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Exploring Loading and Unloading Operations in Relation to Domino Effects in Chemical Industrial Parks

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Past accident surveys reveal that loading and unloading operations (LUOs) are responsible for 11% of fire-related domino accidents. This study investigates the domino accidents during LUOs in the last two decades and identifies the main causes and features of these domino effects. An index-based approach is proposed to assess these domino effects, measuring the periodic escalation capability of installations. The proposed escalation capability index takes into account the special features being present in these accidents, including the spread of vapor cloud due to delayed ignition, multiple fires caused by vapor cloud explosion (VCE), the quantity variation of hazardous substances, and the change of primary event risk due to operations. From a risk management view, an emergency strategy is proposed to tackle the risk caused by LUOs. Therefore, this methodology can identify the most critical areas with regard to the starting or escalating of domino events during LUOs and support the decision-making of alert levels.

1. Introduction

Chemical industrial parks consist of hundreds and sometimes even thousands of installations located next to each other, where large quantities of hazardous substances are stored, transferred or processed (Chen et al., 2019b). As a result, a primary unwanted event at one installation may propagate to others, triggering a chain of accidents, resulting in overall consequences more severe than those of the primary event; a phenomenon which is known as domino effects or knock-on effects (Reniers and Cozzani, 2013). Since the 1990s, many attempts have been made to assess or manage domino effects in the chemical and process industries, including quantitative risk assessment (QRA) methods (Cozzani et al., 2005), graph theory (Reniers and Dullaert, 2007) and Bayesian networks (BN) (Khakzad et al., 2013; Yang et al., 2018). Besides, domino effects caused by special events such as security events (Reniers and Audenaert, 2014) or natural accidents (Cozzani et al., 2014; Khakzad et al., 2018) have received increasing attention in the scientific and technical literature in recent years. However, the LUOs have been overlooked since these operations are conventional and simple compared to more complex chemical processes.
Gómez-Mares et al. (2008) found that the LUO is responsible for 11% of domino accidents involving jet fire. Darbra et al. (2010) analyzed 225 domino accidents which occurred in the chemical industry and concluded that 13.3% of the cases occurred during transfer (loading/unloading) operations. The risk of domino effects caused by LUOs in chemical and process plants should not be underestimated because the time of the LUO is relatively much shorter. Besides, domino effects caused by LUOs may result in severe consequences and even induce catastrophic disasters. Planas-Cuchi et al. (1997) highlighted that more attention should be paid to LUOs, however, such catastrophes still happened in recent years, such as the Puerto Rico accident (USA) in 2009 and the Jinyu (China) accident in 2017.
The present study aims to explore the role of LUO on domino effects from a risk management perspective.

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2. Domino accidents during LUOs

Chang and Lin (2006) analyzed 242 storage tank accidents according to published reports from various sources, indicating that overfilling was the most frequent cause of accidents during LUOs and 13 out of 15 overfilling cases induced domino effects. The U.S. Chemical Safety and Hazard Investigation Board (CSB) found out 17 similar domino accidents caused by overfilling from 1962 to 2010 (CSB, 2015). Six domino accidents occurred during LUOs in the past two decades as listed in Table 1. The details of these accidents are described as follows.

Table 1： Domino accidents during LUOs (1999-2017)

Incident	Laem Chabang (1999)	Glenpool (2003)	Buncefield (2005)	Puerto Rico (2009)	Jaipur (2009)	Junyu (2017)
Cause	Overfilling	Static electricity build-up	Overfilling	Overfilling	Leak	Leak
Hazardous materials	Gasoline	Gasoline, diesel	Gasoline	Gasoline	Gasoline	LNG
Domino sequence	VCE →fire	VCE→fire	VCE →fire	VCE →fire	VCE →fire	VCE →fire
Delayed time to ignition	-	-	23 min	26 min	75 min	2 min
Mass of loss before ignition	-	-	300 tons	500 tons	2000 tons	-
Destroyed installations	5 tanks	3 tanks	20 tanks	17 tanks	11 tanks	9 tanks +15 tank trucks
Burning time	35 hours	21 hours	5 days	60 hours	11 days	15 hours
Fatalities	8	0	0	0	11	10
Total loss	22.3 million	2.4 million	1.5 billion	-	32 million	6.5 million

2.1 The Laem Chabang accident in 1999

At the night of 12 February 1999, a vapor cloud explosion (VCE) and the following fires in an oil storage plant in Laem Chabang, Thailand, led to the damage of five out of nine gasoline storage tanks (250,000 barrels of gasoline), resulting in the death of 8 people and injury to 13 others (Coco, 2003). The fire lasted 35 hours and the total damage cost was estimated as $22.3 million. The vapor cloud was induced by overfilling of a gasoline storage tank when an operator in the storage plant incorrectly opened a valve to fill the tank which was already filled. Although two high-level alarms were set in the control room, the operators in the control room did not notice the alarms. The domino accident sequence can be divided as the following steps: (i) overfilling, (ii) formation of a vapor cloud, (iii) ignition, (iv) vapor cloud explosion, (v) multiple fires and (vi) fire escalation.

2.2 Glenpool accident in 2003

At the night of April 7, 2003, an 80,000-barrel storage tank at ConocoPhillips Company's Glenpool South tank farm in Glenpool, Oklahoma, the U.S., exploded and burned as it was being filled with diesel. The fire burned 21 hours and destroyed two other tanks and a pipeline nearby. Before the loading operation, Gasoline had been removed from the tank earlier during the day. The explosion occurred when a static discharge ignited a flammable fuel-air mixture in the tank. The static electricity build-up was caused by the fast flow rate of the filling since the flow rate ranged from a minimum of 20,409 barrels per hour to a maximum of 27,492 barrels per hour before the explosion, which was between 2.3 and 3 times the recommended maximum flow rate. The total cost of the accident was $2.4 million. There were no injuries or fatalities (NTSB, 2004).

2.3 The Buncefield accident in 2005

In the early morning of December 11, 2005, a series of explosions occurred in the Buncefield oil storage and transfer depot, Hemel Hempstead, the U.K., damaging large parts of the depot and neighboring properties, and causing 43 injuries (Buncefield Major Incident Investigation Board, 2008). The accident resulted from overfilling when a tank received an excessive amount of unleaded gasoline at about 5:20 a.m. A massive explosion and following explosions took place at 06:01 am when the vapor cloud was ignited, generating much higher overpressures than those estimated by methods usually applied (Chen et al., 2019a). These explosions caused a huge fire which engulfed 20 out of 39 large storage tanks. The fire burned for five days, destroying most of the site and causing 2000 people to evacuate their homes.

2.4 The Puerto Rico accident in 2009

A similar domino accident was seen at the night of 23 October 2009, at an oil storage plant of Caribbean Petroleum Corporation, Puerto Rico, the U.S., caused by overfilling when unleaded gasoline was unloaded from a cargo ship to various tanks in the site. The unloading operation started at 8:47 p.m. when the gasoline was first pumped to tank 405. The operator fully opened the value on Tank 409 after tanks 405, 504 and 411 were filled. However, the tank began to overflow between 11 p.m. and 12 a.m. The overfilling induced a vapor cloud which caught fire, leading to a VCE and subsequent fires. The accident destroyed 17 out of 48 tanks and other equipment onsite and caused damage to the neighborhood communities and businesses. The fires burned 60 hours and resulted in an emergency declaration for assistance from President Obama (CSB, 2015).

2.5 The Jaipur accident in 2009

At the night of October 29, 2009, one week after the Puerto Rico accident, a similar domino accident occurred in the Indian Oil Corporation refinery 16 miles south of Jaipur, India. A delivery line leaked when four operators were transferring gasoline to a tank, producing a large vapor cloud which covered a major area of the plant. The release lasted about 75 min before the vapor cloud was ignited, resulting in a powerful explosion, fireball, and 11 tank fires. The plant’s emergency measures never took place since the operators involved had been overcome by the fire. As a result, the fire could not be extinguished and burned for 11 days. It was estimated that over 2000 tons of gasoline were released, 4% of which formed a vapor cloud. The accident finally destroyed the entire site and caused 11 fatalities and over 200 injuries (Siddiqui et al., 2018).

2.6 The Jinyu accident in 2017

Most recently, in the early morning of June 5, 2017, a vapor cloud exploded during unloading LNG from a tank truck at Jinyu chemical plant in Linyi, China, resulting in a severe domino effect, and 10 fatalities and 9 injuries. 15 vehicles with hazardous chemicals, 1 spherical tank, 2 vault tanks, production equipment, the laboratory, the control room, the office buildings, surrounding enterprises and vehicles were damaged. Besides, 6 spherical tanks caught fire although the fires were extinguished after 15 hours. The direct economic loss caused by the accident was about $6.5 million. The accident was caused by a leakage after the connection between the loading arm and the tanker's discharge outlet broke away due to operation errors. The lack of emergency measures was regarded as an important cause of the accident escalation (Zhu et al., 2017).

3. Hazard indicators

To fill in the research gap between LUOs and domino effects, a set of indicators for assessing the domino effect risk caused by LUOs are established to support the management of domino effects during the operations. The indicators are divided into four types: (1) the quantity of hazardous substances, (2) the position of installations, (3) the specific process conditions, and (4) the performance of a prevention system for loading and unloading.

3.1 The quantity of hazardous substances

The quantity of the substance is defined as the total amount of flammable substance contained in the installation, which is essential for assessing the hazard of the installation (Uijt de Haag and Ale, 1999). The burning time mainly depends on the quantity of flammable substances in fire escalation and the peak value of overpressure is also related to the vapor quantity of the flammable substance in a VCE. In fire-related domino effects, heat radiation is usually used as an indicator in the propagation assessment. The heat radiation is however difficult to predict due to the uncertainty of released heat. Besides, the fire escalation capability of an installation also depends on the burning time of the installation (Chen et al., 2018). But past researches on domino effects ignored the change of hazardous quantities and hazardous units caused by LUOs, thus underestimating the risk of domino effects. For the assessment of these domino effects, a quantity indicator (Q) is considered to account for the effect of the quantity of hazardous substances present during operations:

$$Q = \frac{Q_t}{Q_s} \tag{1}$$

where Q_t is the total quantity of flammable substances in the transport unit and in the loading/unloading storage tanks. Q_s, is the storage capability of the storage tank.

3.2 The position of installations

The escalation capability is usually simplified as the ratio of the required safety distance and the actual distance between two installations (Reniers and Cozzani, 2013). However, it overlooks the possible simultaneous damage of multiple installations which could be caused by VCEs a likely phenomenon during LUOs. In other words, the traditional distance ratio may underestimate the risk caused by LUOs, ignoring the spread of vapor clouds. Besides, the safety distance is difficult to predict when it comes to VCEs due to the uncertainty of delayed ignition. The VCE strength depends on the vapor cloud size, the ignition energy, and the congestion and confinement of the area covered by the cloud. The vapor cloud is considered as a hemisphere, thus the cloud radius (R_c) can be obtained as (Assael and Kakosimos, 2010):

$$R_c = \left(\frac{3V}{2\pi}\right)^{1/3} \tag{2}$$

where V is the cloud volume of flammable gas and air. The V mainly depends on the overfilling rate and time and can be estimated according to the method proposed by the U.K. Health and Safety Executive (Atkinson and Coldrick, 2012). The worst condition is considered in this study: the overfilling rate is equal to the flow rate of the LUO and the overfilling time equals the interval between two manual gauging operations. In that case, an impact radius (R_I) can be defined as:

$$R_I = R_c + R_t \tag{3}$$

where R_t is the distance threshold outside the vapour cloud in which the tanks may be damaged by the VCE. Since the overfilling usually induces a large vapour cloud, the R_t is considered to be the distance threshold caused by catastrophic release (700m) (Cozzani et al., 2009). In that case, the tanks within the impact radius may have a high possibility of being damaged simultaneously due to VCE. The number of tanks within the impact radius (N_s) also represents the congestion or confinement of the area. Consequently, a position indicator (P) can be defined as:

$$P = N_s \tag{4}$$

It should be remarked that the layout of the area will be changed as the transport unit should be regarded as a hazardous installation if it is inside the chemical industrial area.

3.3 The specific process conditions

Previous research usually ignored the operation risk of storage tanks in escalation assessment. However, the storage tanks should be regarded as process installation during loading or unloading operations (Uijt de Haag and Ale, 1999). Besides, the loading or unloading flow rate should be considered since the build-up of static electricity depends on the flow velocity, and a high velocity may decrease the likelihood of a successful response in emergency situations. Abnormal high velocity has been found in several domino accidents, such as the Glenpool accident in 2003 and the Puerto Rico accident in 2009. In addition, most of these accidents occurred at night, which may increase the difficulty of monitoring or detection of incidents. To model these special characteristics of LUOs, as such, an operation indicator (O) is defined as:

$$O = \alpha\beta\frac{r}{r_r} \tag{5}$$

where α represents the process conditions of the storage tank. If the tank is in loading or unloading state, α=10, otherwise, it is equal to 1 (Uijt de Haag and Ale, 1999). β is a factor indicating the operation time. If the operation is at night, β is equal to 2 while it equals 1 during daytime. r is the actual flow rate, and r_r is the recommended flow rate (API, 2003).

3.4 Protection system

In the process and chemical industrial areas, protection systems with multiple layers are usually used to protect hazardous installations from overfilling (CSB, 2015). Three layers including the gauging system, the high-level alarm system, and the automatic overfilling protection system are considered in this study, as shown in Figure 1.

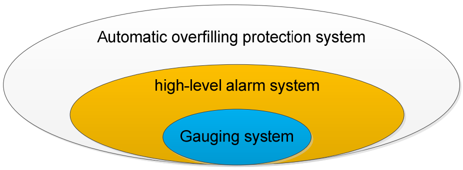

Figure 1: An example of the multiple layers of protection against tank overfilling

Although the protection system can mitigate the risk of overfilling, the systematic failure of the protection system may result in major accidents, such as the Puerto Rico accident in 2009. Therefore, a safety index (*S*) is defined to assess the performance of the protection system as shown in Eq(6).

$$S = S_g \times S_h \times S_a \quad (6)$$

Where S_g represents the performance of the gauging system; S_h represents the performance of the high-level alarm system; S_a represents the performance of the automatic overfilling protection system. If a layer of protection is available, the corresponding parameter is equal to 2, otherwise, it equals 1.

4. Escalation capability evaluation

Loading and unloading are routine operations with a periodic characteristic in the process industry. The periodic risk caused by LUOs is only present during the operations. Besides the overfilling protection system, improving the alert level in chemical industrial areas to reduce emergency response time may be a reasonable measure to mitigate or prevent the possible domino effects due to the delayed ignition and subsequent VCEs. To determine the alert level, an escalation capability index (*E*) can be defined, as shown in Eq(7).

$$E = \frac{Q \times P \times O}{S} \quad (7)$$

According to the value of the escalation capability index (*E*), five alert levels can be defined to measure the risk caused by LUOs, as shown in Table 2.

Table 2: Alert levels

Alert level	The index *E*	Description
Level 1	0~10	Low risk of domino effects, normal operations
Level 2	10~50	General risk of domino effects, the indoor monitoring should be enhanced
Level 3	50~100	Moderate risk of domino effects, outdoor monitoring should be improved, such as extra patrols
Level 4	100~200	High risk of domino effects, the operation should be adjusted, e.g., by decreasing the loading or unloading velocity
Level 5	>200	Very high risk of domino effects, the operation must be shut down and measures should immediately be taken to alleviate the risk

5. Conclusions

This study explores the role of LUOs in fire induced domino effects in chemical industrial areas. We first elaborated on the domino effects which occurred during LUOs in the last two decades, identifying the main causes (overfilling) and features (e.g., VCE → single or multiple fires) of these accidents. Besides, we introduced an index to assess the escalation capability of installations during LUOs. Based on the developed index, an emergency response strategy was proposed to tackle the risk of domino effects during LUOs. This is a preliminary work and will be extended in future studies by developing methodologies for modelling the spatial-temporal spread and ignition of vapor clouds and the escalation of VCE to sequential fires.

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