, q) becomes ARIMA (p, d, q) model.

Due to the seasonal characteristics of casualty accidents, the original time series data need to be adjusted to remove the seasonal factors first. In general, there are two main approaches to the seasonal adjustment, namely a filter-based approach and a model-based approach. To understand how to implement the seasonal adjustment, interested readers can consult Hillmer and Tiao [40], Findley and Hood [41], and Birrell et al. [42]. In this paper, the model-based approach is used. The prediction of the number of casualty accidents in 2018 is based on the adjusted data using model ARIMA. The calculated number of casualty accidents must be re-adjusted to account for the seasonal characteristics.

2.2.3. The Assessment of the Safety Management Level of Hazardous Chemicals Using the Kuznets Curve

Normally, when the output of the petrochemical industry of a province is low, there are fewer economic activities related to hazardous chemicals. Therefore, the number of HCAs will also be low. With the expansion of the petrochemical industry, transitions with hazardous chemicals will increase. Thus, the number of HCAs will also rise. One way to reduce the number of HCAs is better safety management. However, investment in safety management is often delayed. When the petrochemical industry is well-developed, safety management will mature and the number of HCAs will fall. Therefore, the number of HCAs should have an inverted U-shaped relationship with the output of the petrochemical industry. We call this the safety Kuznets curve and use the quadratic function regression to fit the relationship between y and x, as shown in Equation (4):

$$y = ax^2 + bx + c + \varepsilon \tag{4}$$

where y represents the number of casualty accidents; x represents the petrochemical industry output; a, b and c are the estimated parameters, and ε is the random error.

The fitting of the relationship between the number of casualty accidents and the output of the petrochemical industry is used to evaluate the safety management level of hazardous chemicals of 30

Chinese provinces. At the same production level, fewer accidents suggest a higher safety management level. The statistical significance of the fitted curve represents the average level of safety management of hazardous chemicals in China.

3. Characteristics of HCAs in China

3.1. Trend of Number of Casualty and Fatality Accidents

The trend of variation in the number of accidents with casualties and the number of accidents with fatalities can be divided into three phases (Figure 1). The first phase was from 2006 to 2008, and showed a rapid decreasing trend. The number of casualty accidents decreased from 293 in 2006 to 147 in 2008, a 49.83% reduction. The second phase started from 2008 to 2012, with fluctuations in the number of casualty accidents and the number of fatality accidents. For example, in 2008, 2010, and 2012, the number of casualty and fatality accidents was low, while it was high in 2009 and 2011. The number of casualty accidents reached its lowest level in 2010 and 2012. The first reason for this milestone was the Beijing Olympic Games in 2008 and the Shanghai World Expo in 2010, during which time the government allocated significant resources to improving the management of hazardous chemicals. A series of regulatory policies were implemented, and the level of supervision was enhanced. Second, the first revision of the "Hazardous chemicals safety management regulations" was implemented on 1 December 2011. Hazardous chemicals were more strictly regulated in 2012, leading to the decrease in the number of casualty and fatality accidents that year. This suggests that HCAs can be reduced by implementing stricter standards and strengthened management. The third phase was from 2012 to 2017, and exhibited a rapidly increasing trend. The number of casualty accidents increased from 137 in 2012 to 723 in 2016, an 81.05% increase. This means that when the Olympic Games and the World Expo were completed, fewer efforts were devoted to the safety management of hazardous chemicals and the number of casualty and fatality accidents rebounded. The fluctuation of the number of casualty and fatality accidents indicates that the supervision of hazardous chemicals must be a long-term and continuous process.

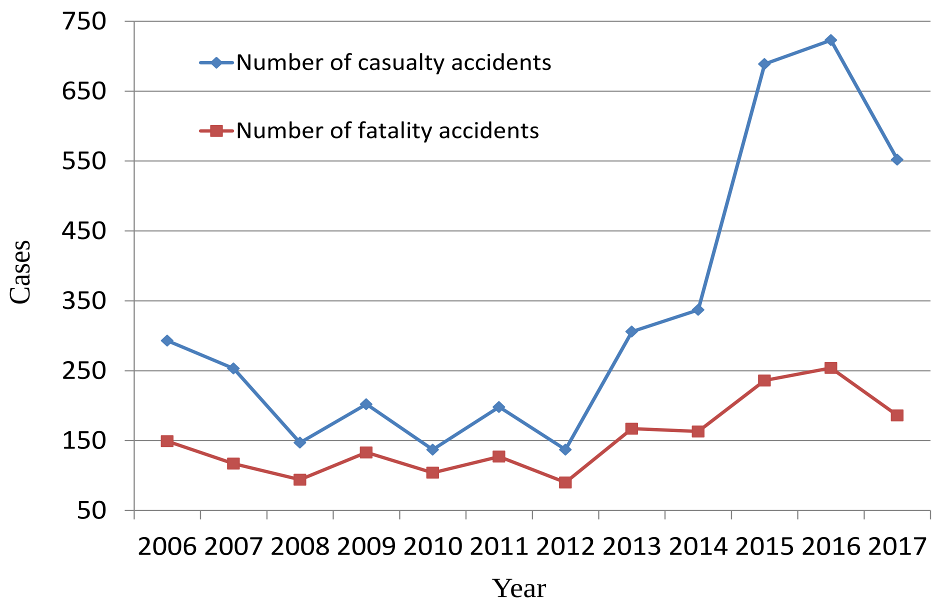

Figure 1. Number of casualty and fatality accidents in China from 2006 to 2017.

The number of fatalities peaked in 2015, reaching 699 deaths (Figure 2). The reason for this is that several major HCAs occurred in 2015. One example is the Tianjin port warehouse explosion, in which 178 people were killed and 677 people were injured. China's safety management of hazardous chemicals requires further improvement.

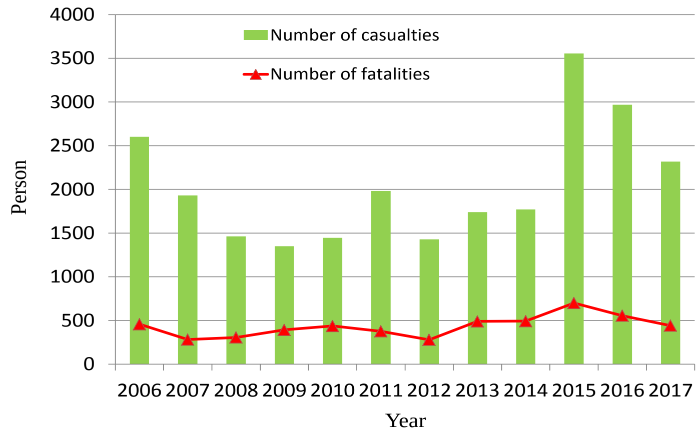

Figure 2. Number of casualties and fatalities in China from 2006 to 2017.

3.2. The Distribution of Casualty Accidents over Time

The average monthly distribution of the 3974 casualty accidents is summarized in Figure 3. The accidents show seasonal variance. There are more accidents in months from April to August than in the other months in the year. From May to August, more than 350 casualty accidents occur each month. This is mainly related to the weather in China. In most parts of China, spring and summer are the seasons with the most rain and the highest temperatures, while autumn and winter are the seasons with clear days and low temperature. On warm and humid days, the likelihood of casualty accidents increases. Weather, as an external factor, significantly affects the number of incidents. Of the winter months, December and January have relatively more accidents. This is because prior to the Spring Festival, there is usually a large demand for hazardous chemicals, such as fire crackers. Moreover, road traffic is often busy during this time period. Additionally, as the Spring Festival holidays approach, safety management is relaxed and workers' safety consciousness is quite low. All of these factors lead to an increase in the number of accidents, even on cold winter days.

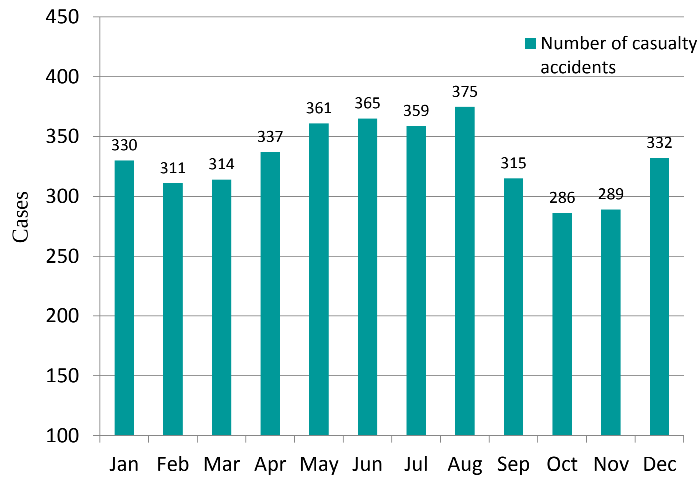

Figure 3. Monthly distribution of casualty accidents in China from 2006 to 2017.

The distribution of casualty accidents within an average day is shown in Figure 4. This fits well with working hours. The number of accidents is low before 6:00 am and after 5:00 pm, which represents the fact that there are fewer HCAs before and after working hours. The number of casualty accidents gradually increases from 6:00 am and reaches a peak at 10:00 am. Then it starts to decrease as lunch time approaches. During the lunch break, normally between 12:00 pm and 1:00 pm, the number of accidents is relatively low, but it peaks again between 2:00 pm and 4:00 pm. Most accidents happen during working hours. The accidents before and after working hours are likely related to storage, utilization, and sometimes transportation of hazardous chemicals.

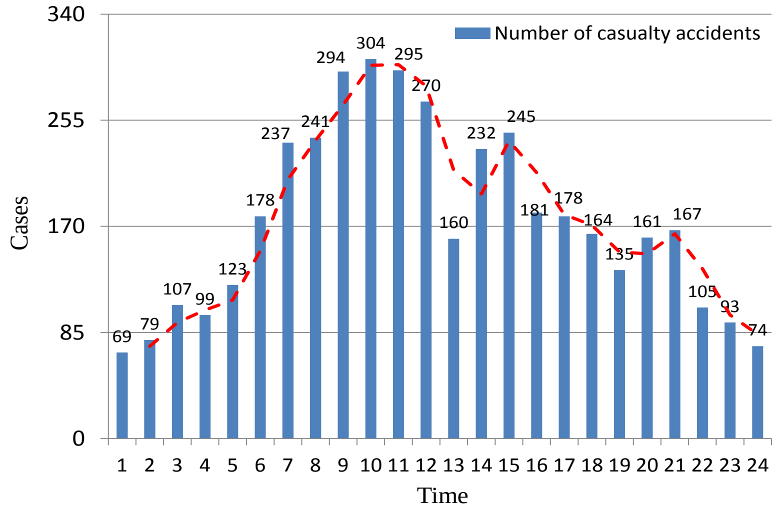

Figure 4. Hourly distribution of casualty accidents in China from 2006 to May 2018.

3.3. The Distribution of Casualty Accidents over the Lifecycle of Hazardous Chemicals

The majority of casualty accidents occur during utilization, transportation, production, and storage (Table 1). Regarding the frequency of incidents, utilization ranks first, accounting for 44.6% of the total number of casualty accidents, since the utilization of liquefied gases and firecrackers is the most prone to generate accidents. Transportation and production rank second and third respectively, followed by storage. 79.92% of fatality accidents occur during utilization, production, and transportation. Regarding the severity of incidents, the production stage causes the highest number of fatalities, almost one-third of the total fatalities. The utilization stage ranks second, resulting in 25.45% of fatalities. The transportation and storage stages rank third and fourth, respectively. However, the utilization stage leads to more injured people. Major accidents occur primarily during production, utilization, transportation and storage, which are the most critical stages of hazardous chemicals management. Accidents with fewer than 3 deaths occur primarily during the sales and disposal stages. Much emphasis has been on the production, transportation and storage of hazardous chemicals. However, our analysis shows that the utilization of hazardous chemicals is actually a stage with high risk. Greater effort should be allocated to the safety management of hazardous chemicals during the utilization stage.

Table 1. Number of casualties and fatalities during the life cycle.

Lifecycle	Number of Casualty Accidents (Cases)	Percent (%)	Number of Fatality Accidents (Cases)	Percent (%)	Number of Deaths (Person)	Percent (%)	Number of Casualties (Person)	Percent (%)	Major HCAs (Cases)
Production	736	17.56	513	27.33	1649	30.94	6658	26.52	239
Storage	345	8.23	189	10.07	746	14.0	3968	15.8	78
Transportation	928	22.14	405	21.58	1110	20.83	4321	17.21	113
Utilization	1869	44.60	582	31.01	1356	25.45	7831	31.19	164
Sales	37	0.88	16	0.85	31	0.58	221	0.88	6
Disposal	276	6.59	172	9.16	437	8.20	2109	8.4	79
Total	4191	100	1877	100	5329	100	25,108	100	679

The trends of casualty accidents occurring during different lifecycle stages are not the same (Figure 5). The number of casualty accidents occurring during sales displays a downward trend while the number of casualty accidents occurring during production and storage fluctuates. Moreover, the number of casualty accidents during utilization, transportation, and disposal increases. This is primarily because safety management efforts are devoted to the production, sales, and storage of hazardous materials but not to the utilization and disposal of hazardous materials, as we mentioned above. Therefore, safety management should focus more on the management of utilization, transportation, and disposal of hazardous chemicals. Meanwhile, one integrated system for tracking hazardous chemicals from production to disposal is needed to ensure the seamless control of hazardous chemicals.

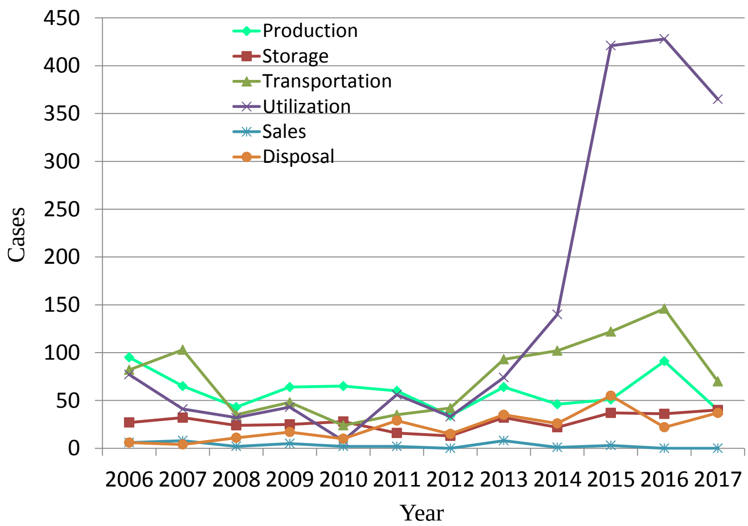

Figure 5. Number of casualty accidents occurring during different stages of the lifecycle.

3.4. *The Distribution of Casualty Accidents by Chemical Types*

Based on the national standard "Hazardous Chemicals Classification and Code" (GB 6944-2005), casualty accidents can be classified by the chemical types shown in Table 2. Currently, the primary hazardous chemicals involved in casualty accidents are compressed or liquefied gases and flammable liquid. Casualty accidents involving compressed or liquefied gases represent 41.09% of all accidents, more than one third of all accidents.

Table 2. Distribution of casualty accidents by chemical types in China from January 2006 to May 2018.

Chemical Types	Casualty Accidents (Cases)	Percent (%)
Compressed or liquefied gases	1722	41.09
Flammable liquid	836	19.95
Explosives	479	11.43
Combustible solid chemicals	451	10.76
Oxidant, organic peroxides	340	8.11
Corrosions	236	5.63
Others	127	3.03

3.5. The Distribution of Casualty Accidents by Accident Types

Based on the classification of accident types, the distribution of casualty accidents is shown in Table 3. The major types of casualty accidents are leakage and explosion, accounting for 59.51% of all casualty accidents. Fire ranks third, accounting for 23.98% of the total casualty accidents. If these three types of accidents could be reduced by 50%, then the total number of casualty accidents would fall by 42%. Measures that prevent explosion, leakage, and fire are especially effective for reducing the number of accidents. Note that some accidents may be counted repeatedly in Table 3, since an accident may involve several accident types.

Table 3. Distribution of casualty accidents by accident types in China from January 2006 to May 2018.

Accident Types	Explosion	Leakage	Fire	Poisoning and Suffocation	Burn	Others
Casualty accidents (cases)	2096	1820	1578	862	100	124
Percent (%)	31.85	27.66	23.98	13.10	1.52	1.89

3.6. Causes of Accidents

Based on the "Production Safety Accident Investigation and Handling Rules" issued by the SAWS [1], the causes of HCAs can be categorized into direct causes and indirect causes, as shown in Tables 4 and 5.

Table 4. Direct causes of HCAs in China from January 2006 to May 2018.

<table>
<tr><th colspan="2">Direct Causes</th><th>Casualty Accidents (Cases)</th><th>Percent (%)</th></tr>
<tr><td rowspan="3">Unsafe state of machinery, chemicals or the environment</td><td>No or defective devices for warning and safety protection</td><td>966</td><td>23.05</td></tr>
<tr><td>Defective equipment, facilities, tools, or accessories</td><td>725</td><td>17.30</td></tr>
<tr><td>Poor environment</td><td>295</td><td>7.04</td></tr>
<tr><td rowspan="3">Unsafe behavior of personnel</td><td>Operation violation</td><td>986</td><td>23.53</td></tr>
<tr><td>Improper maintenance</td><td>800</td><td>19.09</td></tr>
<tr><td>No or improper on-site guidance</td><td>343</td><td>8.18</td></tr>
<tr><td colspan="2">Unknown reasons</td><td>76</td><td>1.81</td></tr>
</table>

We further classified the direct causes of HCAs into "Unsafe state of machinery, chemicals or the environment", which represent causes related to objects, and "Unsafe behavior of personnel", which are causes related to humans. Table 4 shows that both unsafe objects and unsafe human behavior are critical causes of HCAs. "Operation violation" ranks highest in direct causes, followed by "No or defective devices for warning and safety protection" and "Improper maintenance", respectively.

Table 5. Indirect causes of HCAs in China from January 2006 to May 2018.

Indirect Causes	Casualty Accidents (Cases)	Percent (%)
Insufficient production safety training	1190	28.39
No or inadequate preventive measures	972	23.19
No or inadequate safety operation procedures	556	13.27
Contingency plans not implemented	336	8.02
No on-site inspection or misguidance	185	4.41
Unreasonable work plan	142	3.39
Disadvantage in technology and design	479	11.43
Unknown reasons	331	7.90

In indirect causes, "Insufficient production safety training" is the major reason for casualty accidents. "No or inadequate preventive measures" and "No or inadequate safety operation procedures" are also important causes. More safety training in firms is needed to reduce the number of casualty accidents.

4. The Probability of Casualty Accidents

Based on the distribution of casualty accidents from 2006 to 2017, as shown in Table 6, we used the Poisson regression model to estimate the probability of the number of casualty accidents in China. Table 7 shows the probability of casualty accidents and the cumulative probability distribution. As shown in Table 7, the probability of there being fewer than 100 cases per year is small, at only 15.74%; the probability of there being 200 to 600 cases per year is 59.10%; and the probability of there being more than 700 cases per year is again very small, at only 2.01%. It is highly likely that 200 to 600 casualty accidents will occur each year in China.

Table 6. Distribution of casualty accidents in China from 2006 to 2017.

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Hundred cases	2.93	2.53	1.47	2.02	1.37	1.98	1.37	3.06	3.37	6.89	7.23	5.52

Table 7. Probability of casualty accidents in China.

Hundred Cases	0	1	2	3	4	5	6	7	8
Probability	0.0365	0.1209	0.2000	0.2207	0.1826	0.1209	0.0667	0.0315	0.0130
Accumulated probability	0.0365	0.1574	0.3574	0.5781	0.7608	0.8817	0.9484	0.9799	0.9930

5. The Forecast of Casualty Accidents

The forecast for the number of casualty accidents in 2018 is based on the number of casualty accidents from January 2006 to December 2017 using a time series model. Considering that casualty accidents have seasonal characteristics, the original casualty accidents data are adjusted, as shown in Figure 6. The seasonally adjusted data are smoother and have higher regularity than the original data. The seasonal adjustment factors (SAF) are shown in Table 8.

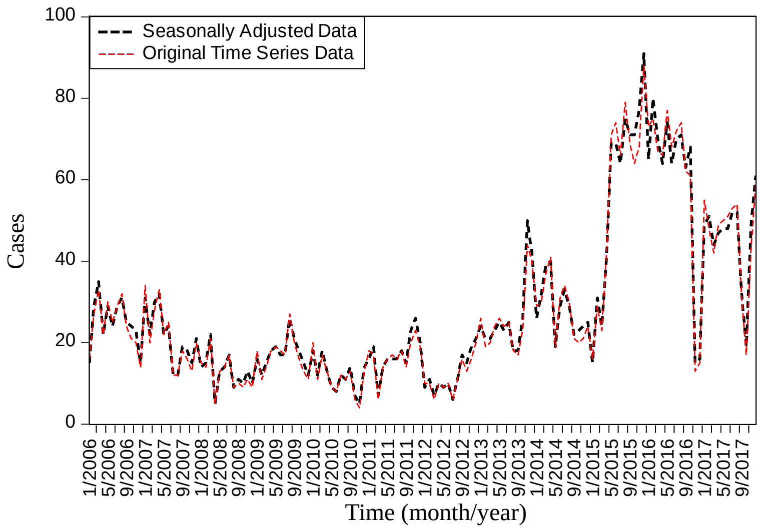

Figure 6. Seasonally adjusted data and original time series data for casualty accidents.

Table 8. Seasonal adjustment factors (SAF).

Month	1	2	3	4	5	6	7	8	9	10	11	12
SAF	1.126	0.943	0.965	1.047	1.043	1.074	1.033	1.057	0.985	0.902	0.886	0.968

The Augmented Dickey-Fuller (ADF) test is applied to validate the stability of the adjusted series, producing a result of -1.679273, meaning that the seasonally adjusted data have a unit root. Then, by implementing the first-order difference, the value of ADF is equal to -11.95606, which is less than the critical values of the 1%, 5%, and 10% significance levels, demonstrating that the seasonally adjusted data have no unit root and that the seasonally adjusted data are a stable series with no stochastic trend after implementing the first-order difference.

Then, the models ARIMA (1, 1, 0), ARIMA (0, 1, 1), ARIMA (2, 1, 0), ARIMA (0, 1, 2), and ARIMA (1, 1, 1) are tested to fit the seasonally adjusted data implementing the first-order difference. Based on the proximity of the Durbin-Watson (DW) statistic to the value of 2, the lower Akaike Information Criterion (AIC) and Schwarz Criterion (SC), and the higher Adjusted R-squared, ARIMA (2, 1, 0) is chosen as the best-fitted model (Table 9). To further test the validity of the model ARIMA (2, 1, 0), the Breusch-Godfrey Serial Correlation LM Test is used to test the residuals. The result shows that the model ARIMA (2, 1, 0) is valid and can be chosen to predict the number of casualty accidents.

Table 9. Results of parameter estimation for ARIMA models.

Model	Parameter	DW	AIC	SC	Adjusted R-Squared
ARIMA (1, 1, 0)	AR (1)	2.056496	7.388666	7.430104	0.022931
ARIMA (0, 1, 1)	MA (1)	1.786861	7.353132	7.394570	0.057775
ARIMA (2, 1, 0)	AR (1) AR (2)	2.002852	7.316376	7.378533	0.098522
ARIMA (0, 1, 2)	MA (1) MA (2)	1.990527	7.310842	7.373000	0.103587
ARIMA (1, 1, 1)	AR (1) MA (1)	1.891109	7.333201	7.395359	0.083054

According to the ARIMA (2, 1, 0) model, we obtained the fitting Equation (5):

$$\Delta y_t = -0.240923\Delta y_{t-1} - 0.302275\Delta y_{t-2} \tag{5}$$

where $\{\Delta y_t = y_t - y_{t-1}\}$ represents the first-order difference of the casualty accident time series.

Applying Equation (5) to forecast the number of casualty accidents in 2018 and applying the seasonal adjustment to the data, we forecast the number of casualty accidents as shown in Table 10.

Table 10. Prediction of the number of casualty accidents in 2018.

Month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Casualty accidents (cases)	44	51	54	49	49	48	49	48	53	60	58	52	615

6. Analysis of the Safety Management of Hazardous Chemicals

Figure 7 shows the total number of casualty accidents and the total output of the petrochemical industry for each province in China from 2006 to 2016. Obviously, Shandong, Jiangsu, Guangdong, Zhejiang, Liaoning, Henan, and Shanghai have a stronger petrochemical industry than other provinces. Meanwhile, there is a significant imbalance in the number of casualty accidents in different provinces and regions. For example, casualty accidents occurred primarily in the southeastern coastal provinces, where economic development is more rapid. Jiangsu, Guangdong, Zhejiang, and Shandong are the top four provinces for casualty accidents. The number of casualty accidents in these provinces exceeds 240. The provinces located in the northern and western parts of the country have fewer casualty accidents, and their economic development is relatively slow. Economic activities, especially those related to hazardous chemicals, such as the production, storage, transportation, sales, utilization, and disposal of hazardous chemicals, have the potential to generate HCAs. Therefore, the number of HCAs or casualty accidents alone cannot represent the safety management level. The level of economic development should also be considered when the hazardous chemical safety management level is evaluated.

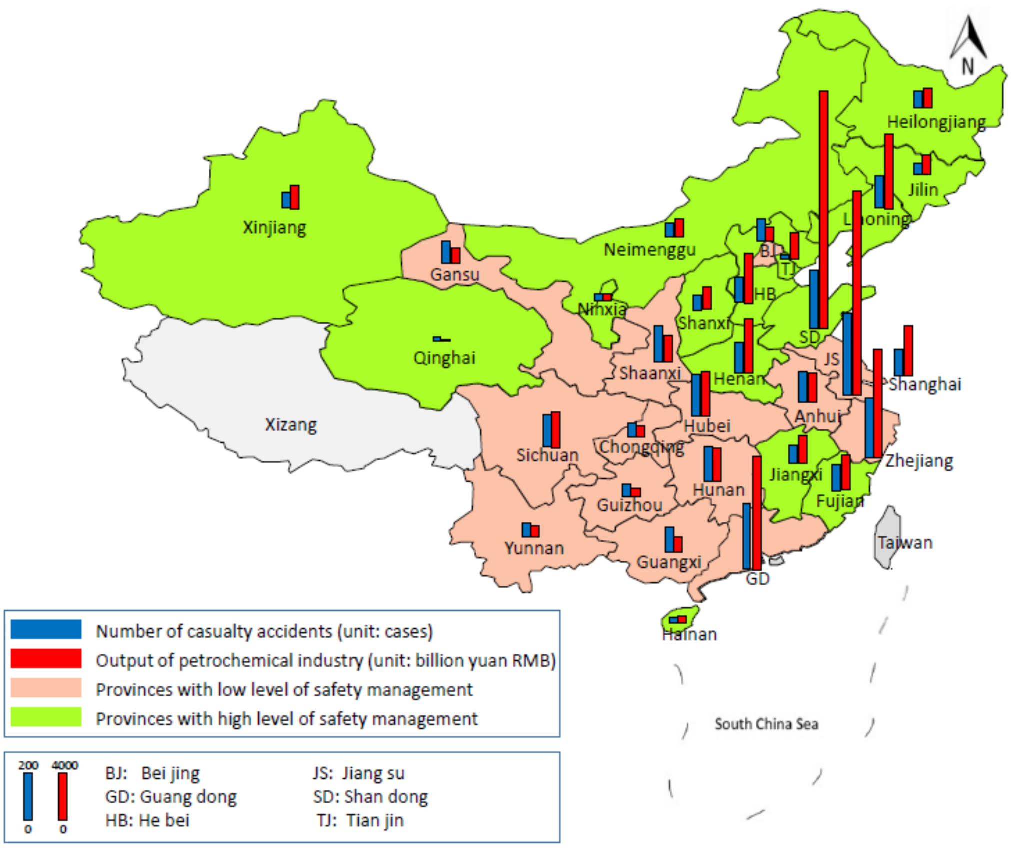

Figure 7. Distribution of casualty accidents (cases) and petrochemical industry outputs (RMB: renminbi) in 30 provinces.

To further analyze the hazardous chemical safety management level, we calculated the average frequency of casualty accidents for each province and compared it to the average petrochemical industry output of that province based on the data from 2006 to 2016, as shown in Figure 8. Equation (4) is used to fit the number of casualty accidents and the output of the petrochemical industry, resulting in the equation:

$$y = -0.0011x^2 + 0.3457x + 2.5545 \tag{6}$$

The correlation coefficient is 0.8345, indicating that the inverted U-shaped Kuznets curve significantly represents the relationship between the number of casualty accidents and the petrochemical industry output. Moreover, p value is less than 0.01, implying that the regression Equation (6) is significant.

To rank the safety management level of 30 provinces, Equation (7) is used to calculate the distance difference between each province and the safety Kuznets curve (Figure 8), where s_i, y_i, and x_i represent the distance difference, number of casualty accidents, and petrochemical industry output of province i, respectively. Then, the safety management level of each province is measured by the distance difference. The larger the value of s_i is, the higher the ranking and safety management level. Negative and positive values of s_i indicate that the province i is above and below the Kuznets curve, respectively. Naturally, the case of $s_i = 0$ represents that the province i is on the Kuznets curve.

$$s_i = -0.0011x_i^2 + 0.3457x_i + 2.5545 - y_i \tag{7}$$

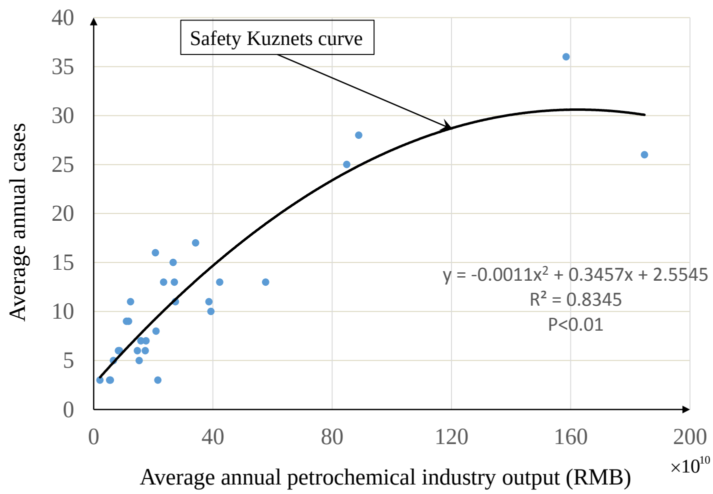

Figure 8. Evaluation of safety management for hazardous chemicals in 30 provinces based on safety Kuznets curve.

In Figure 8, the 14 provinces located above the curve, including Jiangsu, Zhejiang, Guangdong, Hubei, Shaanxi, Hunan, Sichuan, Chongqing, Beijing, Anhui, Guangxi, Yunnan, Guizhou, and Gansu, have lower levels of hazardous chemical management because they have relatively more casualty accidents compared with their petrochemical industry outputs (Figures 7 and 8). The higher the province is above the curve, the lower its safety management level, indicating the need for more safety measures to reduce the frequency of accidents. The 16 provinces located below the curve, including Shanghai, Shandong, Liaoning, Hebei, Tianjin, Henan, Shanxi, Jiangxi, Jilin, Fujian, Heilongjiang, Hainan, Ninxia, Neimenggu, Xinjiang, and Qinghai, are superior in safety management of hazardous chemicals (Figures 7 and 8). The lower the province is below the curve, the higher its level of safety management. For example, Shanghai and Shandong have higher safety management levels, as they have taken effective measures to reduce the risk of hazardous chemicals. In their practices, large hazardous chemical enterprises are required to be located in industrial parks, where centralized management is implemented. The ranking of the 30 provinces with respect to the safety management of hazardous chemicals is given in Table 11. Tianjin, Liaoning, Shanghai, Hebei, and Shandong are the top five provinces for safety management. In particular, although a warehouse explosion occurred in Tianjin port in 2015, Tianjin still ranks first because it has low casualty accidents compared with its petrochemical industry outputs during 2006–2016. However, Hubei, Hunan, Guangxi, Jiangsu, and Shaanxi have lower safety management levels, and Shaanxi ranks last.

Table 11. Ranking of 30 provinces for safety management of hazardous chemicals.

Province	Ranking	Distance Difference	Province	Ranking	Distance Difference
Tianjin	1	6.4986	Fujian	16	0.2104
Liaoning	2	5.8397	Guizhou	17	−0.2039
Shanghai	3	4.4575	Yunnan	18	−0.5295
Hebei	4	3.2836	Chongqing	19	−0.6404
Shandong	5	2.8765	Zhejiang	20	−1.0257
Jilin	6	2.5879	Sichuan	21	−1.8829
Shanxi	7	2.2185	Gansu	22	−2.5376
Henan	8	2.2054	Beijing	23	−2.7749
Hainan	9	1.4662	Anhui	24	−2.9412
Neimenggu	10	1.3907	Guangdong	25	−3.4036
Ninxia	11	1.3890	Hubei	26	−3.9025
Jiangxi	12	1.3084	Hunan	27	−4.0118
Xinjiang	13	1.2986	Guangxi	28	−4.3280
Heilongjiang	14	0.7646	Jiangsu	29	−6.2864
Qinghai	15	0.2891	Shaanxi	30	−6.7443

7. Measures to Improve the Safety Management of Hazardous Chemicals in China

The rapid development of the petrochemical industry in China has brought with it greater challenges from HCAs. Currently, China lacks systematic safety management of hazardous chemicals. A framework for continuous improvement of safety management is proposed in Figure 9. HCA analysis reflects when and where HCAs frequently occur, indicating where greater efforts in safety management are necessary. The probability and forecast of HCAs show the potential for accidents to occur in the future, helping managers to prepare for accident prevention and to increase awareness and improve the response capacity. The safety management evaluation shows the safety management level of each province, identifying provinces that need to improve safety management. When safety management measures are implemented, the characteristics of HCAs can be changed. Therefore, further data collection, analysis, forecast, and evaluation should be conducted to identify new safety management measures. With this continuous safety management improvement process, we can expect to have fewer HCAs, less severe HCAs, and better environment protection and sustainable development.

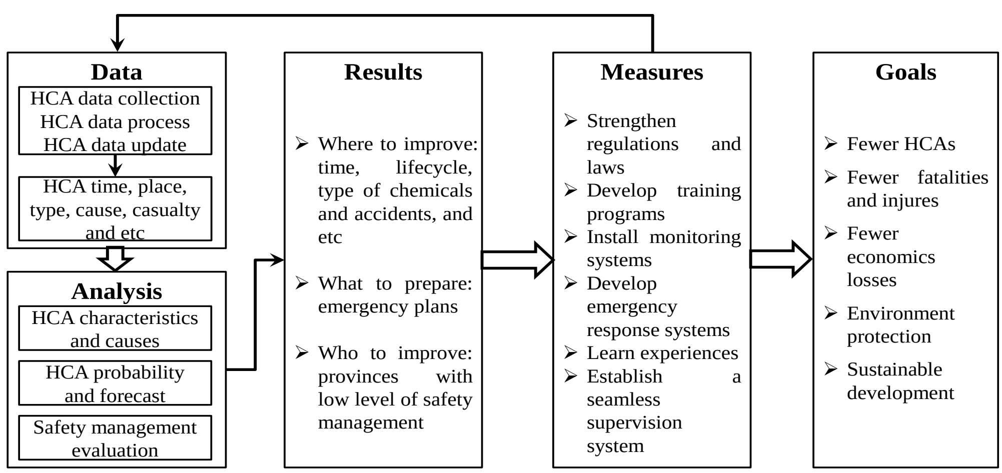

Figure 9. A framework for continuous improvement in safety management.

7.1. Safety Management Measures Based on HCA Analysis

1. Based on the analysis of time distribution of casualty accidents, we argue that safety management efforts should be devoted to spring and summer and 9:00–10:00 am and 2:00–4:00 pm during the day.
2. The majority of casualty accidents happen during transportation and utilization. Advanced technologies, such as global position system (GPS), geographic information system (GIS), electronic toll charge (ETC), and mobile networks can be used to establish an inter-provincial and inter-city monitoring system, resulting in seamless supervision. Moreover, stronger regulation and standard procedures for the utilization of hazardous chemicals are needed. Developing effective training programs for the utilization of hazardous chemicals is also a necessity. The production stage causes almost one-third of the total fatalities, since it involves large amounts of raw chemicals, auxiliary chemicals, and semi-finished and finished products, all of which are very dangerous. Firms that produce hazardous materials should be relocated into a special chemical production zone, in which the management of chemical production is centralized. This relocation can significantly improve the efficiency of management. Storage of hazardous chemicals also results in high casualties. Thus, storage companies must install monitoring systems that provide real-time observations of the environmental factors and the storage facilities. The rapid notification of an HCA occurrence would allow it to be addressed in a timely manner.
3. Compressed or liquefied gases are the most commonly involved chemicals in HCAs. Specific rules or working processes for the production, transportation, and storage of such chemicals need to be implemented to reduce the possibility of related HCAs.
4. The cause analysis shows that firms should implement devices for warning and safety protection. For those who have these devices in place, it is important to check whether these devices work properly. The human aspect is also important. Firms should raise staff risk awareness to prevent operational violations and improper maintenance. More training in the safety management of hazardous chemicals is needed.

7.2. Safety Management Measures Based on Probability and Forecast of HCAs

(1) Based on the probability analysis of casualty accidents, it is highly likely that 200 to 600 casualty accidents will occur each year in China. Thus, to reduce the occurrence of accidents, preventive measures should be taken. Moreover, building a resilient system is necessary for responding to unanticipated disturbances and resuming normal operations quickly [43,44].

(2) The forecast of casualty accidents can provide the basis for emergency response preparation. Considering that hazardous chemicals are usually toxic, flammable, and explosive, and that HCAs may easily lead to secondary disasters such as explosions and chemical pollution, the design of an emergency response system must consider and strengthen the linkage mechanism of agencies including fire departments, safety supervisors, environmental protection, and health, to support a robust emergency response capability.

7.3. Safety Management Measures Based on Safety Management Evaluation

(1) Jiangsu, Zhejiang, Guangdong, Hubei and 10 other provinces are identified as having lower safety management levels. These 14 provinces should be required to take specific actions for the safety management of hazardous chemicals. Within these 14 provinces, Jiangsu, Guangdong, Zhejiang, and Shandong are the top four for the number of casualty accidents in the last 11 years. Stricter supervision and more frequent checks for the safety management of these four provinces are necessary.

(2) Shandong, Shanghai and some other provinces do better in safety management. Some of their best practices should be disseminated to other provinces. Meetings, conferences, and

on-site investigation should be held periodically to disseminate effective measures, technologies, and procedures.

(3) A seamless supervision system for hazardous chemicals should be established and collaborations among the provinces in safety management need to be enhanced. HCAs normally happen in the production, transportation, storage, and utilization stages in different provinces. Currently, each province manages its own hazardous chemicals without much information exchange with other provinces. As a result, no province has a clear picture of its own hazardous chemical situation, which is a key difficulty for safety management. If a seamless supervision system is established, and data of hazardous chemicals are all input into the system and shared, it would be possible to supervise the whole lifecycle of hazardous chemicals, from production to utilization and disposal, and to make each province aware of its own situation.

8. Conclusions

This study comprehensively analyzes the characteristics and causes of 3974 hazardous chemical casualty accidents that occurred between 2006 and 2017 in China. The Poisson regression model is applied to estimate the probability of casualty accidents, and the time series model is developed to forecast the number of casualty accidents. Evaluation of the safety management level of 30 provinces is conducted using the inverted U-shaped curve similar to the environmental Kuznets curve. Finally, based on our analysis and evaluation, we propose measures to improve the management of hazardous chemicals. This study contributes to the body of knowledge on safety management of hazardous chemicals and provides approaches to estimate and forecast HCAs. In particular, using an inverted U-shaped Kuznets curve that fits the relationship between the number of casualty accidents and petrochemical industry outputs is a new attempt to evaluate the safety management of hazardous chemicals.

The statistical analysis shows that the number of casualty accidents declined from 2006 to 2008, fluctuated from 2008 to 2012, and increased rapidly from 2012 to 2017. April to August is the peak season for accidents each year. Each day, the number of casualty accidents peaks at 10 am and 3 pm. Casualty accidents primarily occurred during utilization, transportation, production, and storage. Compressed gases, liquefied gases, and flammable liquids are the primary types of chemicals causing accidents. Leakage and explosion are the primary types of accidents. Operation violation and insufficient production safety training are the major reasons causing accidents. The probability of the number of casualty accidents between 200 and 600 per year is 59.10% in China. More casualty accidents occur in eastern China, with its high economic development level. Sixteen provinces, including Shanghai, Shandong, and Tianjin, are identified as having higher safety management, while others, including Jiangsu, Zhejiang, Guangdong, and Hubei, have lower levels of hazardous chemical management.

There are several possible directions for future work. First, in this study, only the traditional Poisson model is employed to analyze accident frequency. However, when the data show over-dispersion or under-dispersion, other models, such as the negative binomial model, the Conway-Maxwell-Poisson model, the Bernoulli model, and the hurdle Poisson model may be better for fitting HCA frequency. Second, only the quadratic function regression model is applied to fit the relationship between the number of casualty accidents and petrochemical industry outputs. Future research can investigate and compare various alternate models. Third, the ranking of 30 provinces for safety management of hazardous chemicals is determined based on the evaluation of the inverted U-shaped curve. However, in practice, some provinces may have similar safety management levels. It would be more reasonable to consider a clustering analysis. Finally, since the safety management of hazardous chemicals is a complex socio-technical problem, it needs to be further studied from a resilience engineering perspective in future work.

Author Contributions: L.Z. designed the paper framework and research questions, and coordinated the research activities for reaching the proposed objectives of this study; Q.-M.H. conducted the primary research and analytical tasks; Y.Q. and Q.-M.H. wrote the paper; R.J. and M.L. collected and analyzed the data; X.W. provided valuable research insights into the analysis.

Funding: This research is supported by grants from National Natural Science Foundation of China (No. 70673012).

Acknowledgments: The authors would like to thank the anonymous reviewers of this journal.

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

References

1. Production Safety Accident Investigation and Handling Rules. Available online: http://www.gov.cn/flfg/2007-04/19/content_589264.htm (accessed on 13 October 2017).
2. Zhang, H.; Duan, H.; Zuo, J.; Song, M.; Zhang, Y.; Yang, B.; Niu, Y. Characterization of post-disaster environmental management for Hazardous Materials Incidents: Lessons learnt from the Tianjin warehouse explosion, China. *J. Environ. Manag.* **2017**, *199*, 21–30. [CrossRef] [PubMed]
3. Jorgensen, K. Audits, inspections and investigations: reporting and compiling accident statistics. In *ILO Encyclopedia of Occupational Health and Safety*; ILO: Geneva, Switzerland, 1998; pp. 1–31.
4. Chau, N.; Gauchard, G.C.; Siegfried, C.; Benamghar, L.; Dangelzer, J.L.; Français, M.; Jacquin, R.; Sourdot, A.; Perrin, P.P.; Mur, J.-M. Relationships of job, age, and life conditions with the causes and severity of occupational injuries in construction workers. *Int. Arch. Occup. Environ. Health* **2004**, *77*, 60–66. [CrossRef] [PubMed]
5. Hobeika, A.G.; Kim, S.; Sethuraman, R. Characteristics of hazardous-material accidents in Pennsylvania. *J. Transp. Eng.* **1993**, *119*, 226–238. [CrossRef]
6. Shorten, C.V.; Galloway, J.; Krebs, J.G.; Fleming, R.S. A 12-year history of hazardous materials incidents in Chester County, Pennsylvania. *J. Hazard. Mater.* **2002**, *89*, 29–40. [CrossRef]
7. Mannan, M.S.; O'Connor, T.M.; Keren, N. Patterns and trends in injuries due to chemicals based on OSHA occupational injury and illness statistics. *J. Hazard. Mater.* **2009**, *163*, 349–356. [CrossRef] [PubMed]
8. Darbra, R.M.; Palacios, A.; Casal, J. Domino effect in chemical accidents: main features and accident sequences. *J. Hazard. Mater.* **2010**, *183*, 565–573. [CrossRef] [PubMed]
9. Bubbico, R.; Di, C.S.; Mazzarotta, B.; Silvetti, B. Preliminary study on the transport of hazardous materials through tunnels. *Accid. Anal. Prev.* **2009**, *6*, 1199–1205. [CrossRef] [PubMed]
10. Cox, B.L.; Carpenter, A.R.; Ogle, R.A. Lessons learned from case studies of hazardous waste/chemical reactivity incidents. *Process Saf. Prog.* **2014**, *33*, 395–398. [CrossRef]
11. Dakkoune, A.; Vernières-Hassimi, L.; Leveneur, S.; Lefebvre, D.; Estel, L. Risk analysis of French chemical industry. *Saf. Sci.* **2018**, *105*, 77–85. [CrossRef]
12. Cocârţă, D.M.; Stoian, M.A.; Karademir, A. Crude oil contaminated sites: Evaluation by using risk assessment approach. *Sustainability* **2017**, *9*, 1365. [CrossRef]
13. Papazoglou, I.A.; Aneziris, O.; Konstandinidou, M.; Giakoumatos, I. Accident sequence analysis for sites producing and storing explosives. *Accid. Anal. Prev.* **2009**, *41*, 1145–1154. [CrossRef] [PubMed]
14. Raemdonck, K.V.; Macharis, C.; Mairesse, O. Risk analysis system for the transport of hazardous materials. *J. Safety Res.* **2013**, *45*, 55–63. [CrossRef] [PubMed]
15. Verslycke, T.; Reid, K.; Bowers, T.; Thakali, S.; Lewis, A.; Sanders, J.; Tuck, D. The chemistry scoring index (CSI): A hazard-based scoring and ranking tool for chemicals and products used in the oil and gas industry. *Sustainability* **2014**, *6*, 3993–4009. [CrossRef]
16. Heo, S.; Kim, M.; Yu, H.; Lee, W.K.; Sohn, J.R.; Jung, S.Y.; Moon, K.W.; Byeon, S.H. Chemical accident hazard assessment by spatial analysis of chemical factories and accident records in South Korea. *Int. J. Disaster Risk Reduct.* **2018**, *27*, 37–47. [CrossRef]
17. Trulli, E.; Morosini, C.; Rada, E.C.; Torretta, V. Remediation in situ of hydrocarbons by combined treatment in a contaminated alluvial soil due to an accidental spill of LNAPL. *Sustainability* **2016**, *8*, 1086. [CrossRef]
18. Zhong, M.; Shi, C.; Fu, T.; He, L.; Shi, J. Study in performance analysis of China Urban Emergency Response System based on Petri net. *Saf. Sci.* **2010**, *48*, 755–762. [CrossRef]
19. Hosseinnia, B.; Khakzad, N.; Reniers, G. Multi-plant emergency response for tackling major accidents in chemical industrial areas. *Saf. Sci.* **2018**, *102*, 275–289. [CrossRef]

20. Tao, Y. Analysis and countermeasure study on accidents of dangerous chemicals (in Chinese). *Safety* **2010**, *31*, 21–23.
21. Xin, C.L.; Wang, J.L. Review on historical analysis of accidents in the transportation of hazardous materials. *Chin. Safety Sci. J.* **2012**, *22*, 89–94.
22. He, G.; Zhang, L.; Lu, Y.; Mol, A.P. Managing major chemical accidents in China: Towards effective risk information. *J. Hazard. Mater.* **2011**, *187*, 171. [CrossRef] [PubMed]
23. Li, J.; Bai, X.; Ren, Z.; Wu, J. Statistic analysis and countermeasures of hazardous chemicals accidents occurring in China during 2011–2013. *J. Safety Sci. Technol.* **2014**, *10*, 142–147.
24. Yang, J.; Li, F.; Zhou, J.; Zhang, L.; Huang, L.; Bi, J. A survey on hazardous materials accidents during road transport in China from 2000 to 2008. *J. Hazard. Mater.* **2010**, *184*, 647–653. [CrossRef] [PubMed]
25. Tong, S.J.; Wu, Z.Z.; Wang, R.J.; Duo, Y.Q.; Yi, G.X. Statistical analysis and countermeasures on larger and above grades accidents of dangerous chemical enterprises from 2001 to 2013. *J. Safety Sci. Technol.* **2015**, *11*, 129–134.
26. Wei, G.; Yang, Z.; Li, Y. A statistic analysis and countermeasures on non-explosive dangerous chemical accidents in recent in 3 years. *J. Beijing Norm. Univ.* **2005**, *41*, 209–212.
27. Liu, X.; Zhou, R. Analysis on typical serious accidents of caused by dangerous chemicals in China and their prevention countermeasures. *Chin. Safety Sci. J.* **2004**, *14*, 87–91.
28. Duan, W.; Chen, G.; Ye, Q.; Chen, Q. The situation of hazardous chemical accidents in China between 2000 and 2006. *J. Hazard. Mater.* **2011**, *186*, 1489–1494. [CrossRef] [PubMed]
29. Zhang, H.D.; Zheng, X.P. Characteristics of hazardous chemical accidents in China: A statistical investigation. *J. Loss Prev. Process Ind.* **2012**, *25*, 686–693. [CrossRef]
30. Zhao, L.J.; Wu, P.; Xu, K. Statistic analysis and countermeasures on dangerous chemical accidents in China. *Chin. Safety Sci. J.* **2009**, *19*, 165–170.
31. Zhao, L.; Wang, X.; Qian, Y. Analysis of factors that influence hazardous material transportation accidents based on Bayesian networks: A case study in China. *Saf. Sci.* **2012**, *50*, 1049–1055. [CrossRef]
32. SAWS. State Administration of Work Safety. Available online: http://www.chinasafety.gov.cn (accessed on 4 August 2018).
33. National Registration Center for Chemicals. Available online: http://www.nrcc.com.cn (accessed on 4 August 2018).
34. China Safety Production. Available online: http://www.aqsc.cn (accessed on 4 August 2018).
35. Safety Culture. Available online: http://www.anquan.com.cn (accessed on 4 August 2018).
36. Safety Management. Available online: http://www.safehoo.com (accessed on 4 August 2018).
37. Guo Yin safety. Available online: http://www.safety.com.cn (accessed on 4 August 2018).
38. Lu, P.; Tolliver, D. Accident prediction model for public highway-rail grade crossings. *Accid. Anal. Prev.* **2016**, *90*, 73–81. [CrossRef] [PubMed]
39. Nicholson, A.; Wong, Y.D. Are accidents poisson distributed? A statistical test. *Accid. Anal. Prev.* **1993**, *25*, 91–97. [CrossRef]
40. Hillmer, S.C.; Tiao, G.C. An ARIMA-model-based approach to seasonal adjustment. *J. Am. Stat. Assoc.* **1982**, *77*, 63–70. [CrossRef]
41. Findley, D.F.; Hood, C.C. X-12-ARIMA and Its Application to Some Italian Indicator Series. U.S. Census Bureau: Washington, DC, USA, 1999. Available online: http://www.census.gov/ts/papers/x12istat.pdf (accessed on 4 August 2018).
42. Birrell, C.L.; Steel, D.G.; Lin, Y.X. Seasonal adjustment of an aggregate series using univariate and multivariate basic structural models. *J. Stat. Theory Pr.* **2011**, *5*, 179–205. [CrossRef]
43. Hollnagel, E. *Safety-I and Safety-II: The Past and Future of Safety Management*; CRC Press: London, UK, 2018.
44. Patriarca, R.; Bergström, J.; Di Gravio, G.; Costantino, F. Resilience engineering: Current status of the research and future challenges. *Saf. Sci.* **2018**, *102*, 79–100. [CrossRef]