Case study of the Tianjin accident: Application of barrier and systems analysis to understand challenges to industry loss prevention in emerging economies

Abstract

Accident analysis methods are widely used in industry to understand how companies with seemingly strong safety management systems failed to prevent a serious incident. These methods can equally be used to help governments, particularly in emerging economies, to analyse industrial incidents to understand how their institutions may be failing to control risk, providing insight into potential improvements while also extracting lessons for other emerging economies with similar risk profiles. The fire and explosion accident of the Ruihai hazardous goods warehouse at Tianjin Port, China, that occurred on 12 August 2015 is a prime example of a common emerging economy dilemma. Emerging economies typically struggle for years, sometimes decades, to build the capacity sufficient to address the challenges of sustainability that accompany rapid and wide-spread economic development. These economies experience particularly high rates of serious and catastrophic industrial disasters, with significantly higher rates of injury, death and environmental impacts in comparison to more mature developed economies. Yet, in many of these incidents, the country may already have some, or even substantial, legal frameworks in place to address industrial risk. In the case of Tianjin, China has strengthened industrial law substantially since the early 2000's to establish more rigorous control over chemical hazard sources. In this circumstance, understanding the sequence of events, and missed opportunities by various actors to prevent the accident and mitigate its impacts could provide support to targeted improvements to risk governance in China, and also other countries who are striving to impose a higher standard of industrial risk management. This paper describes a study in which accident analysis methods based on bow tie barrier analysis and safety systems theory were used to analyse the institutional failures that contributed to the occurrence and severity of the Tianjin disaster. The resulting analysis shows that the application of accident analysis methods to industrial disasters can highlight weaknesses in the evolving governance systems of emerging economies that may also offer lessons to other countries who are also on a similar path.

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Keywords:

Accident analysis; Hazardous chemical accident; Bow-tie; AcciMap

1. Introduction

To varying degrees emerging economies are actively seeking to build capacity to make their growing economies sustainable over the long term. Rapid economic growth is generally accompanied by a diverse range of negative impacts affecting the health of communities and the environment. As countries experience rapid economic development, they seek to adopt strategies to control the additional pressures on environment and health that threaten sustainability. Faced with more and more complex process operations, researchers develop a series of methods to reduce risks, although risks will never disappear (Florianne, Richart, Efraín, Christian and M. Sam Mannan, 2017). In many cases, these efforts require radical changes to the institutional systems that facilitate economic development, and the establishment of new responsibilities. However, as experts have noted it is far from easy to achieve radical change in many domains over a short period of time (Tukker, 2005).

In particular, many emerging economies face dramatic increases in risk from industrial accidents involving dangerous substances. **Fig. 1** shows results of a study conducted by the European Commission's Joint Research Centre (EC-JRC) of chemical accidents reported in the global media in 2017[1]. The data indicate far higher

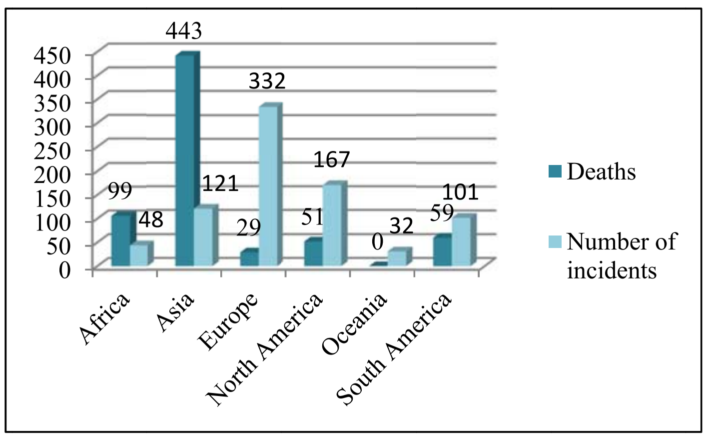

Fig. 1. Deaths reported in association with chemical incidents in the media by continent in 2017 (EC-JRC, 2019)

[1] Date Source: The GMI-CHEM database is a database owned and operated the Major Accident Hazards Bureau of the European Commission's Joint Research Centre (EC-JRC) since 2017 (https://minerva.jrc.ec.europa.eu/en/minerva). It consists of chemical accidents reported daily in local, regional and international news media from all over the world. The majority of reports are obtained from the Internet on a daily basis by the EC-JRC's EMM newsbrief (http://emm.newsbrief.eu).

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number of deaths from industrial accidents in Asia and Africa, continents that largely consist of emerging economies, than there are in Europe and North America that have high concentrations of developed countries.

Chemical disasters are tragic events whose only redeeming outcome may be in learning lessons so that the event never happens again. It is now generally believed that accidents may occur as result of a complex system phenomenon, in which causal factors reside at all levels of complex socio-technical systems, and interact across them (Rasmussen, 1997; Leveson, 2011). In essence, causality of the accident extends beyond site boundaries, such that failures in external risk controls in government and society may also be implicated. It follows then that proactive risk management of industrial accident risk should ensure an improved interaction among the decision making and planning strategies at all levels, advocated (Rasmussen et al., 2000). The principle is well-aligned with the theory of system safety whereby accidents are viewed as arising from the interactions among system components and failures in the system's operation or organization. It is also closely tied with organizational learning and the challenge of organizations in adapting practices to keep pace with change and increasing complexity (Dekker, 2011; Carroll, 2002).

In this sense, an industrial disaster in emerging economies represents an opportunity to learn the weaknesses and gaps in capacity building efforts. Capacity building is itself considered a multidimensional process. In guidelines developed by the OECD DAC in 2006, it is noted that "The 'best fit' approach to capacity development … calls for a systematic effort to think through what might work in the particular circumstances." Van Wijk et al. (2015) proposed a hierarchical process model for capacity building that consists of a structured set of processes hierarchically distributed at different levels of the system, e.g., operator, local government, national government, covering different domains such as human, financial and physical resources and the legal and administrative infrastructure. According to this model, each component at each level is necessary for implementing an effective (and sustainable) government programme for chemical accident risk reduction, as shown in Fig. 2.

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Fig. 2 - A conceptual hierarchical process model (Van Wijk et al., 2015)

Industrial accident risk management is a considerable challenge for emerging economies because it requires both industry and government to possess a high level of competence in principles of risk assessment and risk control of engineering processes together with substantial knowledge about properties of a myriad of dangerous substances that behave differently from each other in different circumstances. The OECD Guiding Principles for Chemical Accident Prevention and Preparedness (OECD, 2003) and the UNEP Flexible Framework (UNEP, 2012) give guidance on elements that should be in place to establish effective governance of chemical accident risk. The Flexible Framework additionally describes a process for governments seeking to strengthen their programmes, and provides a number of supporting tools. Wood et al. (2002) described the different stages of implementation of the EU Seveso Directive by the ten Central and Eastern European Countries, including different phases of the process, to achieve a high standard of industrial accident control. Yet, beyond these publications, the experiences and lessons learned of emerging economies in moving from weak governance to strong governance of chemical accident risks remains largely undocumented.

For this purpose, an analysis of the Tianjin accident using a system approach could be advantageous in revealing how the existing infrastructure failed to prevent or mitigate impacts of the Tianjin fire and explosion. Existing analyses of the Tianjin accident describe the process and physical and direct causes in detail, but pay less attention to the underlying causes in which intermediary agencies and supervisory authorities played an important role (Gui and Jianhao, 2016). This paper describes results of a study that applied two different methods to analyse the Tianjin event in order to understand how institutional failures contributed to the occurrence and severity of the event. Specifically, the study consisted of a synthetic application of the Bow-tie

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and AcciMap analytical methods that together would illustrate the extent to which the accident was a phenomenon resulting from a complex system of interlinked factors all contributing to create the catastrophe that ensured. The Bow-tie model, a combination of Fault Tree Analysis (FTA) and Event Tree Analysis methods (ETA), is a modeling approach that allows analysis of the causes of an event and consequences of an accident in high hazard industries (Ruijter and Guldenmund, 2016) from the perspective of internal process operations. In contrast, the Accimap method typically can help to identify organizational failures involving actors that are mostly external to the site across six organizational levels: government policy and budgeting; regulatory bodies and associations; local area government planning and budgeting (including company management); technical and operational management; physical processes and actor activities; and equipment and surroundings (Gao et al., 2015). The results of this analysis provide evidence that the Tianjin disaster emerged from critical failures in the business management and political infrastructure that were in place to protect workers and the surrounding community from a major industrial disaster. It also offers strong indications on actions that could be taken to reinforce the existing social and political infrastructure to reduce the possibility that a similar catastrophe could occur in China, and more generally, in other emerging economies.

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2. The Tianjian Fire and Explosion

At 22:51:46 on 12 August 2015, a fire broke out in the delivery zone of the Ruihai International Logistics hazardous goods warehouse located in Binhai New Area of the Tianjin city, China. (See Fig.3 for its geographical location) (The delivery zone is an abbreviated form of 'delivery zone for export goods awaiting declaration and shipment' and belongs to the customs supervision areas surrounded by metal fences and secluded from the rest of Binhai New Area.) The first explosion occurred at 23:34:06 then, followed by a second, more violent explosion at 23:34:37. Additionally, there were dozens of small fires at the scene of the accident. At 16:40 on 14 August, all the visible flames in the area were extinguished. The investigation team concluded that the fire and explosion of the Ruihai hazardous goods warehouse at Tianjin Port occurred on 12 August 2015 was an extremely serious accident related to work safety issues. (State Council of China, 2016)

Fig.3 Ruihai's geographical location

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At the time of the incident, several regulations and standards governed the control of industrial risks. The most important of these, in the context of the Tianjin disaster, are as follows:

1. The Business qualification permit: According to relevant laws and regulations（such as *the Port Law* and *the Port Management Regulations*）, the transportation, storage and operation of goods must be approved by the local transportation authority (such as the Tianjin Transportation and Port Administration, Tianjin Customs, Tianjin Transportation Committee, etc.), and supervised by the local government. Enterprises engaged in such business need to obtain administrative licenses or permits such as *The Port Operations Permit* and *The Annex Certificate for Hazardous Goods Operations at Ports*.

2. Regulations for urban planning and engineering construction: According to the laws and regulations, such as t*he Urban and Rural Planning Law*, the local government regulates the construction of the project by formulating and implementing urban planning with comprehensive consideration of environmental protection.

3. Regulations on the evaluation and management of industrial safety and environmental impact: China has enacted *the Environmental Protection Law*, *the Environmental Impact Assessment Law*, *the Environmental Assessment Technical Assessment Guidelines for Construction Projects (HJ616-2011)*, and *the Safety Evaluation Agency Supervision Regulations, the Administrative Measures for Environmental Protection Acceptance of Construction Projects Completion*. The local government is obliged to supervise and manage industrial construction and production to protect the environment and workers. The technical service organization is required to conduct a safety evaluation and an environmental impact assessment of the project in accordance with these technical regulations.

4. Regulations on the operation and management of dangerous goods: Due to the higher risk associated with hazardous substances, the government has also formulated a series of regulations, such as *the Safety Regulations for Loading and Unloading of Container Ports (GB11602-2007), the Safety Regulations for Port Operations of Dangerous Goods Container (JT397-2007), the Regulations on the Safety Management of Dangerous Chemicals, the Conditions and Technical Requirements for the Operation of Dangerous Chemicals Enterprises (GB18265-2000), the Special Equipment Safety Law, and the*

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Special Equipment Safety Supervision Regulations. Enterprises should follow the relevant operational procedures for managing dangerous goods safely and the local government should regulate and supervise that these obligations have been fulfilled accordingly.

5. According to *the Fire Control Law and the Tianjin Fire Control Regulations*, the public security organs should review all the documentation regarding fire prevention design of special construction projects that are stipulated by the Ministry of Public Security.

Before the accident occurred, the site had a history of operating without having fulfilled all the requirements of the law. Ruihai had constructed its hazardous storage yard before obtaining approval and conducted business during the construction. During several periods since it had opened its doors two years before, it ran its hazardous goods business without having the proper licenses, permits or approval. Moreover, it did not identify and assess the major hazard material that was present in its warehouse at Ports, nor report this information as requited to the Tianjin Transport Department. After the accident, evidence showed that, in 2015, Ruihai was processing a volume of hazardous goods that far exceeded the quantities stipulated in the permit, and the maximum quantities allowed for particularly dangerous substances such as potassium nitrate, sodium sulfide and sodium cyanide. (State Council of China, 2016)

It was in this context in which the accident sequence of events occurred, as described below:

(1) At 22:51:46 on 12 August 2015, a fire firstly broke out in the delivery zone of Ruihai International Logistics hazardous goods warehouse located at No. 95, Jiyun 2nd Road in Binhai New Area of Tianjin (39°02′22.98″ N, 117°44′11.64″ E.). The delivery zone was mainly intended for receiving exported cargo containers for customs inspections.

(2) At 22:52 on 12 August, both of the 110 Emergency Response Command Center of Tianjin Municipal Public Security Bureau and the 119 Emergency Response Command Center at Tianjin Municipal Fire Station received calls from Ruihai and the public.

(3) At 22:56, firefighters from the fourth brigade of Tianjin Port Public Security Bureau first arrived at the scene of accident. Subsequently, numerous fire-fighters

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arrived as reinforcements. Approximately 100 people, including staff in Ruihai and neighboring enterprises, were evacuated.

(4) At 23:34:06, the first explosion occurred. The intensity of the first explosion was equivalent to approximately 15 tons of TNT. (According to the simulations made by the State Key Laboratory of Explosion Science and Technology, similarly hereinafter).

(5) At 23:34:37, the second and more violent explosion occurred approximately 20 metres north-west away from the location of the first explosion, resulted from the fire and the blast wave caused by the first explosion. The intensity of the second explosion was equivalent to approximately 430 tons of TNT.

(6) According to the analysis by experts, the hazardous chemicals at the site could have generated several explosions; however, the actual damage was mainly caused by the two huge explosions mentioned above. It is confirmed by the investigation team that the total intensity of all the explosions involved in the accident was equivalent to approximately 450 tons of TNT.

(7) At 16:40 August 14, fire was extinguished at the scene.

3. Accident Analysis with Bow-tie

A bow-tie diagram is so-called because it looks like a "bow-tie". In the middle is the so-called "top event", representing the loss of control of the hazard. The spontaneous combustion of nitrocellulose is taken as the top event. The Fault Tree is on the left side of the top event, which depicts the prevention barriers which prohibit threats from resulting in the top event. It describes the process of the accident and the interrelationships among them (Mulcahy et al., 2017). The Event Tree is on the right side of the top event, which represents the barriers that prevent and mitigate the top event from escalating in to undesirable consequences. It shows how the event may generate different casualties and describes all possible consequences (Mulcahy et al., 2017; Ruijter and Guldenmund, 2016). The bow-tie analysis result is shown in Fig.4, and the failed barriers are framed.

3.1 Threat Analysis

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3.1.1 Top Event

The spontaneous combustion of nitrocellulose is taken as the top event, which ignited the nitrocellulose in the vicinity and gave out a large quantity of heat. The nitrocellulose container was damaged by fire. As a result, a large quantity of nitrocellulose spilt out of the container and set fire to a large area, where many hazardous chemicals in other containers successively caught fire. Ammonium nitrate reached its explosion temperature soon after the fire spread to the nearby containers of ammonium nitrate, which led to the first explosion. As a result of the fire spreading from the containers on the south side and the blast wave from the first explosion, the second and more violent explosion occurred.

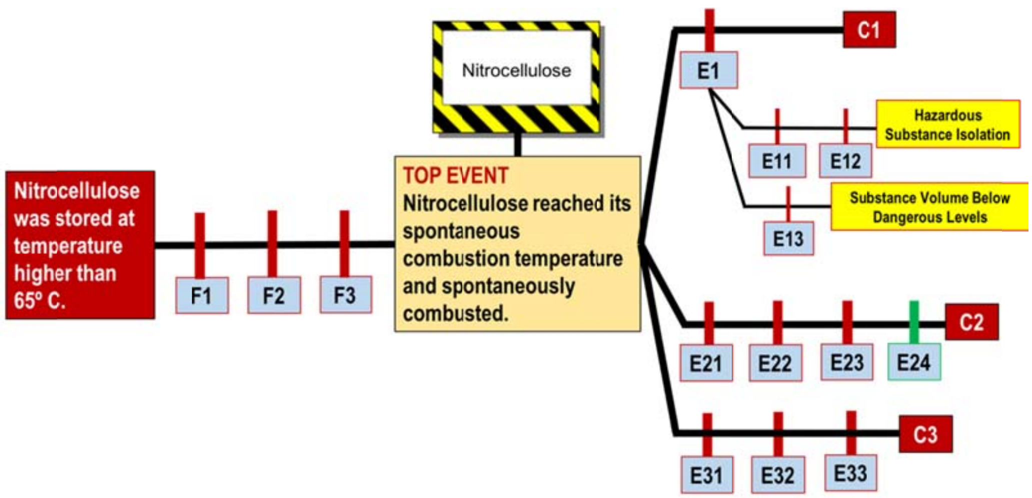

Fig. 4 Analysis result of Bow-tie

Notes:

The red rectangle above means that the barrier failed, and the green one means that the barrier worked successfully.

F1: Ethanol or water should be used as a damping agent in nitrocellulose and should be sealed in thermoplastic.

F2: Hazard chemical goods should be unpacked, transported and unloaded according to regulations.

F3: Specialists should supervise on-site and check the seal.

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E1: Storage area should be designed and managed to prevent ignition of ammonium nitrate (including E11~E13).

E11: There should be adequate separation distances among combustible materials and flammable substances.

E12: Hazardous chemicals should be stored in special warehouses.

E13: The amount of hazardous chemicals stored should be strictly restricted.

C1: Fire spread to ammonium nitrate containers, and the first and second explosions occurred. Subsequent fire caused extensive property damage.

E21: Firefighters should be called to come to the scene as soon as possible.

E22: The security notification to neighbouring enterprises and safety mutual protection agreement should be executed. Evacuation of on-site personnel should start in an organized way as soon as possible.

E23: There should be adequate safety distance between the warehouse and important public buildings and transportation facilities.

E24: Firefighters should organize evacuation of on-site personnel according to the actual situation.

C2: The accident caused mass casualties to workers.

E31: Firefighting access should be kept clear.

E32: Major hazard materials should be officially registered or recorded.

E33: Firefighters should be well equipped and trained to handle the hazard chemical accident.

C3: Firefighters suffered heavy casualties.

3.1.2 Accident Cause and Process Analysis

On the date of the accident, the highest air temperature was 36 ^{o}C. Tests confirmed that when the air temperature is 35 ^{o}C, the temperature inside the container can reach 65 ^{o}C or higher (State Council of China, 2016).

Nitrocellulose ($C_{12}H_{16}N_4O_{18}$) is chemically unstable and highly flammable,

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explosive. If the nitrocellulose packaging is not well sealed, the damping agent will volatilize at a rate that accelerates as the temperature rises. Without damping agent and heat dissipation, its decomposition is accelerated and it can explode at 180 ^{o}C (State Council of China, 2016).

F1: Supplier Management was poor in Ruihai. In this accident, the nitrocellulose without plastic film packaging, supplied by Hebei Sanmu Cellulose Company Ltd. and Hengshui New Eastern Chemical Industry Company Ltd., was a contributing factor. The suppliers were investigated and found to manually package nitrocellulose damped with alcohol into plastic bags, which were only tied up with strings and placed inside paper tubes rather than being sealed in plastic film.

F2: There were serious defects in outsourced operation of goods. When packing and transporting nitrocellulose containers, Ruihai violated safety regulations and the workers used non-explosion proof forklifts to roughly empty the barrels and randomly stacked them. According to statements by the Ruihai employees, there were occasions when the nitrocellulose packaging was damaged and the nitrocellulose spilt.

F3: Ruihai unpacked containers containing nitrocellulose without on-site supervision from specialists and no one noticed or knew what to do when the seal broke (water not used to dampen).

The combination of the various factors above led to the loss of the nitrocellulose damping agent and nitrocellulose partially drying out. At the high ambient temperature, the decomposition reaction was accelerated, generating a large amount of heat until nitrocellulose spontaneously combusted.

3.2 Event Tree Analysis

Unfortunately, this event involved a combination of two potentially unstable substances. Following the spontaneous combustion of the nitrocellulose, the fire spread to the spot where the ammonium nitrate was stored. The events following the top event are described as follows.

E1: Storage area for hazardous chemical goods should be designed and managed thoroughly for prevent ignition for chemicals. Some essential safety measures, such as hazardous substance isolation and limitation to substance volume, should be taken

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(E11~E13).

E11: Not only were different classes of hazardous goods stored together in a chaotic way, leaving little distance between them, but also the phenomenon of over-stacking against the regulations was rampant, and containers were stacked up to 4 or 5 tiers in piles. The failure to remove the nitrocellulose from the loading area and to respect good practice in maintaining appropriate distances caused the fire to spread to the ammonium nitrate.

E12: Ruihai had violated regulations and wrongly stored ammonium nitrate in the open-air area full of containers without special supervision.

E13: Ruihai had stored excessive ammonium nitrate and other hazardous goods in the delivery zone illegally for many times. In 2015, the monthly turnover of the goods at Ruihai was approximately 60,000 tons, 11 to 14 times more than the permitted quantity for monthly turnover. Several kinds of hazardous goods were stored far beyond the legal limit. It was estimated that at the time of the accident, the amount of potassium nitrate stored was 1342.8 tons, 53.7 times higher than its maximum storage capacity; the amount of sodium sulfide stored was 484 tons, 19.4 times higher than its maximum storage capacity; and the amount of sodium cyanide stored was 680.5 tons, 42.5 times higher than its maximum storage capacity. In particular, the amount of ammonium nitrate that was illegally stored in the delivery zone reached 800 tons on the date of the accident.

C1: Solid ammonium nitrate is stable at room temperature, but can explode at temperatures between 433 K and 473 K. The barriers (E11-E13, E1) failed and ammonium nitrate containers exploded firstly. As a result of the fire and the blast wave from the first explosion, the second and more violent explosion occurred, which caused heavy property loss.

E21: Firefighters were called but failed to control the fire.

E22: After the fire accident, the security notification to neighbouring enterprises and safety mutual protection agreement were not executed by Ruihai.

E23: Relevant local governments and authorities seriously violated statutory urban planning policy. The standard safety distance requirements between the warehouse and important public buildings and transportation facilities including the highway

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and a light rail station were violated, which led to heavy loss and casualties of neighboring residents.

E24: Firefighters succeeded in evacuate approximately 100 people, including staff working at Ruihai and neighboring enterprises and the crowd in the vicinity.

C2: Evacuation of on-site personnel commenced too late thus aggravating the casualty rate.

E31: At 22:56, fire-fighters arrived at the scene of accident. However, the firefighting access was blocked by containers and the effort to use cranes to clean passageways failed, so that the fire trucks were unable to approach to and extinguish the flames.

E32: There was no official registration or records of major hazard materials stored in the warehouse. Firefighters should be aware of the quantities and properties of the hazard chemicals in the warehouse before firefighting, but when the firefighter commander questioned the employees of Ruihai for the specific substances that could cause the fire, none of them knew. In this circumstance, firefighters then tried to cool down and protect the neighboring stacks of containers in order to prevent the fire from spreading, but failed either. Later, as the flames became fiercer and radiant heat increased, all the fire engines and firefighters evacuated from the area, and continued to prevent the spread of the fire by spraying water through turret pipes outside the delivery zone.

E33: After receiving a notice reporting that a fire broke out in Ruihai, the firefighters rushed to the scene immediately as they would for an ordinary fire. However, the firefighters were not well equipped for hazardous chemical accidents and did not have adequate knowledge of the substances directly involved in the fire and what else was stored on the site. Planning of the emergency response to a hazardous material incident requires full information on its basic characteristics, including its quantity and dangerous properties, and its location. It is also important to understand firefighting methods for different substances, such as water reactive materials and what measures that they will need to undertake to protect responders from adverse consequences (personal protective equipment, firefighting distances, etc.)

C3: Firefighting before the explosions failed and firefighters failed to protect

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themselves and suffered heavy casualties.

3.3 Description of Consequences

As of 10 December 2015, according to the Accident Investigation Team's estimation, the direct economic loss was 6.866 billion RMB (approximately the equivalent of 0.93 billion euros), based on statistical calculations and relevant regulations, and the Standard for Evaluating Economic Loss Incurred Following Injuries and Deaths of Company Personnel (GB6721-1986). The direct accident losses are listed in Tab. 1 (State Council of China, 2016).

Table.1 Casualties and property losses

Loss categories	Amount	Details
Deaths	165	24 fire-fighters from the public security personnel on duty, 75 firefighters from Tianjin Port Fire Brigade, 11 police officers, 55 civilians from Ruihai, neighbouring companies and residential areas.
Missing	8	5 firefighters from Tianjin Port Fire Brigade and 3 family members of firefighters from the Brigade.
Injuries	798	58 people with severe or moderate injuries, and 740 people with minor injuries.
Destroyed buildings	304	73 office buildings, factories and warehouses, 91 Category I residential buildings, 129 Category II residential buildings and 11 residential apartments.
Destroyed cars	12428	
Destroyed containers	7533	

4. Accident Analysis with AcciMap

Bow-tie analysis places emphasis on the direct technical causes and consequences before and during the accident. It can only recognise management

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activities as a “barrier”. If deeper level causes, especially in the management and supervision level were not disclosed, lessons could not be learned well so that similar accidents may still happen in the future. Contrastingly, Accimap can help to identify the cultural and organizational levels where the management activity occurs and the interlinkages between different organizational levels and activities. This section focuses on analyzing contributing factors of governmental supervision and intermediary agencies’ illegal actions in AcciMap. The Accimap approach was developed as a means of modeling the socio-technical context to identify the combination of events and decisions that contributed to the occurrence of the accident, especially focusing on failures across the six organizational levels. Based on the process of AcciMap, the construction of an accident AcciMap is presented in the Fig. 5. Pertinent preconditions and events are identified and correlated in a graphical way.

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4.1 Analysis of the Accident at Six Levels Level

Level 1: Government policy and budgeting

At Level 1, both of the Tianjin Municipal People's Government and the Ministry of Transport have responsibility for the management of Tianjin Port. Tianjin Port is governed by Tianjin Municipality but Tianjin Port Public Security Bureau and its Fire Brigade are still mainly governed by Public Security Bureau of the Ministry of Transport, which caused an unclear separation of responsibilities for the Ministry of Transport and the Tianjin Municipal People's Government and a conflict of port management.

Level 2: Regulatory bodies & associations

At Level 2, many departments neglect their responsibility for the extremely serious fire and explosion accident, including Tianjin Transport Committee, Tianjin Port (Group) Company Ltd., Tianjin Customs, Tianjin Safety Supervision authorities, Tianjin Municipal Planning and Land Resources Department, Tianjin Market and Quality Monitoring Bureau, Tianjin Maritime Department, Tianjin public security authorities, the Tianjin Binhai New Area Environmental Protection Bureau, the Bureau of Administrative Examination and Approval of Binhai New Area. The

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administrative supervisory authorities and their supervisory responsibilities for Ruihai are listed in the Tab. 2 below (State Council of China, 2016).

At the same time, the Tianjin Municipal Transportation Commission, the Tianjin Construction Commission and the Binhai New Area Planning and Land Resources Administration illegally commissioned Tianjin Port Group Co, Ltd. to carry out administrative tasks, which created a conflict of interest between safety monitoring and business operations, making effective monitoring difficult to realize.

Table. 2 Regulatory bodies and their main issues

Regulatory Bodies	Main Issues
Tianjin Municipal Transportation Committee (TMTC)	1. TMTC illegally gave written approvals to Ruihai for hazardous goods operations at the port; 2. TMTC illegally gave written approvals for Ruihai to carry out trial-period operations of hazardous goods at the port; 3. TMTC illegally issued Ruihai with the Port Operations Permit and Annex Certificate for Hazardous Goods Operations at Ports; 4. TMTC broke laws and regulations during project reviews, leading to the acceptance of Ruihai's construction project of hazardous goods yard which started without prior approval and was against relevant laws and regulations; 5. There was a serious lack of regular supervision.
Tianjin Port (Group) Company Ltd. (TPGCL)	1. TPGCL falsified documents and gave approvals in violation of the law, and did not sufficiently supervise hazardous goods warehouses at the port; 2. Tianjin Port Public Security Bureau under TPGCL did not check or supervise fire prevention capacities of its fire brigade, and did not check or supervise hazardous goods warehouses at the port according to regulations; 3. Tianjin Port Public Security Bureau Fire Brigade under TPGCL issued a fire safety design review without having received Ruihai's permit for construction project planning; 4. Tianjin Port Public Security Bureau Fire Brigade under TPGCL did not

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	supervise daily fire-prevention practices.
Tianjin Customs (TC)	1. Tianjin Customs did not confirm whether Ruihai had permission to operate a hazardous goods business, an activity that was outside the business scope covered by its current license; 2. TC illegally approved individual inspection items before approval was received for the establishment of a customs supervision area; 3. TC illegally granted permission to Ruihai to send delivery reports to the Customs prior to the issuance of a Business Registration Certificate, allowing Ruihai to conduct business operations of hazardous goods illegally. 4. There is a lack of regular supervision stipulated in the regulations.
Tianjin Safety Supervision Authorities (TSSA)	(Including Tianjin Administration of Work Safety, Binhai Administration of Work Safety, The First Branch Office of Binhai Administration of Work Safety, and the Work Safety Supervision and Inspection Station of Tianjin Port Container Logistics Park) 1. TSSA did not regularly supervise or inspect Ruihai's business operations in accordance with laws and regulations; 2. The authority failed to conduct regular supervision as stipulated in the regulations.

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Tianjin Municipal Planning Authorities, Tianjin Land and Resources Authorities	1. Tianjin Planning Bureau failed to identify the unlawful project construction permission given by Binhai Planning and Land Resources Bureau; 2. Tianjin Planning Bureau did not rectify the issue that construction projects in Binhai New District violated the overall planning policy of Tianjin Municipality, and the upper control limit was changed to lower control limit of *warehouse gross floor area - gross building area ratio* according to Industrial Land Use Standards in Binhai New District Regulatory Plan; 3. Binhai Planning and Land Resources Bureau seriously violated Tianjin Municipal Overall Plan and Binhai New District Regulatory Plan; 4. Binhai Planning and Land Resources Bureau did not find out that safety distance was inadequate between the hazardous goods warehouse and

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	the neighboring residential areas and transport routes.
Tianjin Market and Quality Supervision Authorities	1. Tianjin Market and Quality Supervision Committee did not carry out supervision and inspection on special equipment end-users in Tianjin Port, leading to lack of regular supervision on special equipment operated in Tianjin Port; 2. Binhai Market and Quality Supervision Bureau did not identify the lack of management of special equipment in Tianjin Port and did not recognize that operation and management staff were working without permits; 3. The authorities failed to conduct regular supervision as stipulated in the regulations.
Tianjin Maritime Authorities	1. Tianjin Maritime Safety Administration (TMSA) did not have standard training and evaluations of 'Declarers for shipborne hazardous goods' and 'On-site inspectors for cargo containers'; 2. Beijiang Maritime Safety Administration and Dongjiang Maritime Safety Administration under TMSA did not conduct open-box inspections on Ruihai's shipborne hazardous cargo containers.
Tianjin Public Security Authorities (TPSA)	(Including Tianjin Public Security Bureau, the fire department of the Tianjin Public Security Bureau, and Binhai Public Security Bureau) 1. TPSA failed to conduct fire safety monitoring, guidance and inspections.
Binhai Environmental Protection Bureau (BEPB)	1. BEPB failed to review items according to policy; 2. BEPB failed to perform regular supervision with regard to environmental protection.

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Binhai Administrative Examination and Approval Bureau (BAEAB)	1. BAEAB illegally approved the hazardous goods yard renovation project submitted by Ruihai without involving the participation of the design entity, construction entity, or the entity responsible for inspecting environmental protection compliance and drafting a report; 2. BAEAB illegally approved the emergency pool even though the pool did not meet requirements.

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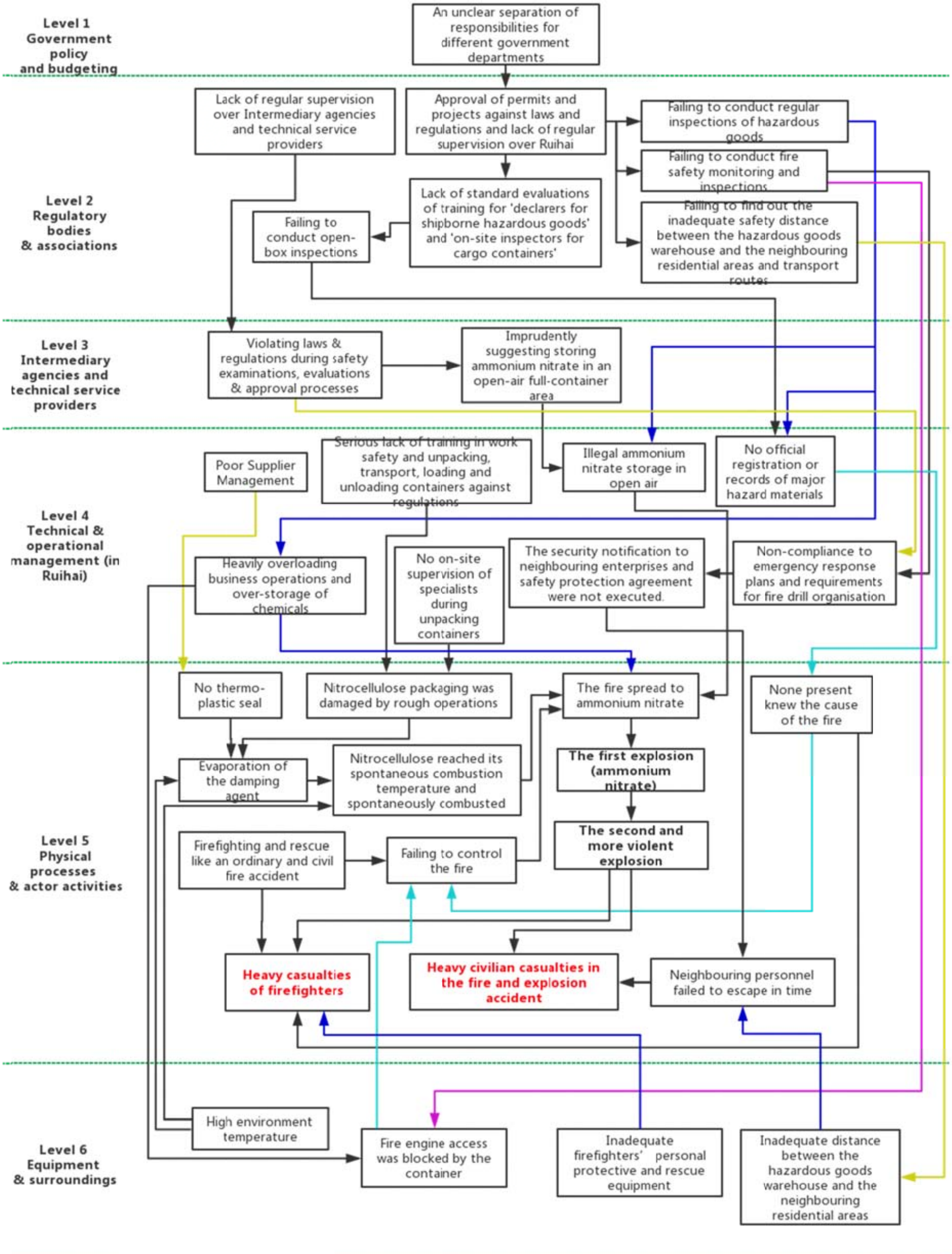

Fig. 5 Analysis result of AcciMap

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Level 3: Intermediary agencies and technical service providers

At Level 3, intermediary agencies and technical service providers have a significant role to play.

According to the investigation team (State Council of China, 2016), intermediary agencies and technical service providers violated laws and regulations and falsified documents during safety examinations, evaluations and approval, which is listed in the Tab. 3 below. For instance, the Tianjin Chemical Engineering Design Institute approved the Ruihai hazardous goods yard renovation project design, even though it violated the Tianjin Municipality urban planning policy and Binhai New Area regulatory planning policy. Construction design documents for the renovation project were illegally provided even though Ruihai did not provide the necessary project approval documents or planning permission documents. The facility's original safety report and site plan mistakenly suggested storing ammonium nitrate (Hazard Class 5: Oxidizing Agents) and sodium cyanide (Hazard Class 6: Toxic Substances) in an open-air full-container area. After the fire and explosion, the institute directed the employees to illegally modify the original site plan.

Table. 3 Intermediary agencies and their issues

Bodies	Main Issues
Tianjin Zhongbinhaisheng Technology Development Company, Ltd. and Tianjin Zhongbinhaisheng Health Safety Evaluation Company, Ltd. (the same legal entity, TZTD)	1. TZTD illegally accepted Ruihai's safety assessment prior to start and safety assessment upon acceptance at the same time and the data was falsified or fabricated; 2. TZTD deliberately covered up non-compliance with safety requirements.
Tianjin Centre for Water Transportation Safety Evaluation (TCWTSE)	1. TCWTSE failed to conduct a strict examination for the safety requirements of the hazardous goods yard renovation project, the facilities design safety report and facility safety inspection.

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Tianjin Chemical Engineering	1. TCEDI violated the Tianjin Municipality urban planning

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Design Institute (TCEDI)	policy; 2. TCEDI mistakenly suggested storing ammonium nitrate (Hazard Class 5: Oxidizing Agents) and sodium cyanide (Hazard Class 6: Toxic Substances) in an open-air full-container area in the facilities design safety report and site plan.
Tianjin Transport and Building Design Institute (TTBDI)	1. TTBDI illegally lent planning and drafting qualifications to Tianjin Port Construction Company.
Tianjin Appraisal Centre for Environment and Engineering (TACEE)	1. TACEE failed to seriously examine the environmental impact statement during its evaluation of Ruihai's proposed hazardous goods yard renovation project.
Tianjin Boweiyongcheng Technology Company Ltd. (TBTCL)	1. TBTCL violated regulations during its surveying and setting out, review of chalk lines, and final measurement of Ruihai's hazardous goods yard renovation project.

Level 4: Technical & operational management

At the technical management level, safety management and training in Ruihai is poor and chaotic, and the relationships among these factors are shown in AcciMap. The operator did not fulfill legal requirements associated with management of process risks on the site, including registration of hazardous substances, and notification of neighbouring businesses of emergency response necessary in case of an accident on the Ruihai site. Ruihai also provided false safety documentation and site maps to technical authorities and consultants to obtain approval for site construction and operation. Moreover, it did not foresee any training for its employees in handling dangerous substances or in responding to a potential emergency involving such substances.

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Level 5: Physical processes & actor activities

At this level, the physical process in the accident and actor activities, especially firefighters' activities, and the relationships among these factors are shown in AcciMap. The lack of training led to errors in handling the nitrocellulose that subsequently led to its release and explosion. Furthermore, a failure to have an appropriate emergency plan or to timely inform surrounding enterprises about the accident led to a failure to control the incident so that it escalated into a full-scale disaster.

Level 6: Equipment & surroundings

At this level, the lack of compliance with emergency response requirements resulted in the death and injury of responders and extensive damage to the surrounding community. The lack of any mitigation measures onsite meant that the fire continued to burn and increase, creating very high temperatures for the responders. They lacked adequate protection and many of them died. The site violated distance requirements between hazardous sites and local business and residential areas, exposing a large population to the disaster.

4.2 Evaluation

These two analyses give ample evidence that the fire and explosion at the Ruihai site in Tianjin was the result of failures of numerous controls at many levels, including onsite risk management and emergency planning and preparedness, as well as the entire regulatory framework designed to prevent businesses from operating unsafely. The bow-tie analysis illustrates the sequence of events on site that led to the accident and identifies the direct failures in prevention, mitigation and emergency response that led to the heavy loss of loss and severe property damage. The analysis shows that there was no safety management system whatsoever for controlling risk of explosion, fires or toxic releases on the site. The only barrier established regarded the evacuation of employees during an emergency event and this apparently was implemented during the event. Although under existing law the operator should have been required to register hazardous chemicals present on the site, to handle them

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according to their specified storage and storage conditions and safety regulations, and to regularly organize firefight drills and safety trainings in preparation for potential hazardous materials events, there was apparently no oversight or enforcement of these obligations. Moreover, this finding suggests that the operator was not concerned that the site would incur any penalties due to the lack of minimum risk controls required by the law.

AcciMap provides an exhaustive description in regard to the role of government regulatory bodies, intermediary agencies and technical service providers, as well as enterprise management in Ruihai itself (Level 1-4). At every level, it appears that regulators, and their technical divisions, willfully failed to obey the law. During site development, they accepted documentation on safety preparations, site construction, and emergency management that were not in compliance with the law. They allowed the site to operate without the necessary licenses and to ignore every violation of law pertaining to the control of risks associated with handling large quantities of dangerous substances.

Based on the AcciMap and the bow-tie, some views and suggestions on the accident and the future improvement of enterprise safety management and government supervision are listed below.

(1) Establish an awareness campaign for all operators of hazardous industry and all levels of government that aims at dramatic improvements in the safety culture of those responsible for enforcing or implementing measures for preventing and mitigating effects of chemical incidents. While laws were in place to control the chemical hazard, there was a widespread lack of commitment to their implementation by the operator as well as a vast number of government agencies responsible for oversight of the risk. The failure to respect the law shows not only a manifest misunderstanding of the seriousness of chemical accident risk among all actors in the system, but also a significant safety culture problem. Ongoing education and awareness training coupled with strong enforcement against those who violate the law is urgently necessary to achieve a higher level of risk governance and a mature safety culture.

(2) Improve the regulatory system and management of hazardous chemicals and

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related industries in a coordinated and consistent way. The administrative management system of Tianjin Port was chaotic and the safety management was poor. As mentioned at Level 1&2, there is an obvious defect in Tianjin port management and an ambiguous separation of responsibilities for several authorities and some local governments and authorities seriously violated statutory urban planning policy even. Furthermore, there is a lack of a national unified information management platform for hazardous chemicals which helps different authorities share information with each other and understand the whereabouts and situation of hazardous chemicals timely and clearly.

And there is also a lack of coordinated and consistent national law on the prevention and control of environmental risks of hazardous chemicals in China. The current Safety Regulations on the Management of Hazardous Chemicals do not give clear or specific instructions on the transport and use of hazardous chemicals. Enterprises may be confused about the intricate system of hazardous chemicals safety management that involves varied stages, authorities, laws, regulations and different technical standards. Additionally, compared to developed countries and some developing countries, the costs of violation are too low to stop individuals and companies from violating the current regulations in China.

(3) Strengthen supervision over intermediary service agencies.

Intermediary service agencies provide enterprises with a variety of important technical services such as project design, safety assessment and environmental risk assessment. The reliability and compliance of these services contributes to the risk management and emergency response in Chinese enterprises. The improvement of the engineering ethics of intermediaries and technical service agencies also has an active and crucial role in the safety management and sustainable development of Chinese industrial enterprises and parks.

(4) Improve the safety management and technical operations of hazardous chemical industry. Ruihai stored its materials chaotically in violation of regulations, over-stacked hazardous goods, unpacked containers containing hazardous goods without on-site supervision from specialists with substandard equipment and

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conducted heavily overloaded business operations. Ruihai did not make emergency response plans or organize drill as required and did not register or file a record of these major hazard materials at Tianjin Transport Department, which aggravated the casualty rate and caused great difficulties in firefighting and cleaning up hazard chemicals. Additionally, supplier management was poor in Ruihai. In this accident, the nitrocellulose supplied without thermoplastic packaging was a contributing factor.

(5) Strengthen the emergency response capacity for hazardous chemical accidents in China. When incidents occur, appropriate response measures, including evacuation, sheltering, and firefighting, should be taken in order to minimize the adverse impacts of the incident on the environment, property, and human life and health (Trent Parker, Ruiqing Shen, Michael O'Connor, Qingsheng Wang, 2019). However, there is a lack of competent professionals and dedicated planning and preparation for hazardous chemical accidents in China, which cannot meet the needs of multiple and complex hazardous chemical accidents nowadays. Therefore, the development of enterprise rescue team needs to be improved as soon as possible. In the industrialized countries, the chemical enterprise rescue team is an important force in addition to firefighter, police and civil defense and other rescue teams. In addition to regular drills, joint training and preparedness between onsite and offsite responders also promotes site hazards identification and advance preparedness. It also helps communication to go well in an emergency. If there are not sufficient onsite responders, the offsite responders should organize training and preparedness exercises directly with the management. The Awareness and Preparedness for Emergency at Local Level (APELL) offers chemical industry enterprises a simple structured method to assess and improve their operating procedures to identify and reduce risk with community involvement (Zhao et al., 2014). Exhaustive and careful risk identification and emergency preparedness plays a significance role in the prevention of the accident, which is the process of discovering, confirming,

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describing and reducing the risks. Furthermore, it is necessary to systematically assess the risk by applying risk identification and assessment methodology to control risk (GeunWoong Yun, William J. Rogers, M. Sam Mannan, 2008; Nir Keren, Harry H. West, and M. Sam Mannan, 2002).

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5. Conclusion

The Tianjin disaster has many lessons learned to offer China as well as other emerging economies. It shows the risk many countries face when changes in laws are adopted that are not accompanied by an equivalent change in priorities and practices within the organizations charged with implementing the law. In Tianjin, there were many regulations and standards in place that, if they had been followed, could have prevented the accident from happening, or at the very least, would have prevented loss of life and substantial damage to the surrounding community and environment.

Industrial growth brings tremendous prosperity but also great responsibility to protect the communities and the environment from the unintended harm that industry can cause. Establishment and strengthening of laws to prevent harmful impacts from industry are an essential step. Tianjin is a strong reminder that governments may need to take additional measures to reinforce the change both practically and culturally, so that the new responsibilities are well accepted and equally valued by all the actors involved. The following are some recommendations for that China and other growing economies might consider to strengthen enforcement of chemical accident prevention and preparedness programmes:

(1) Activate a Coordinating Group, such as recommended by the UNEP APELL process, representing the various constituencies that have or should have a voice in the community's emergency preparedness efforts (UNEP, 2015). It is notable that, in the day-to-day management, Ruihai did not conduct detailed and responsible risk identification, evaluate hazards and risks faced by the community or inform the stakeholders of their own risks and contingency plans, such as neighboring hospitals, schools, residential areas, other neighboring enterprises in the industrial park. (Hans J. Pasman, William J. Rogers, M. Sam Mannan, 2017)

(2) Establish a national unified information management and supervision platform for hazardous chemicals. It can help the communication among supervisory authorities and to build a more robust co-ordination mechanism to promote and implement supervisory duties at the authority level.

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(3) Strengthen work safety emergency response capacity and encourage high-risk industries and enterprises to set up part-time emergency rescue teams. It is necessary to develop specialized equipment, set up professional teams to meet complex emergencies involving hazardous chemicals and provide technical training of emergency response.

(4) Strictly supervise and control intermediary agencies responsible for environmental protection and worker and community safety, based on, for example, routine audit and inspection, or specific performance measures tied to enforcement objectives, etc.

(5) Further streamline safety management to ensure efficiency and avoid fragmentation of responsibilities. For example, the need to improve the Tianjin port safety management system is a lesson learned from the Tianjin disaster. The port police, fire- fighting and other related administrative and regulatory functions were supposed to be undertaken by the local authorities. The port's efforts to ensure safety would also be strengthened by the establishment of a specialized area strictly limited to the storage and logistics of hazardous goods at the port.

These are just a few recommendations that can be derived from the study of the Tianjin disaster as a collective failure of the socio-technical system surrounding the operation of a hazardous site. Each chemical disaster is a tragedy but also an opportunity for improvement. Chemical disasters in emerging economies are typically more severe and more frequent than those in industrialized countries. Countries with lower industrial accident rates have often achieved these rates the hard way, by learning from their chemical disasters and committing to a new way of doing business. In the same way, countries who are fast developing their industrial economies today should also be seeking to learn how they can change as a society from their chemical disasters. As this paper shows, Bow-tie and AcciMap are both useful methods for assisting countries with this process, analyzing not only the direct causes of the accident but also the contribution of other actors in government and society, in order to make lasting improvements to protect workers, communities and the environment in future.

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