Dynamic Risk Analysis of

Dust Explosions

BY

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To my parents, Changxiu Chen and Douxu Yuan …

ABSTRACT

Dust explosion is a continuous threat to equipment safety and human health in process industries. Although many works have been performed in the context of dust explosion mechanism and its prevention measures, a comprehensive risk analysis model which can be applied in various industries is absent. One of the barriers to such a risk model has been the wide variety of industries threatened by dust explosions, as well as complex and interlinked contributors to dust explosions. Selecting safety measures satisfying the requirements of safety regulations and the limitation of budget at the same time has been another barrier. Moreover, there has not been any work devoted to the propagation of dust-domino-effects, although it has frequently been reported in process industries.

In this research, dust explosion root causes as well as other features such as ignition sources have been collected and listed in a comprehensive database. Applying Bow-tie (BT) diagram, a conventional quantitative risk analysis (QRA) method, a generic model of risk assessment for dust explosions has been established using the developed database. In this model, the basic causes contributing to dust explosions are organized according to their cause-effect relationships. Furthermore, potential consequences of dust explosions have been analyzed depending on the function/malfunction of relevant safety barriers. The applicability and efficacy of proposed safety measures to reduce the risk of dust explosions have also been discussed.

To overcome the limitations of BT such as its inability to model conditional dependencies and common-cause failures, Bayesian network (BN) has been used in this research to capture dependencies and to perform diagnostic analysis and sequential learning.

According to the results, dust particle properties, oxygen concentration and lack of safety training are identified as the most critical root causes leading to dust explosions. Further, a risk-based methodology has been proposed for cost-effective allocation of safety measures. Moreover, in this research, the occurrence probabilities of dust explosions in dust-domino-effects have been estimated based on BN.

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Abbreviations

BE: Basic event

BLEVE: Boiling liquid expanding vapour explosion

BN: Bayesian Network

BT: Bow-tie

BP: British Petroleum

C: Consequence

CD: Catastrophic damage

CDC: the US Disease Control and Prevention

CE: Critical event

CFD: Computational Fluid Dynamics

CPT: Conditional probability tables

CSAWS: China State Administration of Work Safety

CSB: The U.S. Chemical Safety Board

DAG: Directed acyclic graph

DEA: Domino effect analysis

E: Evidence

EC: Explosion containment

EI: Explosion isolation

ES: Explosion suppression

EV: Explosion venting

EVA: Evacuation

ET: Event Tree

FT: Fault Tree

GDP: Gross Domestic Product

HUGIN: Bayesian Network Software Tool

IE: Intermediate Event

LOC: Limiting oxygen concentration

MD: Minor damage

MEC: Minimum explosible concentration

MIE: Minimum ignition energy

MIS: Mishap

MIT: Minimum ignition temperature

NIOSH: National Institute for Occupation Safety and Health

NM: Near miss

NFPA: National Fire Protection Association

NRRG: Net Risk Reduction Gain

OFC: Operation and Fixed Cost

OSHA: the US Occupational Safety & Health Administration

PSA: Probabilistic safety analysis

QRA: Quantitative risk analysis

RRI: Risk reduction index

RC: Regular cleaning

SB: Safety barrier

SD_1: Suitable design

SD: Significant damage

SM: Safety measure

ST: Safety training

TE: Top Event

TM: Tramp metal

VCE: Vapor Cloud Explosion

Symbols

A_d: the area of dust layer

A_{floor}: min (enclosure floor area, 2000 m^2)

AM: Mass of accumulated dust in a unit

C: The bulk density of the dust layer

C_B: Budget allocated for the safety strategy

C_i: Cost potential index

C_j: Cost of safety measure j

D: Depth of the dust layer in a target area or unit

H: min (enclosure ceiling height, 12m)

L_i: the corresponding losses

M_{th}: Corresponding threshold value

$Pa(A_i)$: The parents of A_i

P_i: Probability of the i-th consequence

P_{max}: Maximum pressure generated from a dust explosion

P_r: Overpressure reaching a dust layer

$P(D_p)$: Probability of dispersion

P(DL): Probability of a dust layer

P(O): Joint probability distribution of variables O

P_{max}: Maximum explosion pressure

r: The distance of the target (dust layer in this study) from the vent

R_{ai}: Risk of the system after the application of the i-th safety measure

R_b: Risk of the system before application of safety measures

R_s: The distance of the blast center from the vent

K_{St}: Maximum rate of pressure rise

V_j: Objective parameter

W_R: Available resource

ω_i: A weighting factor indicating the importance of a particular objective estimated by decision makers

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1 Introduction

1.1 Overview

Significant losses and damage to humans, assets, and the environment caused by dust explosions are reported worldwide. The earliest record of dust explosions dates back to the late 1800s (Eckhoff, 2003) and the most serious reported dust explosion in history might be the one that occurred in a coal mine in Liaoning province, China, in 1942, causing 1594 deaths and 246 injuries (Mining-technology, 2014). Accident statistics from various countries illustrate the worldwide threat of dust explosions in process industries. According to Yan and Yu (2012), dust explosions in China from 1980 to 2011 caused 518 injuries and 116 deaths. Zheng et al. (2009) collected 106 dust explosions that occurred in Chinese coal mines from 1949 to 2007. This terrible safety situation due to dust explosions can also be observed in the U.S. The U.S. Chemical Safety Board (CSB) collected 197 dust explosions that took place in the U.S. from 1980 to 2005, which were responsible for 109 fatalities and 592 injuries (CSB, 2006). Among the cases, an aluminum dust explosion occurred in the Hayes Lemmerz plant, Huntington, Indiana, in 2003, causing 1 death, 6 injuries, and severe damage to equipment (CSB, 2005). The fuel of this explosion was identified as aluminum dust in a dust collector, where the combustible dust was probably ignited by heat, impact sparks or burning embers. In the same year, another dust explosion in West Pharmaceutical Services, Kinston, North Carolina, claimed 6 lives and caused 38 injuries (CSB, 2004). The CSB believed the accumulation of combustible dust above a suspended ceiling was the main combustible source. Also, the ignition of rubber vapor, overheated electrical ballast, an electrical spark, or an electric motor have been the ignition source for the explosion. Reports about dust explosions can also be seen in other literature (Blair, 2007; Giby and Luca, 2010; Marmo, et al., 2004; Piccinini, 2008; John and Vorderbrueggen, 2011). Emerging accident reports worldwide reveal the urgent problem in prevention and mitigation of dust explosions as well as the imminence requirement for a comprehensive understanding of dust explosions' mechanism.

1.2 Dust explosion

The essential factors for a dust explosion can be attributed to combustible dust, oxidants, ignition sources, mixing and confinement, according to research on the mechanism of dust explosions. This implies a dust explosion will occur when a suspended combustible dust cloud in a confined space is ignited (Ebadat, 2007). Among the factors, combustible dust can be observed in a wide range of process industries (e.g. pharmaceutical manufacturers). According to the U.S. NFPA (National Fire Protection Association), dust can be defined as solids 420 μm or less in diameter. For individual material, the diameter of particle size should be located in its explosible particle size range (Eckhoff, 2003). Otherwise, dust is considered to be without explosibility. Mixing means the combustible dust is suspended to form a combustible dust cloud which could be ignited by ignition sources with enough temperature or energy. Oxidant mainly refers to the oxygen in the air, and confinement means the spaces where dust explosions occur are confined or partially confined to enable heat accumulation. To estimate the explosibility of combustible dust, various factors are applied. The minimum ignition temperature (MIT, °C) is defined as the temperature above which the combustible dust cloud will be ignited. A higher MIT indicates the mixture of combustible dust and oxygen is more difficult to ignite. Otherwise, the combustible dust cloud is ignited more easily. Similar to MIT, the minimum ignition energy (MIE) expresses the energy required to ignite a combustible dust cloud. Minimum explosible concentration (MEC, g/m^3) means a combustible dust cloud cannot be ignited when its concentration is lower than MEC. Further, limiting oxygen concentration (LOC) is the amount of the oxidant, above which a deflagration can occur. Further, the severity of a dust explosion can be represented by other indicators, such as the maximum explosion pressure (P_{max}), with the unit of bar(g), and the maximum rate of pressure rise, usually represented as K_{St} (Hassan, 2014). Moreover, the influence of certain factors on the severity of a dust explosion could also be observed. For example, P_{max} could increase with decreasing particle size and decrease with increasing moisture content (Lees, 1996).

Compared to other types of explosion, dust explosions can lead to more severe damage. This results from more combustible dust being involved in a series of dust explosions triggered by a primary one, which gives rise to higher overpressures and temperatures. It should also be noted that toxic gases, such as carbon monoxide, as likely byproducts of dust explosions can noticeably increase the extent and intensity of damage.

1.3 Risk assessment methods

Risk analysis methods can be applied to qualitatively and quantitatively estimate risks of accidents. The traditional qualitative risk assessment methods, i.e. HAZOP, are mainly used to screen the possible hazard scenarios in a system. The quantitative risk analysis (QRA) methods, e.g. Event Tree Analysis (ET), focuses on occurrence probability of various accident scenarios with different losses. The widely applied QRA methods include Fault Tree Analysis (FT), Bow-tie Analysis (BT) and Bayesian Network (BN).

Although conventional QRA methods are most commonly seen in risk analysis, the limitations of these methods are in considering common unwanted factors resulting from the independent assumption among these factors and the dynamic update of risk with the latest available information from the system (Khakzad et al., 2011). To overcome these limitations, BN, based on the Bayesian theorem, is introduced and has become a robust method in risk assessment (Cai et al., 2012; Khakzad et al., 2013a; Khakzad et al., 2013b; Khakzad et al., 2013c; Hanea and Ale, 2009; Langseth, 2007.).

1.4 Safety strategy determination

Many safety measures have been recommended to prevent dust explosions or mitigate the damage caused by the explosions. One of the most applied methods to protect units from dust explosions is venting, which will function when the pressure produced from a dust explosion is beyond a designed value (Abbasi and Abbasi, 2007; Ferrara et al., 2014.). Other efficient safety measures include housekeeping (Frank, 2004), containment and installation of a fire suppression system (Going and Snoeys, 2002), et al. Further, inherent principles, relying on the properties of materials or design of a process, are also recommended for dust explosion prevention (Amyotte et al., 2009). For example, solid inertants are usually mixed with coal dust to reduce its explosibility in coal mines. Although various safety measures, categorized into different types, are alternatives, the difficulty is how to select suitable safety measures to efficiently reduce the risks of dust explosions in a system under the limitations, e.g. the budget.

1.5 Domino effects of dust explosions

Secondary/tertiary dust explosions triggered by the initial ones are usually the main contributors to the severe losses in an accident due to more combustible dust being involved. The chain of dust explosions is also called the domino effect of dust explosions which originates from the primary dust explosion. The process of a secondary dust explosion can be simply illustrated as: When the overpressure produced from an initial one reaches a dust layer, it could be dispersed to form a combustible dust cloud which could be ignited by the flames accompanying the overpressure (Abbasi and Abbasi, 2007). Moreover, secondary/tertiary dust explosions are often observed far from the location where the primary one occurs, which induces difficulties in safety measures' application. The other concern comes from various accidents potentially triggered by dust explosions, e.g. toxic gas leakage, which can lead to more serious damage. Depending on the layouts of equipment in workshops and the working conditions of safety barriers on the propagation routes, physical effects from dust explosions on various target units might be different, which further leads to different occurrence probabilities of dust explosions.

1.6 Problem statement

As mentioned, in the academic area of dust explosions, the focus has been mainly on dust explosion mechanisms (Eckhoff, 2003, 2009; Callé et al., 2005; Amyotte et al., 2005; Cashdollar and Zlochower, 2007; Pilão et al., 2006; Benedetto et al., 2010) or preventive and mitigative safety measures (Eckhoff, 2003, 2009; Li et al., 2009; Myers, 2008; Marian and Rudolf, 2012; Amyotte et al., 2007, 2009). Only a few publications have mentioned risk analysis of dust explosions (van dert Voort et al., 2007; Abuswer et al., 2013). The challenges in risk estimation of dust explosions are to include the wide variety of industries related to dust explosions as well as the complex interlinked contributors. QRA methods, e.g. fault tree (FT), are widely applied in estimation of occurrence probabilities of accident scenarios, but in the area related to dust explosions they are seldom seen. To conveniently evaluate the risk of dust explosions in various industries, it is necessary to establish a generic risk analysis model for dust explosions, which can be tailored to different cases with or without slight modifications.

Secondly, being static and taking advantage of generic failure data are the main limitations of conventional risk assessment methods (Meel and Sieder, 2006; Rathnayaka et al., 2010; Ferdous et al., 2007; Khakzad et al., 2011). Because variations almost always occur during operational time, the conventional methods with the static structure, such as BT, cannot easily reflect these changes. This raises the need for a dynamic risk analysis model that can take varying operational and environmental parameters into consideration and adapt itself as new observations become available.

Thirdly, a primary dust explosion is usually followed by a secondary or more dust explosions, which are able to more seriously damage nearby units. In triggering a secondary dust explosion, both the overpressure and flames from the primary dust explosion play an important role. A magnitude of overpressure is required with enough strength to disperse dust layers to form a combustible dust cloud, and the flames should have with enough energy or a high enough temperature. However, due to the limited knowledge about chain dust explosions, more research is needed.

Fourthly, though various safety measures have been recommended to prevent or mitigate dust explosions, the method of estimating their effects is still absent. Further, in determining safety measures strategies, engineers usually have to choose among various available safety measures, even for one critical factor, which leads to the discussion about a preference of safety measures selection. Another dilemma is to balance risk level of dust explosions in a system and the available resources, e.g. budget. Thus, a reliable methodology considering risk control as well as limited resources is required.

1.7 Motivation

Firstly, in this research, the characteristics of dust explosions in various industries are investigated and discussed based on a statistical result for dust explosions worldwide. Another aim in current research is to develop a generic risk analysis model of dust explosions. To deal with the variety of contributors to dust explosions in systems, a dynamic risk analysis method, i.e. BN, is also introduced in risk analysis of dust explosions. Further, optimal methodology of safety strategy determination satisfying the requirements of risk reductions and the limitation of budgets should be developed to reasonably allocate resources for safety improvement. Finally, attention should also be paid to analyze the domino effects of dust explosions. Brief introductions are presented in the following section.

1.7.1 Accident statistics of dust explosions

Dust explosions in different industries exhibit individual characteristics. The accidents in some countries during different periods will be gathered first. Based on the statistical results, the features of dust explosions, i.e. the spatial and temporal distribution, will be further discussed. To represent individual characteristics in the different economic structures and safety management levels in developed and developing countries, the U.S. will be compared with China, the largest developing country in the world.

1.7.2 Development of a generic risk analysis model for dust explosions

BT has already proved to be a reliable and efficient method in risk assessment due to its ability to combine basic events, critic events, and safety barriers with consequence categories regardless of its static characteristic. One of the motivations in this research is to introduce the QRA method of BT into the area of risk analysis for dust explosions:

- A generic risk assessment model for dust explosions is absent. Although the essential factors for dust explosions and their sub-level factors (Eckhoff, 2003) are widely discussed in the literature, interlinks among the factors are needed to be further teased apart, which will be the basis of the generic risk model of dust explosions.
- BT is composed of an FT on the left and an ET on the right. Taking advantage of the FT, various factors of dust explosions can be organized according to the cause-effect relationships. In the ET, safety barriers and their relevant reliabilities are taken into account to estimate the consequence scenarios resulting from accidents and relevant occurrence probabilities.
- The generic risk analysis model for dust explosions based on conventional BT lacks the capacity for dynamic analysis. Due to the static characteristic of FTs and ETs, conventional BTs are difficult to use in dynamic risk analysis using real-time data obtained from operations.

1.7.3 Dynamic risk analysis of dust explosions

BN has been applied to perform dynamic risk analysis in many areas. Similar to conventional QRA methods, such as BT, BN can be used in forward probability prediction. Moreover, other advantages of BN make it a robust method in risk analysis.

- By using BN, the vulnerable factors in a system for dust explosion can be determined by backward analysis. In this step, the latest observed accidents are set as evidence to renew the probability of each node, called posterior probability, in

BN. Based on the posterior probabilities of basic events, the vulnerable parts needing to be improved can be determined.

- The latest information from a system can be introduced into risk estimation using BN. Taking advantage of probability adapting, the field records describing abnormal events, such as misoperation, can be applied in the risk analysis model to increase the accuracy of the results.

1.7.4 Optimal safety strategy methodology for dust explosions

Certainly, the efficiencies of safety measures should be considered first in safety strategy determination for a system. However, it is not the only factor that needs to be taken into account. In real cases, the available resources, such as the budget, are other factors which cannot be ignored. For example, the available budgets for potential safety strategies should also be satisfied, which means the cost of the safety strategies should be kept within the budget.

This research also focuses on developing an optimal safety strategy method to reduce the risk of dust explosions satisfying the limitations of budgets.

- The number of available factors is usually huge. The numerous contributors to a dust explosion increase the difficulty of determining safety strategy. However, taking advantage of the developed risk analysis model of dust explosions, the objectives of decision makers can be limited to the most vulnerable parts in a system.
- Efficiencies of safety measures can be estimated by the QRA model of dust explosions. Based on the developed risk analysis model for dust explosions, the

efficacies of individual safety measures or potential safety strategies on risk reduction can be calculated and compared.

- Optimal safety strategy for dust explosion prevention and mitigation needs to be discussed. The potential safety strategy should satisfy the requirements of both system risk control and limited budgets. More safety measures' application can certainly benefit risk control for dust explosions in a system. However, the total cost will no doubt increase.

1.7.5 Domino effects of dust explosions

The domino effects of accidents have been widely reported and relevant research has been published. As five essential factors should be present for a dust explosion to occur, it is difficult to estimate the physical effects of a dust explosion on nearby units where a secondary dust explosion might be triggered. In this research, the escalation probability of a dust explosion will be quantified to benefit domino effect analysis of dust explosions.

- The escalation probability of a dust explosion is still absent. The essential factors of dust explosions could influence the occurrence probability of a secondary dust explosion. For example, the overpressure received by a dust layer should be strong enough to arouse the dust layer to form a combustible dust cloud. In this research, this problem could be addressed with ET, which can represent the dependency of potential consequences on initial explosions.
- Discussion about domino effects of dust explosions is seldom seen. Since a dust explosion chain is usually observed in real cases, understanding the mechanism of the dust explosion chain is critical for domino effects analysis of dust explosions

and further mitigation of the potential damages. In this research, taking advantage of BN, the occurrence probability of a dust explosion chain will be analyzed.

1.8 Organization of this thesis

This thesis is organized based on five manuscripts in five different chapters (i.e., Chapters 4, 5, 6, 7 and 8). The outline of each part is presented as follows.

Chapter 1 introduces an overview about dust explosions and risk analysis methods. The challenges in current research and the motivation of this research are also discussed.

Chapter 2 demonstrates the innovations and contributions of this research. **Chapter 3** is the literature review related to this thesis, including the mechanism of dust explosions, risk analysis methods, i.e. BT and BN, application of risk analysis in dust explosions, etc.

Five research papers compose **Chapter 4**, **Chapter 5**, **Chapter 6**, **Chapter 7** and **Chapter 8** respectively, covering the research scope of dust explosion accident statistics, a generic risk analysis model of dust explosions development, a dynamic risk analysis model of dust explosions, an optimal safety strategy methodology and domino effects analysis of dust explosions. Among these papers, four have been published and others have been submitted for publication in international journals.

Research paper 1

Dust Explosions: a Threat to world Industries (2015). Process Safety and Environmental Protection, 98(11): 57-71.

Research paper 2

Risk-based Design of Safety Measures to Prevent and Mitigate Dust Explosion Hazards (2013). Industrial & Engineering Chemistry Research, 52(50):18095-18108.

Research paper 3

Risk Analysis of Dust Explosion Scenarios using Bayesian Networks (2015). Risk Analysis: an international journal, 35(3): 278-291.

Research paper 4

Risk-based optimal safety measure allocation for dust explosions (2015). Safety Science. 74(4): 79-92.

Research paper 5

Domino Effects Analysis of Dust Explosion by Bayesian Networks. (Submitted to Reliability Engineering & System Safety for publication, 2015)

Chapter 9 reports the summary and conclusions drawn from this research. Prospective relevant work is also provided at the end of this thesis.

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2 Novelty and Contribution

2.1 Overview

The main contribution of this research can be classified into the following categories:

- Development of a comprehensive model for risk analysis of dust explosions
- Development of a cost-effective safety measure allocation to reduce the risk of dust explosions

A brief explanation of the novelties and contributions is given in this chapter while more details can be found in the next chapters.

2.2 Development of risk analysis model for dust explosions

2.2.1 Developing a generic risk analysis model based on BT

In this research, a generic risk analysis model is established using BT. In the generic BT model, the factors potentially contributing to dust explosions as well as potential consequences are listed and organized according to the cause-effect relationship. The generic BT model can readily be tailored to analyze the risk of dust explosions in specific cases. More details on the generic BT model can be found in Chapter 5.

2.2.2 Dynamic risk analysis

To model conditional dependencies and also to perform probability updating, the generic BT model of dust explosions is transferred into a BN. Using BN, both probability prediction and probability updating can be performed. As a result, the most critical factors contributing to dust explosions can be identified. In addition to probability updating, the BN facilitates the probability adapting which can be of great importance in sequential (experience) learning. In Chapter 6, this issue is discussed in more detail.

2.2.3 Domino effects analysis

The domino effects of dust explosions are also discussed in this research. To quantify the escalation probability of initial dust explosions, ET is introduced combining the essential factors for a dust explosion with its potential consequences. Based on an analysis of potential propagation routes of escalation vectors, the domino effects analysis model for dust explosions can be developed using BN. A more detailed description of this innovation can be found in Chapter 8.

2.3 Modification of safety measures allocation in safety strategy based risk analysis

In this research, a methodology of safety measures allocation for dust explosions, combining an optimal method and risk analysis model, is proposed. To overcome the limitation of qualitative analysis, widely used in safety strategy determination, the risk analysis model of dust explosions is introduced in this method to estimate the effects of safety measures on risk level of dust explosions in a system. The details about this contribution are discussed in Chapter 7.

3 Literature Review

3.1 Dust explosions

3.1.1 Mechanism of dust explosions

Five factors, including combustible dust, oxidant, ignition source, dispersion of dust (mixing) and confinement have been proven to be essential for a dust explosion and form the pentagon of dust explosions shown in Figure 3.1. Among them, combustible dust widely exists in process industries, such as coal mining and plastic manufacturing and processing industries, and different definitions of dust can be found for different materials. For example, dust is defined as having a particle diameter lower than 76 μm according to BS2955 (CSB, 2006; BS2955, 1958). However, NFPA (National Fire Protection Association) holds an opinion that a powder 420 μm or less in diameter should be called dust (NFPA68, 2007). Oxidant usually refers to the oxygen in the air. The mixture of combustible dust and oxygen in the form of a combustible dust cloud is the necessary element for a dust explosion. Ignition sources, ranging from hot surfaces to friction sparks, can provide enough temperature or energy required for a dust explosion. Confinement is also needed for a dust explosion to accumulate enough heat.

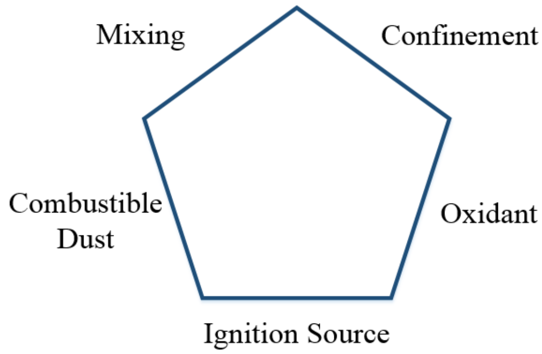


Fig. 3.1 Dust explosion pentagon (Kauffman, 1982)

Various indices are applied to measure dust explosibility and the severity of a dust explosion as aforementioned. And the research in relevant areas is continuously reported. Kuai et al. (2011) revealed magnesium dust explosion characteristics under different conditions, e.g. particle size, through experiments. Similarly, Mittal (2013) investigated the limiting oxygen concentration of Indian coals by experiments. The influence of dust properties on dust explosion parameters was also discussed (Lees, 1996). For example, MEC increases with increasing moisture content, and decreases with decreasing particle size. However, K_{St} increases with decreasing particle size. Recently, Kuai et al. (2013) compared explosion behaviors of light metal and carbonaceous dusts triggered by different ignition energies. Di Benedetto et al. (2010) developed a model to quantify the effect of particle size on dust reactivity.

Besides the five essential factors listed above, there are a number of primary events, identified as indirect causes of dust explosions, contributing to the essential ones. Thus, in hazards assessment of industries prone to dust explosions, determining the primary events should depend on a variety of factors, involving defects in design, operation and management. For example, dust accumulation can result from an *inefficient ventilation* *system*, which could further be the result of a series of sub-factors, e.g. *equipment failure*. *Poor housekeeping* can also lead to dust accumulation in a system. However, in some process industries (e.g. silos), dust accumulation is considered as a normal operation condition. Therefore, hazards should be identified according to the characteristic of individual processes.

3.1.2 Safety measures for dust explosions

Safety measures for dust explosion prevention or elimination are mainly concentrated on removing one or more essential factors for dust explosions in a system, and damage mitigation, also known as safety barriers, refers to reducing potential damage caused by dust explosions. For prevention safety measures, *housekeeping* is a typical example, due to the fuel elimination. Explosion suppression systems, applied to prevent further development of a dust explosion, are among the commonly used safety barriers. Besides above, venting system is also an efficient way to reduce damage caused by a dust explosion. Holbrow (2013) tested reduced dust explosion pressures through small vessels venting and flameless venting. Yan and Yu (2013) studied the influence of relief pipe diameter and pipe length on overpressure characteristics of aluminum dust explosions.

Safety measures can be further classified into inherent, engineered and procedural safety measures according to safety management principles. Inherent safety depends on reducing the hazards due to the properties of a material or the design of a process. Four key principles for inherent safety, including minimization, substitution, moderation, and simplification, have been categorized (Amyotte et al., 2007, 2009; Kletz, 1978, 2003). The principles of inherent safety are also introduced in dust explosion prevention (Amyotte et al., 2009, 2010, 2012). Among the three types of safety measures, inherent ones are normally considered more reliable than the others which rely on the performance of additional safety devices or the physical or psychological condition of operators. Engineered safety measures, such as venting systems, are applied to reduce the frequency of accidents or to lower their severity via setting additional barriers which could be further divided into passive and active according to the type of operation (Dianous and Fievez, 2006). For passive safety measures, no additional activator, actuator or human intervention is required (e.g. explosion relief vents) whereas active safety measures depend on the function of additional control systems (e.g. automatic suppression systems). Procedural or administrative safety measures, on the other hand, rely on management methods to prevent accidents (e.g., training) or mitigate their damage (e.g., evacuation and emergency response). These safety measures are influenced by human factors such as safety training effectiveness or human response time.

3.2 Quantitative risk analysis methods

There are many methods for risk assessment of envisaged accident scenarios in the process industries, such as quantitative risk assessment (QRA), and maximum credible accident analysis (Khan, 2001; Khan and Abbasi, 1998c). Although these methods consist of different steps and follow specific procedures, e.g. identifying the accident scenario causing the most serious damage in maximum credible accident analysis, accident scenario identification in terms of both mechanism and likelihood is a common and central step for all of them. Among the different models available to identify and analyze accident scenarios, the fault tree model (FT), event tree model (ET), and bow-tie model (BT) have been well proven to be reliable and efficient tools.

3.2.1 Fault tree

FT is a diagnostic technique applied for presenting the possible causes contributing to various sub-events which can result in an undesired event, also known as the top event (Khan and Abbasi, 2000). An FT can be constructed downwards from the top event and further details can be dissected according to causality until all primary factors leading to the top event are known. In an FT, primary events, with binary (two) states, are considered statistically independent. Various gates are applied to represent the relationships between events. AND-gates and OR-gates are the two most widely used types among them. FTs can be used in both qualitative analysis, based on Boolean algebra, and quantitative analysis, calculating probability of the top event by obtaining the occurrence probabilities of the primary events.

Usually, computerized methods, i.e. Monte Carlo simulation, are required in analysis of complex FTs. Fuzzy set theory and evidence theory are also introduced in FT analysis to reduce the margin of error due to inaccuracy and incompleteness of the data of the primary events (Ferdous et al., 2009; Markowski et al., 2009; Yuhua and Datao, 2005).

FT has been widely used in estimating occurrence probabilities of unwanted accidents (Khan et al., 2001b; Volkanovski et al., 2009; Zhang et al., 2014; Lindhe et al., 2009; Chen et al., 2007). However, for complex systems, especially in which the factors dependent on each other, the usage of FT is limited.

3.2.2 Event tree

ET, an inductive method, is widely used in safety analysis to assess potential consequence scenarios caused by accidents. It originates from an unwanted event and analyzes possible consequences along potential progression routes considering safety barriers in chronological order. Using occurrence probability of the initiating event, consequence scenarios can be quantified in ET depending on the working situations of safety barriers (success or failure). When the safety barrier functions, the progression route will follow an upward branch, otherwise the lower branch when it fails (shown in the Figure 3.2, the ET part).

ET has been used in the field of accident modeling (Bearfield and Marsh, 2005; Rathnayaka et al., 2011), dynamic failure assessment (Meel and Seider, 2006), and dynamic risk assessment (Kalantarnia et al., 2009, 2010).

3.2.3 Bow-tie

Bow-tie (BT), a graphical method, combines FT and ET to explore both the primary causes and consequences of a critical event. It also provides system reliability if effects of safety measures are considered (as Figure 3.2. shows).

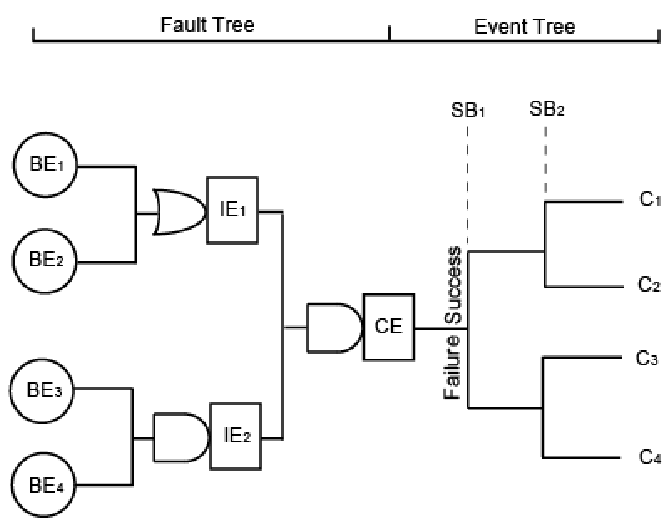


Fig. 3.2 Structural representation of Bow-tie (BE: Basic event; IE: Intermediate event; CE: Critical event; C: Consequence; SB: Safety barrier)

A BT illustrates an accident scenario, beginning from the basic events (BE) and ending with the potential consequences (C). These consequences result from the CE and the failure of safety barriers (SB). Using the probabilities of primary causes, along with failure likelihoods of safety measures, the probabilities of consequences can be estimated. As Figure 3.2 shows,

$$P(C_1) = P(CE) * \left(1 - P(SB_1)\right) * (1 - P(SB_2)) \qquad (3.1)$$

where P(CE) is calculated from the FT.

BT has been widely used in the risk analysis area. Dianous and Fiévez (2006) established a risk assessment methodology based on BT to evaluate the efficacy of risk control measures. Shahriar et al. (2012) introduced fuzzy theory into BT to analyze the risk of oil and gas pipelines and provided suggestions for the risk management process. Khakzad et al. (2012) coupled Bayesian analysis and physical reliability models with a BT diagram for risk analysis of dust explosions in a sugar refinery. Bellamy et al. (2007) proposed a tool, called Storybuilder, to identify the dominant patterns of safety barrier failures, barrier task failures and underlying management flaws using BT. A systematic HAZID method based on BT, named DyPASI, was suggested by Paltrinieri et al. for a comprehensive hazard identification of industrial processes (2013). Khakzad et al. (2013a) introduced a methodology to map BT into a Bayesian network (BN) and applied it to risk analysis. Despite its wide applications in QRA, BT suffers from a static nature due to FT, and cannot easily be updated when new information becomes available. However, there have recently been efforts to overcome this limitation either by coupling BT with Bayesian updating (Khakzad et al., 2012) or via using more dynamic methods such as Bayesian networks (Khakzad et al., 2011, 2013a, 2013b).

3.2.4 Bayesian network

The Bayesian network (BN) is an inference probabilistic method. It is a directed acyclic graph (DAG) which is composed of nodes, arcs and conditional probability tables (CPT). Nodes represent random variables while arcs represent dependencies among linked nodes. The types and strength of these dependencies are defined via CPTs (Torres-Toledano and Sucar, 1998).

In BNs, if the direction of an arc is from node A to C, node A is called the parent node of C. Node C is called a child node of A (as shown in Figure 3.3). The nodes without parent nodes are called root nodes and the nodes without child nodes are named leaf nodes. The other nodes are called intermediate nodes, each of which is companied with a CPT.

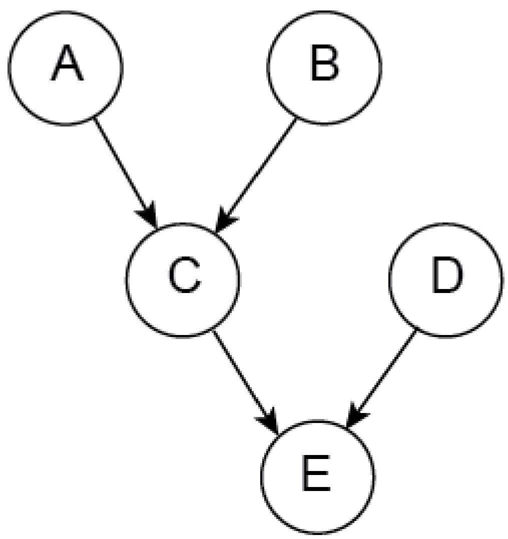
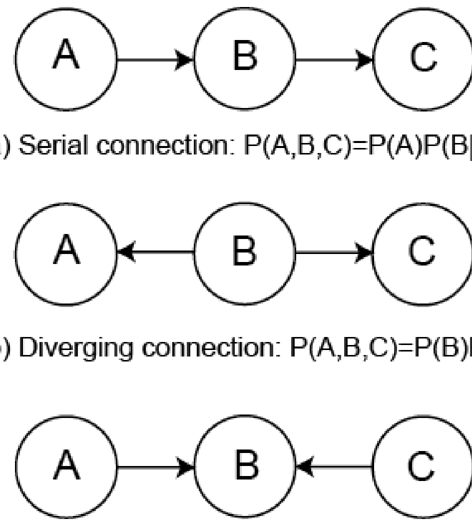


Fig. 3.3 Different definitions of nodes in BNs (A, B and D: Root nodes; C: Intermediate node; E: Leaf node)

Another important definition in BN is “d-separation”, which is about the rules of information transmission among nodes. There are three kinds of connections among nodes: serial connections, diverging connections and converging connections (shown in Figure 3.4).



(a) Serial connection: P(A,B,C)=P(A)P(B|A)P(C|B)

(b) Diverging connection: P(A,B,C)=P(B)P(A|B)P(C|B)

(c) Converging connection: P(A,B,C)=P(A)P(C)P(B|A,C)

Fig. 3.4 Probabilities relationships based on the chain rule and local dependencies

As (a) and (b) in Figure 3.4 shows, if the state of B is known, then the chain is blocked and information from A cannot transmit to C. In this case, A and C are independent, which signifies that nodes A and C are d-separated given B. For converging connection (Fig. 3.4 (c)), nodes A and C are d-separated when B is unknown.

Based on the conditional independence and the chain rule, BNs represent the joint probability distribution $P(O)$ of variables $O = \{A_1, A_2, A_3, \dots\dots, A_n\}$ in BNs as:

$$P(O) = \prod_{i=1}^{n} P(A_i|Pa(A_i)) \qquad (3.2)$$

where $Pa(A_i)$ stands for the parents variables of A_i, $P(A_i|Pa(A_i))$ is the probability of A_i given its parent variables, and $P(O)$ reflects the properties of the BN (Jensen and Nielsen, 2007).

Based on equation (3.2), the joint probability of variables in BN in Figure 3.3 can be presented as:

$$P(E) = P(A)P(B)P(D)P(C|A,B)P(E|C,D) \quad (3.3)$$

BN takes advantage of new information over time (called evidence, represented as E in equation 3.4), which means BN can be used in risk analysis for dynamic systems, such as dust explosions. The risk of dust explosions and their potential consequences could be updated as the system runs and will help to determine the most fragile factors in the system and relative safety measures.

$$P(O|E) = \frac{P(E|O)}{P(E)} = \frac{P(E,O)}{\sum_O P(E,O)} \qquad (3.4)$$

In risk analysis for various types of accidents/systems, BN has be proven as a robust method. Cai et al. (2012) proposed a Bayesian network model to estimate the reliability of a subsea blowout preventer control system. A new methodology based on the Bayesian network is proposed by Khakzad et al. (2013b, 2013c) to analyze domino effects and risk in offshore drilling operations. Zhang et al. (2013) developed a model based on BN to estimate the safety of the Yangtze River. A general framework for the risk-based reconfiguration of a safety monitoring system logic of a dynamical system is proposed by Kohda and Cui (2007). As aforementioned, the other advantage of BN is that it can be developed directly from FT, ET or BT based on a mapping algorithm (Bobbio et al., 2001; Bearfield and Marsh, 2005; Khakzad et al., 2011; Khakzad et al., 2013a). This bridges the gap between static and dynamic risk analysis methods as well as considering the features of BT and BN.

3.3 Safety measure strategy determination

In safety management, risk control for potential hazards is usually the first concern for decision makers. Ideally, after figuring out the defects of a system, the relevant safety measures should be chosen to improve the safety level in a system. However, due to the limited resources, i.e. budgets, not all safety measures can be allocated. Therefore, maximizing the potential safety strategy's effects on risk control with limited resources is a big challenge for policy makers.

Some optimizing models have been introduced to benefit decision-making (Kim et al., 2006; Caputo et al., 2011, 2013; Kazantzi et al., 2013; Bernechea and Arnaldos Viger, 2013; Ramírez-Marengo et al., 2013), among which the knapsack problem is usually considered to represent the dilemma of safety strategy allocation. The description of the knapsack problem originates from the selection methodology of maximizing the total values of materials put in a bag (the objective) with limited gross weight (the constraint). Therefore, this kind of problem, the relationship between the objective and resource constraints, can be expressed as

$$\text{Max}Z = \sum_{j=1}^{n} V_j x_j \qquad (3.5)$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^{n} W_j x_j \leq W_R \\ x_j = 0 \text{ or } 1 \qquad (j = 1, \dots, n) \end{cases}$$

where V_j and W_j stand for the objective parameter, i.e. the value of material j, and the resource used to obtain the objective parameter, respectively. W_R means the available resource, i.e. the rated weight of the bag. In the knapsack case, when the material j is chosen, 1 will be given to x_j, otherwise it equals 0.

The first function, called the objective function, means the goal of the potential strategy is to maximize the sum of the objective parameter, i.e. the total value of selected materials. The second function, named the constraint function, stands for the available resources, i.e. the target weight, which should be considered in decision making.

Although optimizing models have already been applied in safety measure allocation, Cox (Cox, Jr., 2012) suggested more attention should be given to the optimization of safety management. Caputo et al. (2013) proposed a method based on a multi-criteria knapsack model to help select the measures with the most efficient in safety management. Combining the risk matrix with the knapsack model, Reniers and Sörensen (2013) performed a cost-benefits analysis for determining safety strategy.

3.4 Domino effects of dust explosions

The domino effects of accidents have been widely reported (Gómez-Mares et al., 2008; Abdolhamidzadeh et al., 2011; Hemmatian et al., 2014; Darbra et al., 2010). According to the description of a domino event by Cozzani et al. (2006), it is "an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events resulting in overall consequences more severe than those of the primary event." In this definition, the primary event means the original accident of the domino accidental sequence. The physical effects of accidents (i.e. pool fire), named escalation vectors and categorized into radiation, fire impingement, fragments, and overpressure, are responsible for the escalation of triggering the secondary scenarios, and the relevant thresholds of escalation vectors are also suggested using experimental data and regression methods for a number of atmospheric and pressurized units as well as auxiliary equipment (Cozzani et al., 2006). Generally, only when values of escalation vectors (i.e. radiation) generated from a primary accident is beyond the relevant thresholds, could damage to secondary units and secondary accidents occur. For estimating the probability of damage to a target unit, some methods can be found in this area. Khan and Abbasi (Khan and Abbasi, 1998a, 1998b, 2001) analyzed the likelihood of domino effects in a cluster of industries based on the developed methodology, called domino effect analysis (DEA), with DOMIFFECT software. Cozzani and Salzano (2004a, 2004b, 2004c) discussed the quantitative assessment of domino effects caused by overpressure. Subsequently, Cozzani et al. (2005) developed a quantitative risk assessment procedure for a domino effect and the impact probability triggered by fragments was also discussed by Zhang and Chen (2009). A quantitative methodology based on probabilistic models and physical equations was further proposed by Kadri et al. (2013) to assess domino effects at industrial sites.

However, research about domino effects of dust explosions is seldom seen, though the severe consequences of dust explosion chains are widely reported in accident reports (CSB, 2005). Compared to the domino effects of other accidents (i.e. projected fragments), the mechanism of a secondary dust explosion is more complicated. As aforementioned, the overpressures from primary dust explosions should have enough strength to arouse dust layers providing enough dust to form a combustible dust cloud. The ignition sources (the flame from a primary dust explosion or other existing ignition sources) should also have enough energy or high enough temperature (Abbasi and Abbasi, 2007).

Propagation probability of flames and blast waves from a dust explosion can be observed in limited published papers. According to the suggestion from van der Voort et al. (2007), the propagation probabilities of dust explosions to nearby units can be given as 0.1 and 0.01 for a direct neighbouring module and a remote neighbouring module, respectively. Kosinski and Hoffmann (2006) revealed that the probability of transmission of an explosion from one unit to a nearby unit decreases with decreasing diameter and increasing length of the connecting pipeline, based on simulation results using Computational Fluid Dynamics (CFD). Zalosh and Greenfield (2014) proposed an empirical equation for calculation of propagation probability between units based on test data. Besides blast wave propagation among connected units, attention was also paid to dust lifting by overpressures. Kosinski and Hoffmann (2005) studied the dust lifting behind blast waves using the Lagrangian model. An experiment for dust lifting caused by a blast wave was also performed by Klemens et al. (2006). Similarly, Utkilen et al. (2014) simulated dust lifting by strong pressure waves using the Eulerian-Eulerian method. Based on reviewing the research in relevant areas, the occurrence probabilities of dust explosions given an initial dust explosion have not been seen, which will be discussed in section 8.

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4 Dust Explosions: a Threat to the Process Industries

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Preface

A version of this manuscript has been published by Process Safety and Environmental Protection. The first author collected the accidents, analyzed the statistic characters in various aspects and discussed causes leading to the situations. The co-authors, Dr(s) Khakzad, Khan and Amyotte supervised and reviewed the methodology, proposed valuable suggestions and corrections to improve the quality of the manuscript.

Abstract

This paper considers more than 2000 dust explosion accidents that occurred worldwide between 1785 and 2012. The statistical features of these cases are first examined spatially and temporally. Accident frequencies at different levels of economic development are further discussed. China and the United States are chosen as examples to represent the differences in distribution features of dust explosions in countries with different economic development levels. Data for combustible dusts leading to dust explosions in both China and the United States are also collected and categorized. The features of ignition sources for dust explosions, the types of enterprises with high risk, and the critical equipment in such enterprises are also analyzed. The results could help identify hazards of dust explosions in various industries, monitor the critical equipment, and further suggest safety improvement procedures to reduce the probability and damage of dust explosions.

Key words: Dust explosion, Data analysis, Accidents

4.1 Introduction

A dust explosion could be triggered when flammable particulates suspended in air encounter ignition sources with sufficient energy (Amyotte and Eckhoff, 2010). According to the Occupational Safety & Health Administration of the US (OSHA), combustible dust can be considered as combustible materials in finely divided forms. Combustible dust can be found in the form of byproduct in various industries such as drilled-charcoal powder in coal mining and wood powder in the wood industry, or in the form of raw materials or intermediate products such as sugar powder in food processing plants. Aside from high temperatures and overpressures caused by dust explosions, toxic gases can also be produced in such violent chemical reactions (Eckhoff, 2003). Thus, dust explosions present significant threats to people, assets, and the environment. Dust explosions have caused numerous losses in industry (CSB, 2006). The dust explosion that occurred in a coal mine in Liaoning province, China, in 1942, causing 1594 deaths and 246 injuries, might be the most serious case in history (Mining-technology, 2014).

According to previous research (Eckhoff, 2003), fuel, oxidant, ignition source, confinement, and suspension are the essential factors for a dust explosion. For example, Callé et al. (2005) discussed the effects of size distribution and concentration on wood dust explosion. Various safety measures have also been proposed to eliminate the foregoing essential factors or reduce damages caused by dust explosions (Eckhoff, 2003). For instance, altering the composition of a dust by admixture of solid inertants, recommended by Amyotte et al. (2009) as an inherent safety measure, can be applied to reduce the reactivity of the dust. Similarly, effective housekeeping could also be considered a useful method to lower the probability of dust explosions and their potential damage, because of the elimination of the accumulated amount of combustible dust in high risk areas (Khakzad et al., 2012).

Also, there has been some research to estimate the occurrence probability and risk of dust explosions. In this regard, Hassan et al. (2014) proposed a model based on characteristics of combustible dust (e.g., dust particle diameter). Van der Voort et al. (2007) developed a quantitative risk assessment tool for dust explosions consisting of a series of sub-models. More recently, Yuan et al. (2013, 2015) proposed a dust explosion risk analysis model based on the Bow-tie method and Bayesian network. In the aforementioned methodologies, the common step is the identification of hazards, which requires wide knowledge of both dust explosion mechanisms and examination of where the dust explosion takes place. However, in real industrial plants, a large number of potential hazardous factors contributing to dust explosions cannot usually be enumerated. Learning from past accidents could help identify frequent hazardous factors as well as vulnerable units in various industries, and thus enforce monitoring of vulnerable units and prevent dust explosions.

Relevant data for dust explosion accidents can be found in accident reports, literature, reports from professional agencies, and the mass media. For example, the US Chemical Safety Board (CSB) collected data for 197 dust explosions that happened in the US from 1980 to 2005, and these accidents were reported to have caused 109 fatalities and 592 injuries collectively (CSB, 2006). Similarly, data for accidental dust explosions in China from 1980 to 2011 have been collected by Yan and Yu (2012). Zheng, et al (2009) collected 106 dust explosion cases in Chinese coal mines from 1949 to 2007, and analyzed characteristics of Chinese coal dust explosions. Abbasi et al. (2007) gathered some cases in 2004 and made an attempt to investigate the causes, consequences, and prevention methods of dust explosions. Also, according to a report from the National Fire Prevention Association (NFPA) (1957), 1123 dust explosions occurred in the US from 1900 to 1956, while 426 dust explosions happened in Germany from 1965 to 1985 (Eckhoff, 2003).

This chapter is organized as follows: resources for data collection are introduced in section 4.2. Spatial and temporal features of accidents and casualties, types of combustible dust, the type of industries involved in dust explosions, ignition sources, and critical equipment are discussed in section 4.3. In section 4.4, the contributors to the distributions of accidents, combustible dusts and industries are discussed, while the main conclusions are summarized in section 4.5.

4.2 Information of dust explosions collection

During information collection for the present research, some difficulties were met. First, the number of reported dust explosions is far below their actual occurrence. According to Mannan (2004), the gap between the reported and actual numbers decreases as damages increase, implying that accidents with less damage tend to be more easily neglected by related agencies, as opposed to those with severe damages. Second, different information sources may include inconsistent data in terms of casualty and damage even for a similar accident. Further, reporting time could affect the accuracy of the information. For example, in many cases, fatalities and injuries may increase with time after an accident happens. Therefore, seven days following an accident is considered as a term to record losses resulting from the traffic accidents or fire accidents in China (Government of the People's Republic of China, 2007). Also, sometimes factories or governments are suspected to intentionally under-report consequences of accidents to reduce or escape punishment, which also leads to inaccurate information (a very serious problem in China). Related punishment notices for hiding accidents can be found on the website of the China State Administration of Work Safety (CSAWS). Aside from the above-mentioned problems, uncertainty also exists throughout the dust explosion investigation process. For example, assessments of dust explosion origins largely rely on experts' opinions and experience as the accident scenes are usually severely damaged. Moreover, it can be observed that some information (e.g. ignition sources) is absent in accident reports as a result of limited budgets and human resources, or seriously damaged scenes.

The collected dust explosion accident data in this work are mainly from the following sources:

- Reports and accident statistics from professional organizations and national agencies such as NFPA, CSB, CSAWS and OSHA

- Process safety text books presenting dust explosion cases
- Academic papers
- Local newspapers

Thirteen percent of the collected cases is shown in Appendix A and categorized according to the following factors:

- Date of accident
- Country
- Type of combustible dust
- Equipment involved
- Type of industries
- Number of injuries and deaths
- Ignition source

In Appendix A, metal dust mainly includes aluminum, magnesium, iron and associated combustible alloy dusts. Flour, corn, sugar dusts, and other combustible edible dusts are categorized as food dust. The inorganic dust, excluding metal dust and coal dust, includes the other types of inorganic combustible dust such as sulfur powder.

4.3 The characteristics of hazardous dust explosion accidents

As shown in Appendix A, the collected cases come from a large range of times and industrial types. Features of dust explosions, such as casualties, vary with individual countries and periods. Due to the process characteristics of individual industries, various features can also be observed in ignition source, involved equipment, and so forth.

4.3.1 Spatial distribution of dust explosions

Performing statistical analyses, the distribution of dust explosions in various countries is presented in Figure 4.1.

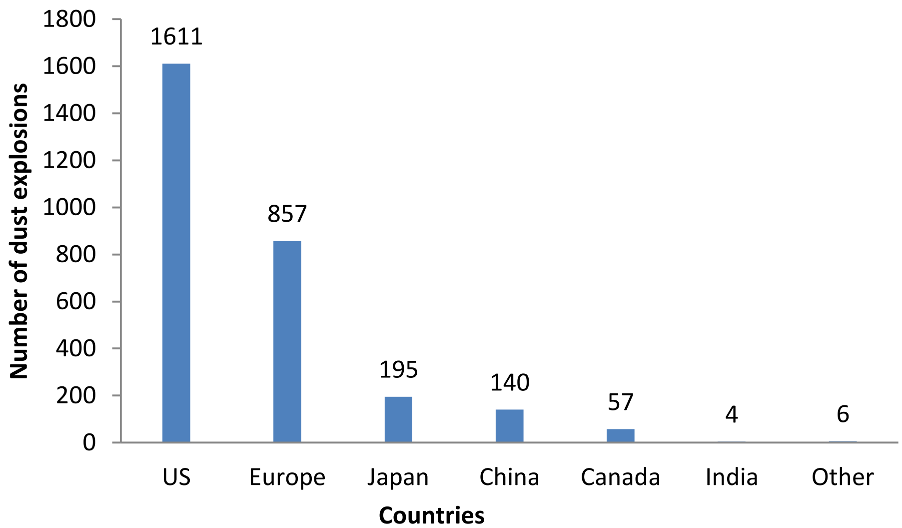


Fig. 4.1 Dust explosion numbers in different countries

As can be seen from Figure 4.1, the dust explosion reports are mainly from the US, Europe, Japan, China and Canada. Among them, the number of dust explosions in the US is 1611 - far more than in other countries. The following is Europe, in which the numbers from Germany and the UK account for the majority, holding 426 and 411 respectively. In other European countries, including Norway, Sweden, France, Italy and Spain, the accident reports are also observed.

One contributor to accident distribution might be differing economic development levels in different countries, due to the close relationship between dust explosions and manufacturing activities. The link between economic activities and occupational accidents has been widely discussed (Van Beeck, et al., 2000; Gerdham and Ruhm, 2006, Wang, 2006; Song, et al., 2011). In the current work, the Gross Domestic Product (GDP) and industrial output (U.S. dollars) of the top 9 industrial countries or areas (World Bank, 2002, 2012) are collected and shown in Figure 4.2 for further discussion.

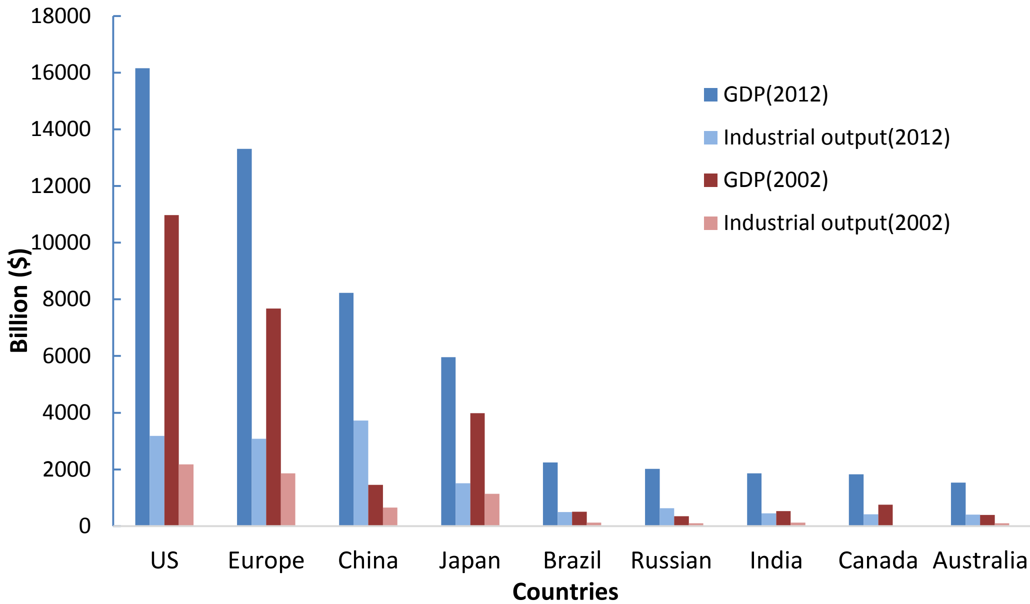


Fig. 4.2 GDP and industrial output of main industrial countries in the world (2002, 2012, World Bank)

It should be noticed that the data of industrial output from Canada in 2002 is absent (World Bank, 2002, 2012). The top countries or areas in GDP and industrial outputs are located in North America (2), Asia (3), Europe (5), Oceania (1) and South America (1). Among them, the GDP of the United States reached 16,163 billion US dollars and Europe (including Germany, the UK, Norway, Sweden, France, Italy and Spain) held 13,317 billion US dollars in 2012, followed by China with 8,229 billion US dollars. Similar to GDP, unbalanced development can also be seen in the amount of industrial output of different countries. The top output country is China with 3,725 billion dollars in 2012, higher than the US with 3,185 billion dollars and Europe with 3,075 billion dollars. The relationship between economy and accidents will be discussed further in section 4.4.

4.3.2 Temporal distribution of dust explosions

The first reported dust explosion accident is possibly a flour explosion in Turin in 1785 (Echhoff, 2003). Subsequently, dust explosions were gradually recognized as accidents capable of causing severe damage, stimulating research on the mechanisms of dust explosions and related safety measures to prevent them or to protect plant personnel. Research regarding combustible dusts and dust explosions inevitably affected the operations at worksites. The distribution of accidents along with different time periods is represented in Figure 4.3.

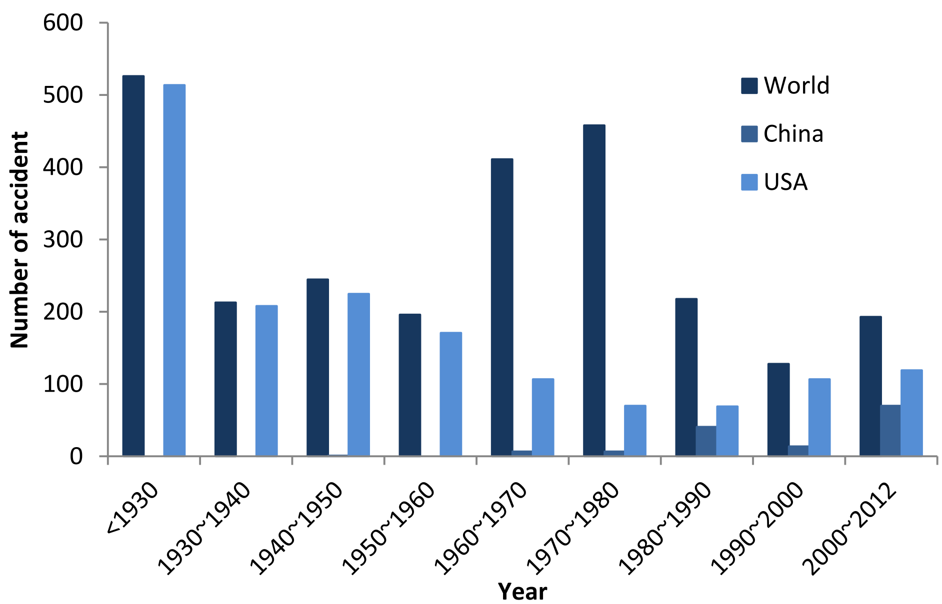


Fig. 4.3 Number of dust explosions in different time periods

The numbers of reported accidents worldwide appears to be generally decreasing with time, especially over the past 20 years. Compared to 526 reported dust explosions before 1930, the total number has been reduced to 193 since 2000. Though a spike appears during 1970-1980, the trend is decreasing, which might result from the continual emergence of safety management system worldwide. From Figure 4.3, it can also be observed that the number of reported accidents in China has greatly increased since 1980 from 7 during 1970-1980 to 41 in 1980-1990 to finally 70 since 2000. This might be explained by rising industrial activities since the Chinese economic reform of the 1980s. The number of dust explosions and industrial output from 2003 to 2012 in China are depicted in Figure 4. As can be noted, the number of accidents increased during 2003-2012 along with the increase of industrial output.

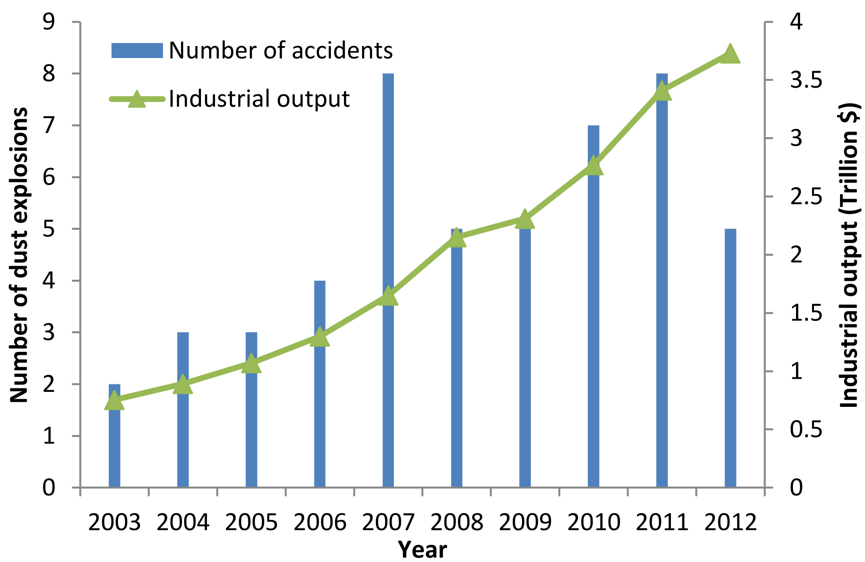


Fig. 4.4 Number of dust explosions and industrial outputs in China from 2003 to 2012

4.3.3 The trend of fatalities in dust explosion accidents

The fatalities and injuries per accident during various periods are provided in Figure 4.5.

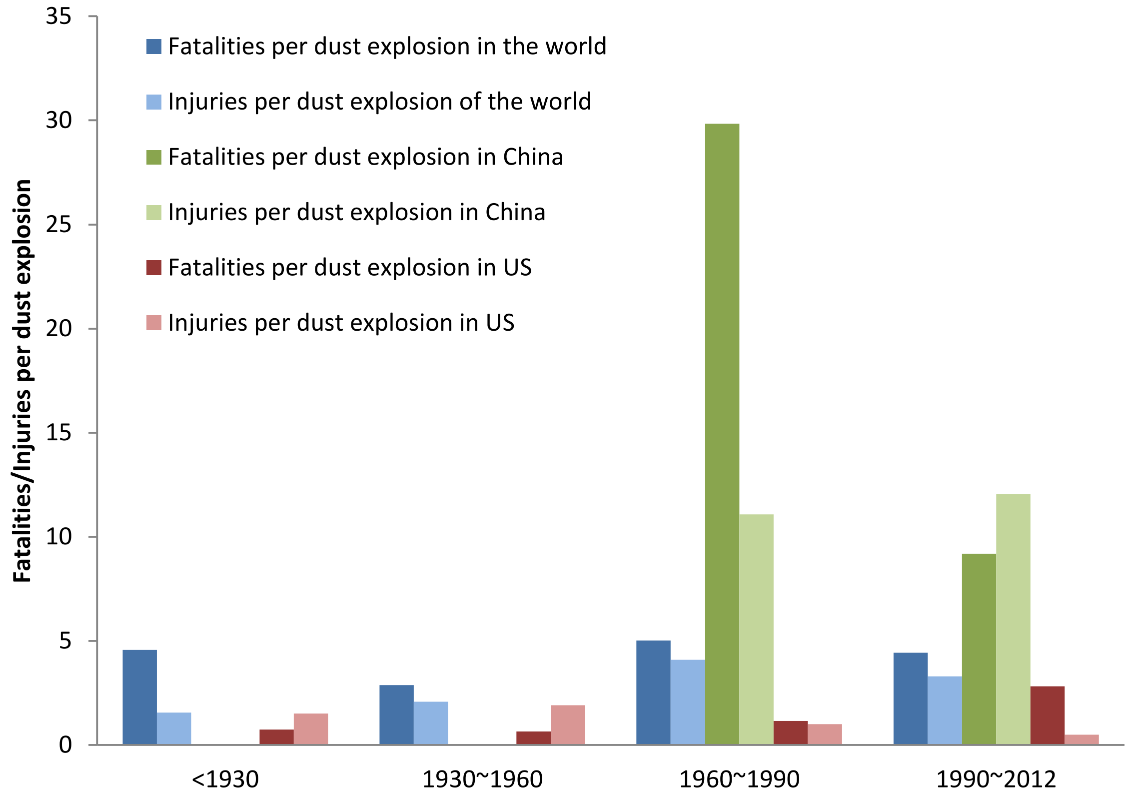


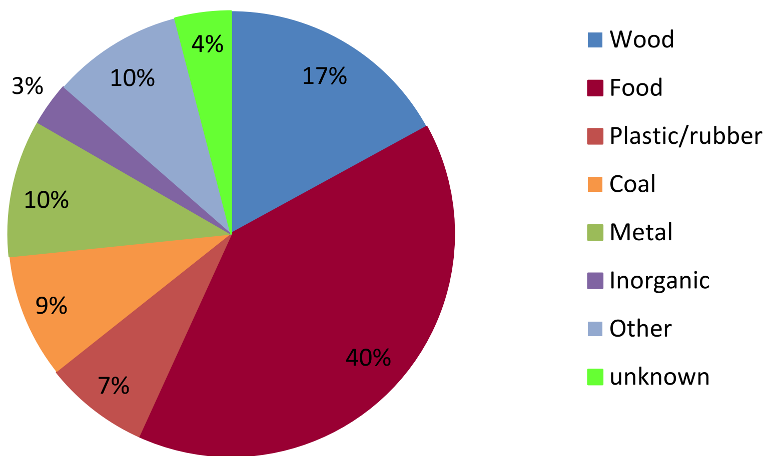
Fig. 4.5 Fatalities/injuries per accident in different periods

The worldwide fatalities per dust explosion decreased from 4.6 before 1930 to 2.9 between 1930 and 1960. However, it increased to 5.0 between 1960 and 1990. After this period, the downward tendency of casualties reappeared, and the value declined to 4.4. The higher number of fatalities in developing countries, such as China, might be the main contributor to the higher rate after 1960. As Figure 4.5 shows, the fatalities per accident in China reached a high number, 29.8, during 1960 and 1990, which is much higher than the worldwide level in the same period. Though the rate decreased drastically to 9.2 after 1990, it is still twice as high as the average level of the world. It should be noted that the lack of accident reports before 1960 in China made it impossible to calculate the number of fatalities before 1960. Conversely, fatalities and injuries per dust explosion in the United

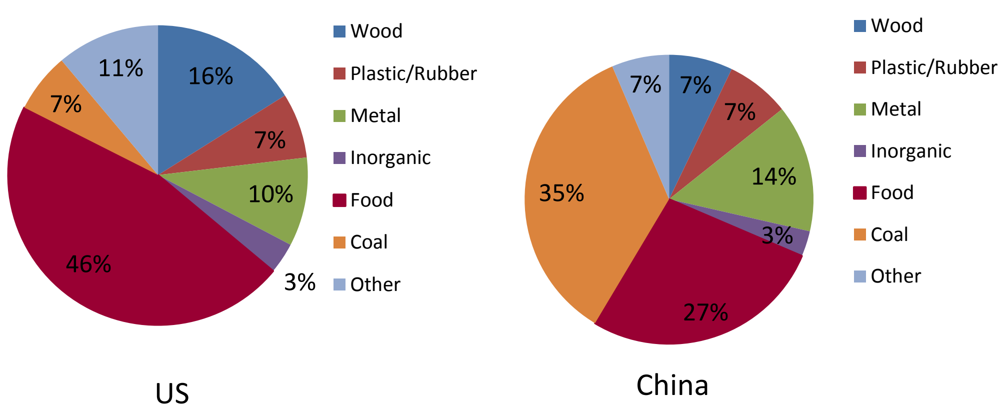
States are lower than that of the world in various periods, especially compared to China.

4.3.4 Statistic features of combustible dust involved in dust explosions

Combustible dust leading to dust explosions worldwide can be categorized as displayed in Figure 4.6a.



a. Dust explosions worldwide



b. Dust explosions in US and China

Fig. 4.6 Contribution of different dusts to dust explosions

As shown in Figure 4.6a, 40% of dust explosions worldwide are caused by food dust, such as wheat, flour and feed dust. This is an important type of combustible causing explosions in China and the US, accounting for 27% and 46%, respectively (Figure 4.6b). Coal dust explosions represent the largest proportion of dust explosions in China, leading to 35% of dust explosions.

4.3.5 Industrial distribution of dust explosions

According to the International Standard Industrial Classification of All Activities (United Nations, 2008), the types of factories involved in dust explosions are divided into manufacturers of food products, the mining of coal and lignite, warehousing, manufacturers of wood and wood products, manufacturers of chemicals and chemical products, manufacturers of fabricated metal products, manufacturers of rubber and plastics products, electricity suppliers, manufacturers of textiles and other products (including the mining of metal ores, other mining and quarrying). The number of dust explosions for each type of enterprise is shown in Figure 4.7 (shown in Appendix A).

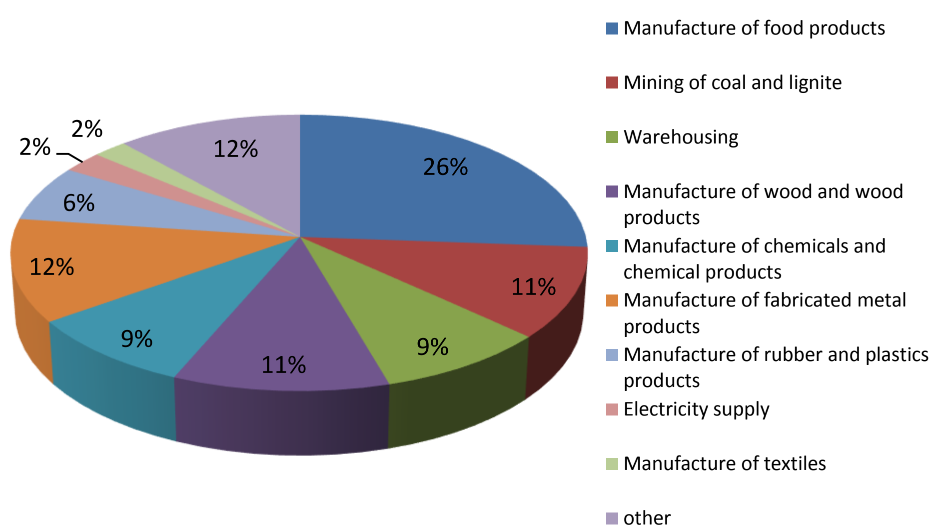


Fig. 4.7 Dust explosions in various industrial types

It can be seen that 26% of the dust explosions occurred in food product manufacturing.

Other industries with high risk of dust explosions are also represented in Figure 4.7. Compared with the statistical results of dust explosions in the US from 1980 to 2005 (Joseph and CSB Hazard Investigation Team, 2007), aforementioned important industrial types, except coal and lignite mining, are also the critical areas which are more easily threatened by dust explosions in the US.

4.3.6 Ignition source for dust explosions

Ignition sources, as an essential element of dust explosions, are divided into eight types: flame and direct heat, hot work, electrical sparks, static electricity, impact sparks, self-heating and smoldering, friction sparks, and hot surfaces (Abbasi and Abbasi, 2007), which are also listed in Appendix A. The contribution of each type has been depicted in Figure 4.8.

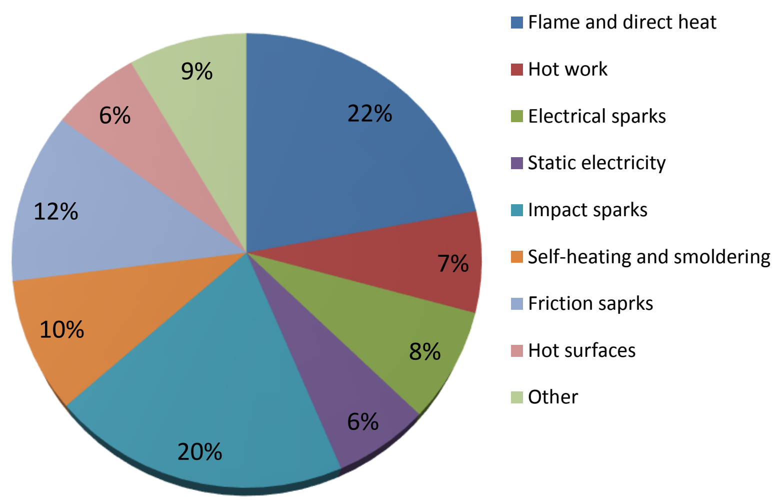


Fig. 4.8 Ignition sources for dust explosions

As shown in Figure 4.8, flame and direct heat, accounting for 22% of the data set, is the largest category of ignition sources contributing to dust explosions. Further ignition sources in various types of enterprises are also categorized and shown in Figure 4.9.

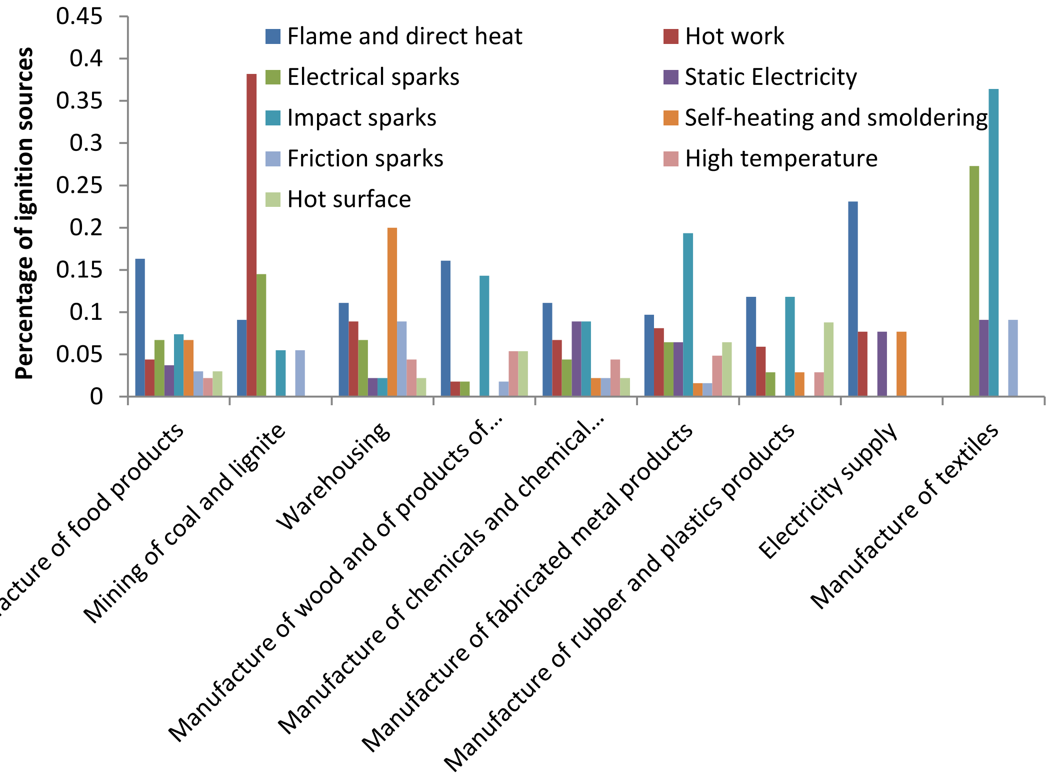
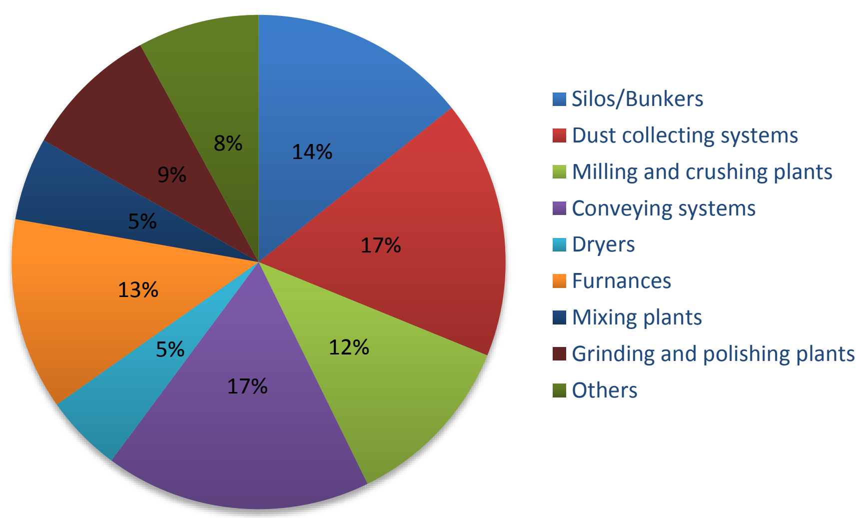


Fig. 4.9 Contribution of ignition sources in various industries

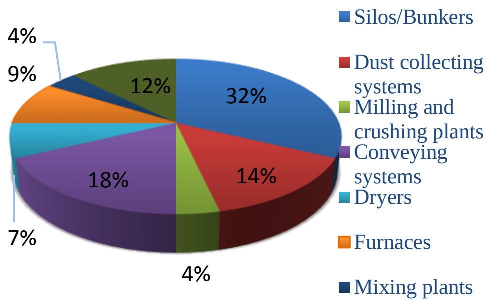
In Figure 4.9, the primary ignition source in the manufacturing of food products is flame and direct heat. However, in the mining of coal and lignite, the main ignition source is hot work, which mainly refers to blasting operations. In China, sub-standardized operations in blasting, such as inadequate stemming (a muddy filling used to plug blasting holes), are often seen in coal mining. In warehousing, the top ignition source is self-heating and smoldering caused by heat accumulation from chemical reactions of combustible dusts.

4.3.7 Equipment involved in dust explosions

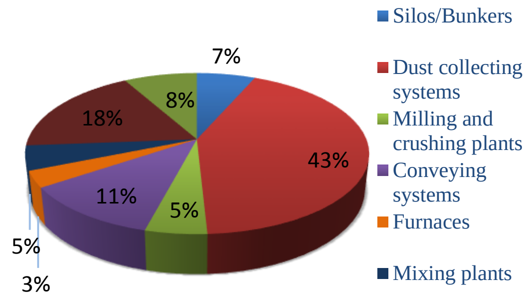
According to the statistical analysis of accident records conducted in the present work, equipment with higher frequency involvement in dust explosions can be categorized into silos/bunkers, dust collecting systems, milling and crushing plants, conveying systems, dryers, furnaces, mixing plants, grinding and polishing plants and others. The proportion of each type of equipment is depicted in Figure 4.10a. Because of the differences in production processes of various industries, different distributive characteristics can be observed for respective critical equipment. Therefore, in this paper, the critical equipment is also categorized according to individual industries with high risks of dust explosions based on the results of Section 4.3.5. The results are presented in Figure 4.10b.



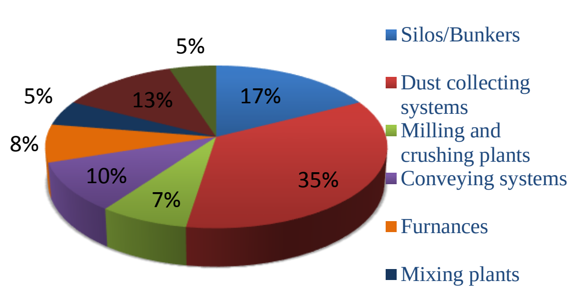
a. Equipment involved in dust explosions



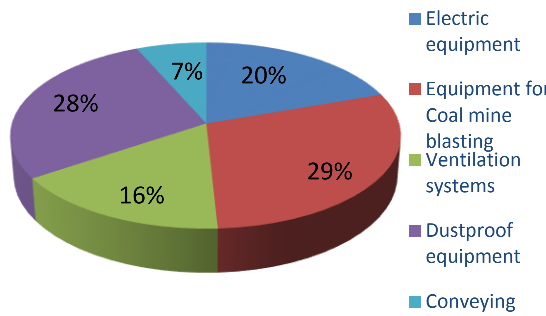
Manufacturers of food products



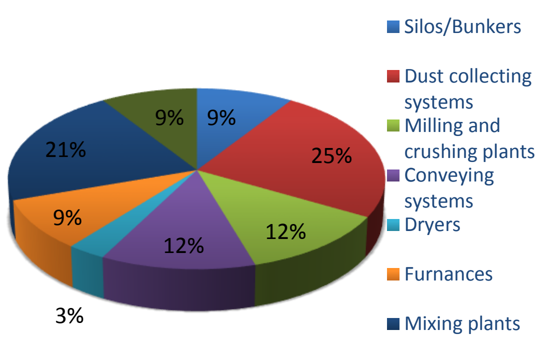
Manufacturers of fabricated metal products



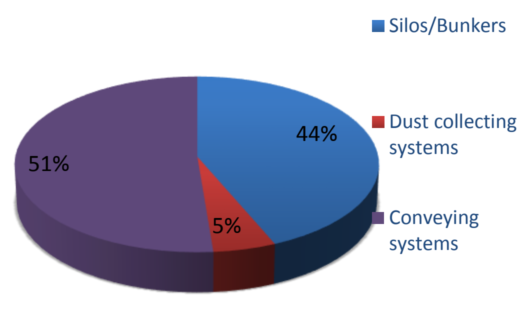
Manufacturers of wood and wood products



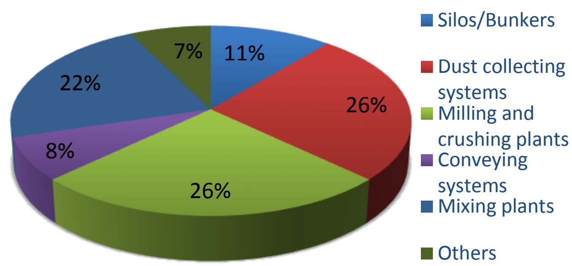
Mining of coal and lignite



Manufacturers of chemicals and chemical products



Warehouse



Manufacturers of rubber and plastic products

b. Equipment involved in various types of enterprises

Fig. 4.10 Equipment involved in dust explosions in various industries

As can be seen from Figure 4.10a, the critical equipment having the most contribution to dust explosions are dust collecting systems and conveying systems. The critical equipment in different industries is also represented in Figure 4.10b.

The techniques in either coal mining or warehouses differ from other types of industries. As mentioned above, coal mining belongs to the mineral mining industry, and is involved with fewer chemical reactions. Most dust explosions occur in underground roadways, especially during blasting operations. So the equipment which is used in blasting, such as detonators, accounts for the highest proportion, 29%, of the total number. Moreover, dustproof systems, reported to be damaged in different degrees before or after dust explosions accidents, are involved in 28% of accidents in mining coal and lignite. Another critical unit in coal mining is electrical equipment or cable, which is reportedly participating in 20% of dust explosions. On the other hand, warehouses are mainly used to store raw materials or intermediate products, which is a simpler process compared to other types of enterprises. Therefore, the diversity of equipment involved in warehouses is less than in other industries. According to the statistical result, the conveying system is involved in dust explosions in more than half the cases, followed by silos and/or bunkers.

4.4. Discussion

4.4.1 Cases mainly distributed in countries/areas with higher industrial output

According to the statistical results, the majority of accidents are reported in the countries with higher industrial output, such as the US, Germany, the UK, Japan and China, because dust explosions are closely related to industrial activities. The other reason might be the relatively well-organized systems of accident reporting and research in these countries, which provide analysis with a more abundant and detailed inventory of accident records. One typical example is the U.S. Occupational Safety & Health Administration (OSHA), which provides not only standards and regulations about health and safety but also statistics of occupational accidents (OSHA, 2013). Similar agencies can also be found in other industrial countries. However, a large number of dust explosions are still missed or unreported. According to the estimation by Eckhoff (2003), around 160 dust explosions each year happened in Germany from 1965 to 1985, which means the total number of accidents could be as high as 3200, but only 426 accidents were reported during the same period as determined in the current work. Regardless of the huge gap between the number of reported and actual dust explosions, the reported data could help to better understand the mechanisms of dust explosions and further effectively prevent accidents.

4.4.2 Trends of dust explosions and casualties per dust explosion

Despite a limited statistical sample, the decreasing tendency of dust explosions numbers can be seen from the analysis (Figure 4.3). The accident reduction could result from the growing understanding about the mechanisms of dust explosions (Kauffman, 1982.; Eckhoff, 1984, 1986, 1995, 2009; Edwards and Prugh, 1987; Dahoe, 1996; Benedetto et al., 2010; Amyotte et al., 2006), the progress of prevention measures (Craven and Foster, 1967; Frank, 2004; Amyotte et al., 2009; Holbrow and Tyldesley, 2003; Going and Lombardo, 2007; Amyotte et al., 2010; Eckhoff, 1996), and continuous research interest in dust explosions. With the help of the Engineering Village database, the number of published academic papers (journal papers in English only) relating to dust explosions in various periods are collected (Figure 4.11). The number of academic papers about dust explosions has vastly increased since 1990.

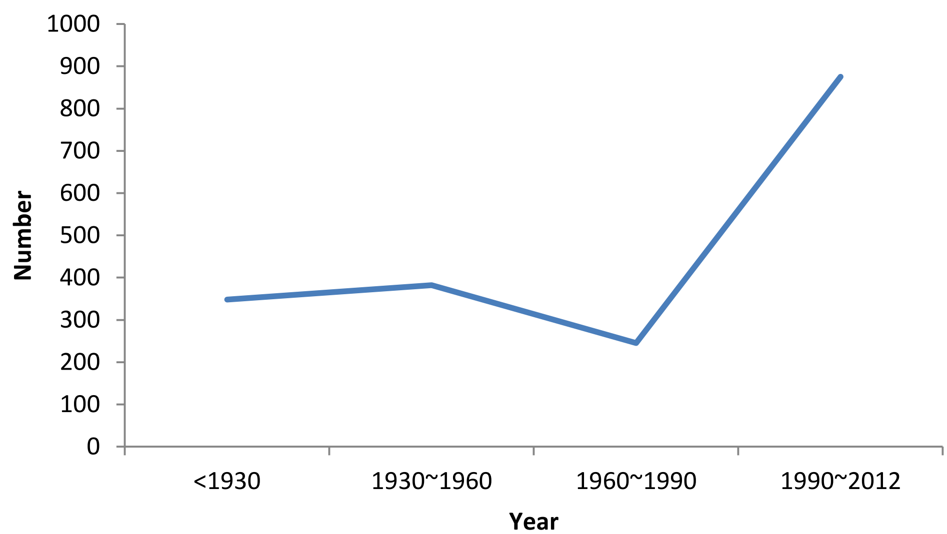


Fig. 4.11 Academic papers relating to dust explosions in various periods

However, in some countries or during a specific period, the increasing tendency of dust explosions can be related to well-organized accident reporting systems. For example, a spike of dust explosion number is observed during 1970 and 1980 as shown in Figure 4.3. Another typical example is China, where there has been established a series of regulations and laws about production safety and accident reporting (Duan et al., 2011), in order to help prevent illegal activities such as purposely concealing accidents. This in turn has led to a large number of reported dust explosions after 2000. Furthermore, considering the influence of the economy on occupational accidents at a national level (Song et al., 2011), the number of dust explosions grew with the increasing industrial output in China (Figure 4.4). According to the five stages of production safety defined by Wang (2006), China is estimated to be in the middle stage of industrialization with fluctuation in a high level of safety accidents and with the positive relationship with economic development (Duan et al., 2011).

Decreasing tendencies can also be found in both fatalities and injuries per dust explosion before 1960. However, after 1960, the trend of either fatalities or injuries per dust explosion has increased which is mainly caused by the accidents with severe damages in developing countries, especially China. As Figure 5 shows, between 1960 and 1990, the fatalities per dust explosion in China reached a very high level of 29.8, which is far higher than the world average level in the same period. If the cases from developing countries are left out of the analysis, the fatalities per dust explosion in the developed industrial countries are greatly reduced to 0.8. After 1990, the fatalities per accident decreased to 4.4 worldwide, and this decrease also benefits from the reduction of fatalities per accident in developing countries.

4.4.3 Contributors to the difference in the casualties between China and the United States

Examining the casualties per dust explosion during various periods in China, it is obvious that they are far higher than the world average levels in the same periods, whereas the casualty levels in the U. S. are always much lower than worldwide. Many factors could contribute to the enormous differences between China and the United States. Firstly, they have different levels of safety management. As pointed out by Feng and Chen (2013), the safety management level in the US is in a relatively mature stage characterized by the priority of production safety, compared to China's developing stage with the feature of improving investment in safety. For production safety inputs, mainly in safety equipment updating and safety training, in the two countries, there are huge differences too. The budget for safety research at the National Institute for Occupation Safety and Health (NIOSH) and the Center for Disease Control and Prevention (CDC) in the United States is 208 times larger than for safety research in China in 2012 (Feng and Chen, 2013). At the same time, according to the Fiscal Year of the Occupational Safety and Health Administration (OSHA), 10.71 million dollars was used in safety training in 2012 and the spending increased to 10.77 million dollars in 2013 (United States Department of Labor, 2014). However, a separate list of safety training budgets is not found in the Fiscal Year of the China State Administration of Work Safety (2013). Finally, the gap between safety supervision in China and the United States is also enormous. According to statistical results by Duan et al. (2011), almost 90% of chemical accidents happened in small enterprises between 2000 and 2006 in China. Enterprises, especially smaller ones, usually lack the motivation to improve safety measures for workers because of the huge investment required and the indirect benefits. Meanwhile, the lack of effective supervision by relevant official departments or their indifferent enforcement worsened the situation. However, for developed countries, like the US, there are a series of strict regulations like NFPA 61, 69, 86 and 654, and laws (OSHA) in an attempt to assure employers provide safe workplaces and also that enterprises use safety supervision at different levels, from firms and independent organizations to local governments.

4.4.4 Distributions of combustible dusts and factories involved in dust explosions

The distributions of combustible dusts and factories involved in dust explosions largely depend on the industrial structures of specific countries. As shown in Figures 6 and 7, a large part of combustible dust leading to dust explosions can be classified as food dust. Similarly, in the analysis of industries with high risk of dust explosions, food processing or production is characterized as having the highest risk. This could be due to the high output of the food industry. For example, the output value of food manufacturing and the related processing is 8.3% of the total industrial output in China in 2011 (Statistical Yearbook of China industrial economy, 2011). Similarly, the food industry accounts for 11.5% of industrial output in the US in 2012 (U.S. Department of Commerce, 2013). Further, other important industry types with high output include chemicals and chemical products manufacturing, electrical machinery and communication and computer, plastic or rubber manufacturing, wood and wood products manufacturing, coal mining and washing industries, which also have higher dust explosion risks, according to the statistical results. It should be noted that the output of the coal mining and washing industry only accounts for 3.4% of industrial output in China (Statistical Yearbook of China industrial economy, 2011), but coal dust contributes to 35% of dust explosions, which illustrates the severe lack of safety in coal production in China. High dependence on coal for energy consumption is one of the main causes of dust explosions in China. As Zheng et al. (2009) argue, the percentage of coal in total energy consumption is higher than 70% in China. Furthermore, from BP Statistical Review of World Energy (BP, 2013), coal production and consumption in China account for 47.5% and 50.2% of the world's coal production and consumption, respectively, in 2012. Both of the percentages are far higher than any other country.

4.4.5 Distributions of ignition sources in various industries

Flame and direct heat, the most commonly seen ignition sources in dust explosions, could originate from lamps, open lanterns, nearby explosions or unsuitable heating methods in production. With the growing understanding of dust explosion mechanisms, lighting equipment with potential to cause open fires, such as lamps and open lanterns, has been prohibited by relevant regulations in areas with a high risk of dust explosions.

Meanwhile, safety barriers, such as the screw conveyor (Eckhoff, 2003), are proposed to be installed between hazardous sources to isolate the propagation of fires and pressures from nearby explosions. Next to flame and direct heat, impact sparks occupies the second highest proportion in all kinds of ignition sources. They could be caused by many factors, such as mechanical failure or tramp metal. The other ignition sources with higher frequencies in dust explosions include friction sparks, self-heating and smoldering, electrical sparks, hot work, static electricity and hot surfaces.

Further, the ignition sources appear to vary in different industries, as depicted in Figure 4.9. In food product manufacturing, flame and direct heat - the most commonly seen ignition source - are mainly from heating equipment in different processes, such as drying processes. A similar situation can also be found in other areas, such as wood and wood product manufacturing, electricity supply, and chemicals and chemical product manufacturing. However, in coal mining, as explosion accidents frequently occur during blasting operations, hot work is the most frequent ignition source, especially in China (Zheng, et al., 2009). In warehouses, with the heat coming from exothermic reactions, the temperatures could increase beyond the threshold of self-ignition when warehouses have no, or malfunctioning, suitable temperature control systems. As a result, the stored combustible dust might be ignited, leading to more serious accidents.

4.4.6 The critical equipment involved in dust explosions

The statistical result regarding critical equipment shows that equipment that is managing combustible dusts, such as ventilation systems, or equipment which are a potential ignition sources themselves, such as dryers, are more often involved in dust explosions. According to the analysis, the dust collecting system and conveying system are the two most critical pieces of equipment for dust explosions, which is similar with the analysis results from the Federal Republic Germany (Abbasi and Abbasi, 2007). One reason is that these two systems are widely applied in various industries (Klinzing et al., 2010; Piccinini, 2008; CSB, 2005). The other reason is that combustible dust clouds can be easily formed in these units and thus could be ignited by heat, fire, or spark (Eckhoff, 2003; CSB, 2009). Therefore, more attention should be paid to these units in production. For the dust collecting system, one effective way to prevent dust explosions is to reduce the amount of accumulated dust, for example, by cleaning out the dust at filters or in ducts regularly (Yuan et al., 2015). The other type of safety measure for a dust collecting system is to eliminate potential ignition sources; for example, by installing magnetic separators at the inlet to remove tramp metal to eliminate impact sparks (Amyotte et al., 2009). The next critical unit is the silo/bunker, widely used to temporarily store pulverized raw materials or products. As discussed above, the main ignition sources in this type of equipment are self-heating and smoldering and external flame or heat. Therefore, the safety measures are mainly focused on reducing accumulated heat, by the installation of a temperature control system in silos/bunkers (Yuan et al., 2013), and eliminating oxygen by installing inert gas devices (Amyotte et al., 2003). Furnaces, similar to dryers, are the third critical equipment as providing enough heat for dust explosions. Thus, the key measure is to isolate the heat from furnaces and combustible dust clouds (NFPA 86, 2007). Other critical units include milling/crushing plants and grinding/polishing plants. For these units, a large amount of heat could be produced along with combustible dust clouds. Therefore, the main way to prevent dust explosions is to reduce the concentration of the dust cloud by applying ventilation systems and dissipating produced heat as soon as possible, by installing cooling systems (Eckhoff, 2003).

4.5 Conclusion

In industrial production, dust explosions are a threat worldwide and have caused huge losses to operators, shareholders and the environment. By collecting accident records, reviewing and analyzing the information, dust explosions can be better understood and prevented in the future.

According to the analysis, dust explosions are closely related to industrial activities and the number of dust explosions worldwide is decreasing with time. However, for specific countries, like China, the number of reported dust explosions is increasing because of the country’s rapid industrial development and the lack of enough investment in safety improvement and safety management, which also leads to the far higher casualties per dust explosion in China compared to other countries. Combustible dust categorizations and enterprise types with dust explosion risk depend on the industrial structures of specific countries. Usually, the larger the economic output of a specific industry, the more easily the combustible dust in the industry could be found involved in dust explosions. Moreover, flame and direct heat is estimated as the most commonly seen ignition source leading to dust explosions, and dust collecting systems as well as conveying systems are determined to be the most critical equipment in industrial production. Thus, for critical units in various industries, particular attention and supervision should be dedicated in operations, and suitable safety measures need to be applied to prevent dust explosions or mitigate potential damage caused by such accidents.

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5 Risk-based Design of Safety Measures to Prevent and Mitigate Dust Explosion Hazards

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Preface

A version of this manuscript has been published in the Journal of Industrial Engineering & Chemistry Research. The principal author developed the generic risk analysis model of dust explosions based on extensive literature review, categorized safety measures and presented the application of this generic model by a case study. The co-authors, Dr(s) Khakzad, Khan, Amyotte and Reniers supervised and reviewed the methodology, proposed valuable suggestions and corrections to improve the quality of the manuscript.

Abstract

Dust explosion is one of the main threats to equipment safety and human health in industries. Complex factors leading to accidents, serious consequences and relevant safety measures are the main interests of governmental agencies, researchers and industrial companies. However, a generic risk analysis model for dust explosions is absent. The bow-tie model can be used to investigate the relationships among basic causes, safety barriers and possible consequences of an accident scenario. In this paper, a framework is established for quantitative risk assessment of dust explosions based on bow-tie analysis method via review and analysis of previous major dust explosions. A large inventory of relevant safety measures is presented, and the implementation and efficacy of such safety measures to reduce the risk of dust explosions is thoroughly discussed. Finally, the methodology is applied to a case-study. The results show that the generic bow-tie developed in this study can be tailored to a wide variety of dust explosion accident scenarios with minimal manipulation; also, implementation of relevant safety measures can significantly reduce the risk of dust explosions.

Keywords: Dust explosion; Quantitative risk analysis; Bow-tie method; Safety measures

5.1 Introduction

When suspended combustible dust in a confined space is ignited, a dust explosion occurs (CSB, 2006). Compared to other types of explosion, dust explosions can lead to severe damage as they may result in a series of secondary dust explosions, causing higher overpressures and temperatures. It should also be noted that toxic gases as likely byproducts of dust explosions can noticeably increase the extent and intensity of damage.

Dust explosions have been causing significant loss to humans, assets, and the environment. According to the U.S. Chemical Safety Board (CSB, 2005), a dust explosion at the Hayes Lemmerz plant, Huntington, Indiana, in 2003 caused 1 death and 6 injuries. The cause of this accident was identified as aluminum dust in a dust collector, probably ignited by heat, impact sparks or burning embers. In the same year, another dust explosion at West Pharmaceutical Services, Kinston, North Carolina, claimed 6 lives and 38 injuries (CSB, 2004). The CSB believed the accumulation of combustible dust above a suspended ceiling was the main source of the combustible material. Also, the ignition of rubber vapor, an overheated electrical ballast, an electrical spark, or an electric motor was determined to be the ignition source. Dust explosions have widely been reported in the literature (Blair, 2007; Zheng et al., 2009; Giby and Luca, 2010; Marmo et al., 2004; Piccinini, 2008; John and Vorderbrueggen, 2011). Therefore, conducting quantitative risk analysis (QRA) for dust explosions is necessary for process facilities dealing with different types of dust-producing activities, ranging from wool to food and metal industries. Usually, hazard identification is the first step in QRA, followed by accident modeling, cause-consequence analysis, and risk estimation.

In the context of dust explosion QRA, however, the focus has mainly been on dust explosion mechanisms (Eckhoff, 2003, 2009; Callé et al., 2005; Amyotte et al., 2005; Cashdollar and Zlochower, 2007; Pilão et al., 2006; Benedetto et al., 2010) or pertinent safety measures to prevent or mitigate the damage of accidents (Eckhoff, 2003, 2009; Li et al., 2009; Myers, 2008; Marian and Rudolf, 2013; Amyotte et al., 2007, 2009). van dert Voort and Klein (2007) developed a QRA tool for the external safety assessment of industrial plants prone to dust explosion hazards. In their method, the risk of the entire plant is divided into individual risks of constituting units according to their size, shape and constructional properties. However, sometimes, dividing a plant into units and choosing proper explosion models for each unit are difficult, if not impractical, for complex processing facilities. In this paper, a generic comprehensive risk analysis model based on the bow-tie method is developed, which can be used in risk assessment and safety measure design of dust explosions with different characteristics. This model can conveniently be used to assess the risk of dust explosion in various industries.

The part is organized as follows: fundamentals of the bow-tie method and the role of safety measures in risk analysis are recapitulated in Section 5.2. An inventory of potential contributing factors to dust explosions is presented in the form of a generic bow-tie in Section 5.3 while a list of pertinent safety measures, their applicability and implementation are given in Section 5.4. To illustrate the generality and the efficacy of the developed bow-tie, the approach is applied to a case-study in Section 5.5. Section 5.6 summarizes the main conclusions of this study.

5.2 Background

5.2.1 Bow-tie method

Many probabilistic techniques have been used in QRA, among which fault tree analysis (FT) and event tree analysis (ET) are the most popular. FT investigates primary causes of a critical event (e.g., system failure, system unavailability, release of hazardous material, etc.) while ET explores the possible consequences arising from a critical event (e.g., fire, explosion, injury, death, etc.). Bow-tie (BT), a graphical method, integrates both the primary causes and consequences of a critical event into a logical model. It also provides system reliability if effects of safety measures are considered. Using the probabilities of primary causes, along with failure likelihood of safety measures, the probabilities of consequences can be estimated. Dianous and Fiévez (2006) established a risk assessment methodology based on BT to evaluate the efficacy of risk control measures. Shahriar et al. (2011) used fuzzy theory based on BT to analyze the risk of oil and gas pipelines and provided suggestions for the risk management process. Bellamy et al. (2013) presented an application of BT in industrial practice, 'Storybuilder' method, to identify the dominant patterns of safety barrier failures, barrier task failures and underlying management flaws. Their BT model comprises six lines of defense, three on either side of the critical event, a loss of containment event. Despite its wide applications in QRA, BT suffers from a static nature, and cannot easily be updated when new information becomes available. However, there have recently been efforts to overcome this limitation either by coupling BT with Bayesian updating (Khakzad et al., 2012) or via substituting with more dynamic methods such as Bayesian networks (Khakzad et al., 2011, 2013).

5.2.2 Safety measures

In the context of risk management, safety measures are classified into three types: inherent, engineered and procedural safety measures (Khan and Amyotte, 2003). When applying safety measures to improve system safety, inherent safety measures are given priority over the two other types of safety measures. Generally, inherent safety is aimed at reducing hazards, relying on the properties of a material or the design of a process. Four key principles for inherent safety have been suggested (Amyotte et al., 2007, 2009; Kletz, 1978, 2003):

- Minimization: using smaller quantities of hazardous materials and performing a hazardous procedure as few times as possible.

- Substitution: using a less hazardous material or implementing a less hazardous procedure.
- Moderation: using hazardous materials in their least hazardous forms or under less hazardous processing conditions.
- Simplification: designing process equipment and procedures to eliminate opportunities for errors.

Inherent safety measures are normally considered the most reliable as they do not depend on the performance of additional safety devices or the physical or psychological condition of operators.

Engineered safety measures refer to reducing the frequency of accidents or lowering their severity via setting additional barriers. Based on the type of operation, these safety barriers could be further divided into passive and active. For passive safety measures, no additional activator, actuator or human intervention is required (e.g. explosion relief vents) whereas active safety measures depend on the function of additional control systems (e.g. automatic suppression systems). Usually, passive safety measures are preferred to active ones since no additional interventions or control systems are required.

Procedural or administrative safety measures, on the other hand, rely on management methods to prevent accidents (e.g., training) or mitigate their damage (e.g., evacuation and emergency response). These safety measures are influenced by human factors such as safety training effectiveness or human response time.

Once a BT is developed, the effect of safety measures can easily be analyzed. In the context of BT method, safety measures can be categorized under four guide words (Dianous and Fievez, 2007):

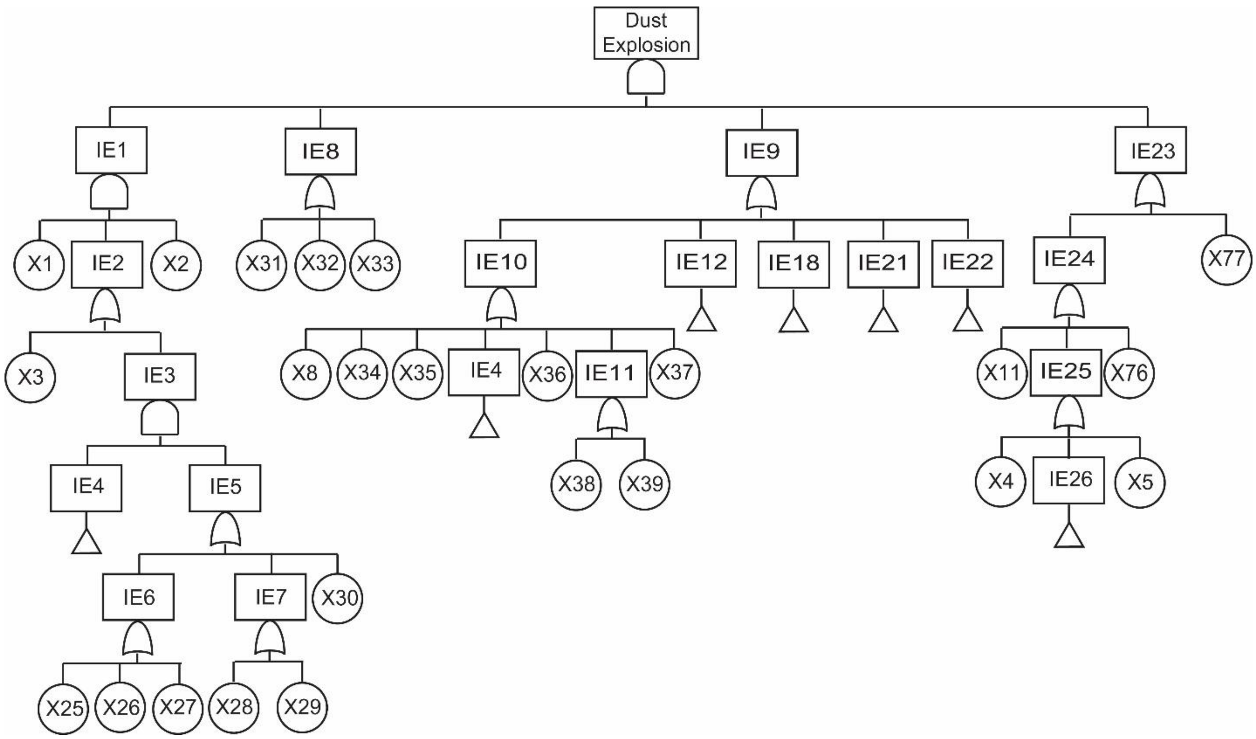
- Avoid: making an event not happen. An "Avoid" safety measure functions before a basic event occurs on the FT (i.e., is given temporal or spatial precedence over the event). As a result, the basic events for which "Avoid" safety measures have been implemented can be eliminated from the BT, and is no longer considered in the accident scenario sequence.
- Prevent: reducing the frequency of an event. A "Prevent" safety measure acts before a basic event happens, whether on the FT or ET. For example, in an ET, *emergency training* can be considered to reduce the failure probability of *evacuation* as a safety measure.
- Control: controlling an event or recovering a system to a safe state. A "Control" safety measure acts before a basic event occurs on the FT while it acts after an event occurs on the ET. For example, *fire walls* are installed to control flame and overpressure during dust explosions.
- Mitigate: reducing the effect of an event on equipment, human health or environment. A "Mitigate" safety measure acts after an event occurs on the ET. For example, *using the emergency response and rescue system* can reduce the probability of severe injury and death.

5.3 Dust explosion causes and consequences

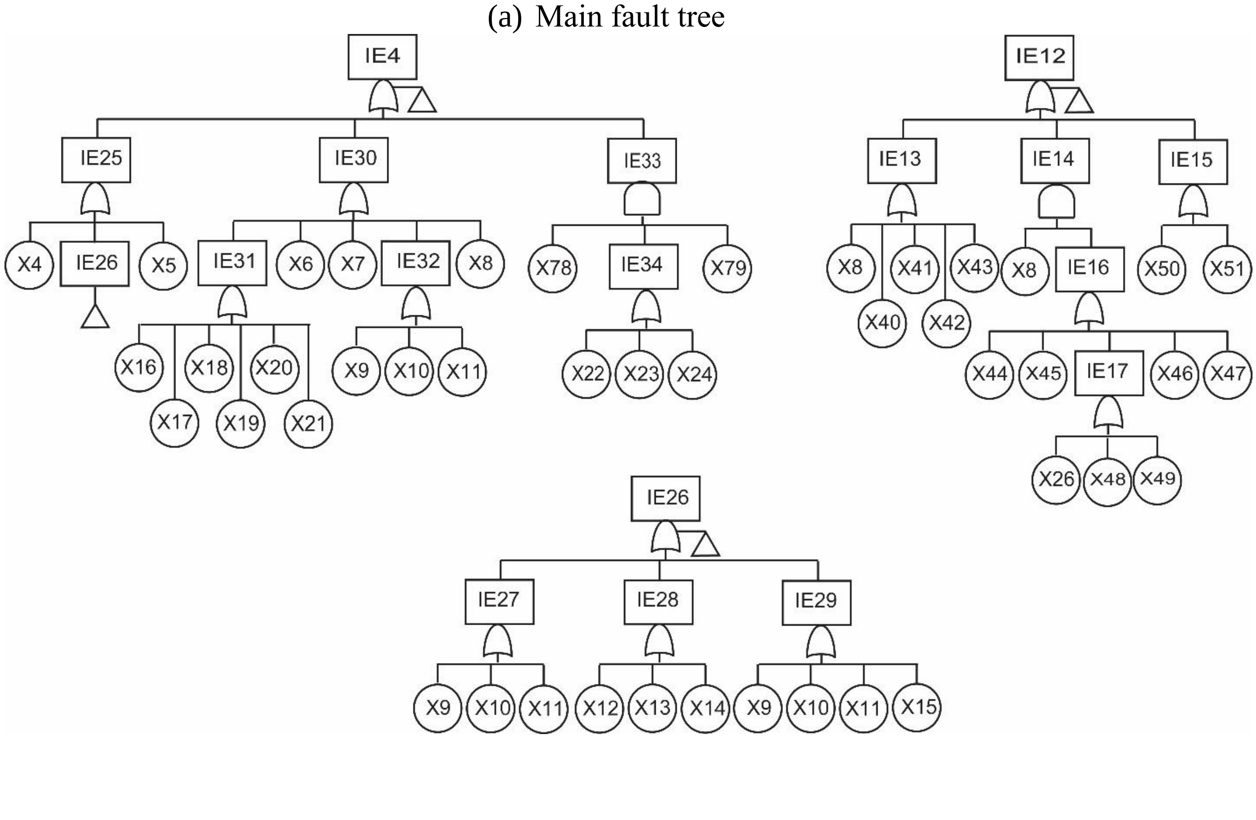
5.3.1 Generic fault tree

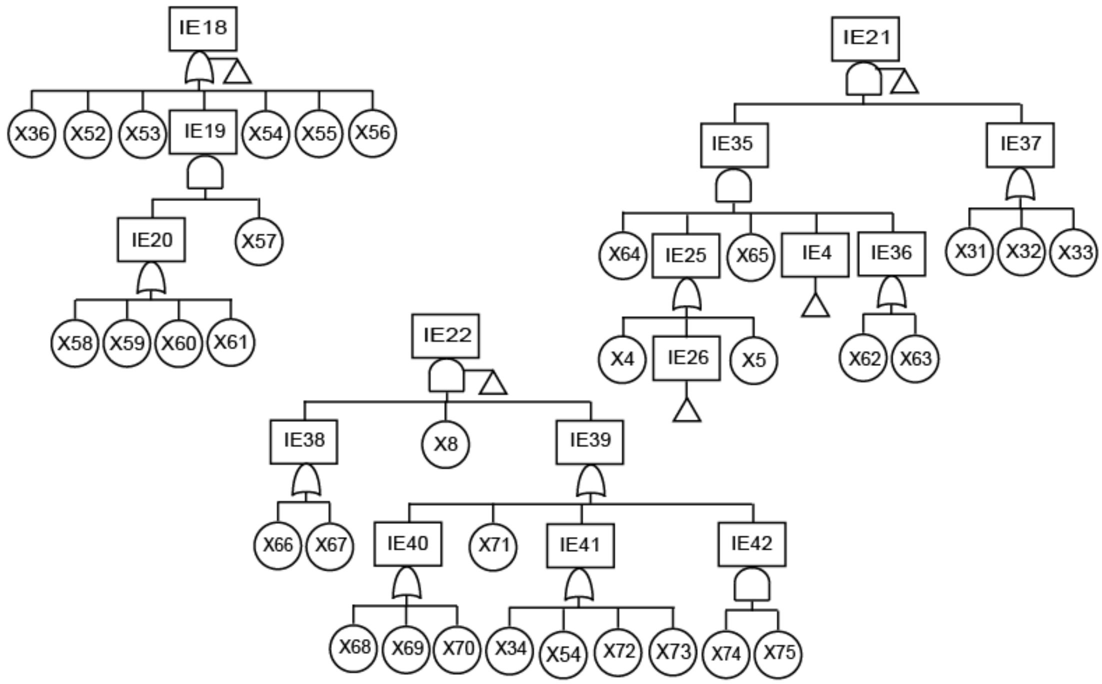
The primary causes of dust explosions have already been investigated and modeled using FT (Abuswer et al., 2013). In the present study, a more detailed and broader range of elements based on past accidents in the process industries are considered. These elements are illustrated and organized according to their cause-effect relationships in the form of a generic FT in Figure 5.1. This generic fault tree is comprehensive and can be fitted to a wide variety of dust explosion accident. Basic events of the FT and their probabilities are listed in Table 5.1. These probabilities have been either drawn from literature (OREDA, 2002; Mannan, 2005; Moss, 2005; Rathnayaka et al., 2011) or calculated using existing relationships. For example, the probability of the basic event *Particle size in explosive range* is calculated using an equation given by Eckhoff (2003), considering the percentage of particle sizes ranging from 20μm to 125μm (see Table A1 in the appendix (Eckhoff, 2003)). Other data such as the probability of *Calm* which is related to the local atmospheric condition is estimated using expert opinions. The intermediate events and undeveloped events are also shown, in Table 5.2.

This generic FT is based on the dust explosion pentagon comprising five elements: combustible dust, oxidant, ignition source, dispersion of dust, and confinement of dust, and also 79 primary events, involved in various areas, such as human factors (e.g. *Not wearing protective clothes to eliminate electrostatic*), leading to these five elements.



(a) Main fault tree





(a) Transfer gates

Fig. 5.1 Generic fault tree of dust explosion including (a) the main part, and (b) transfer gates.

Table 5.1 Basic events of generic fault tree in Figure 5.1 (Eckhoff, 2003; Mannan, 2005; Moss, 2005; Rathnayaka et al., 2011; Eckhoff and Amyotte, 2010)

Symbol	Description	Probability	Symbol	Description	Probability
X1	Lack of inert dust for explosible dust	0.3	X41	Misalignment of components	0.1
X2	Particle size in explosive range	0.71	X42	Equipment with high potential to produce friction sparks	0.085
X3	Lack of filter in air ventilation system/Filter system failure	0.01	X43	Malfunction of equipment such as belt slip	0.04
X4	Not satisfying the latest construction code	0.02	X44	Tramp metals impact internal walls of metal equipment	0.05
X5	Equipment failure of ventilation system	0.04	X45	Use of unsuitable tools	0.01
X6	Lack of written procedure for housekeeping	0.033	X46	Equipment made of material with high potential of sparking	0.067
X7	Incorrect housekeeping methods	0.067	X47	Loose objects	0.03
X8	Lack of regular inspection	0.01	X48	Lack of daily documented operation procedures to avoid impact sparks	0.04

X9	Lack of design codes	0.033	X49	Improper operation procedures to avoid impact sparks	0.067
X10	Improper design codes	0.04	X50	Lack of spark arresters	0.045
X11	Failure to follow design codes	0.045	X51	Malfunction of spark arresters	0.05
X12	Dust collectors malfunction	0.04	X52	Unsuitable switches	0.1
X13	Leakage of air from ventilation system	0.05	X53	Blown fuse	0.08
X14	Blockage in ventilation system	0.145	X54	Short circuit	0.05
X15	Lack of enough knowledge about previous system before reconstruction	0.1	X55	Damaged insulation	0.01
X16	Not strictly applying relevant guideline	0.045	X56	Lightning	0.000001
X17	Inadequate stewardship program of manufacturers of raw materials	0.09	X57	Not wearing protective clothes to eliminate electrostatic	0.06
X18	Lack of methods to identify hazards	0.033	X58	Electrically nonconductive components	0.045
X19	Ignoring combustible dust in hazard communication program	0.09	X59	Lack of grounding device	0.01
X20	Employee unaware of dust explosion hazard	0.1	X60	Failure of grounding device	0.004
X21	Inadequate safety training about combustible dust hazard	0.05	X61	Too high breakdown voltage	0.01
X22	Lack of coverings on cleanout, inspection and other openings	0.083	X62	Lack of gas/temperature detection system	0.045
X23	Dust-tight system malfunction	0.006	X63	Failure of gas/temperature detection system	0.148
X24	Lack of dust-tight system	0.045	X64	No measures/procedures when onset of self-heating is detected or after certain storage periods	0.067
X25	Lack of operational procedures for dealing with settled dust	0.04	X65	Unsuitable storage methods	0.045
X26	Inadequately safety trained operators in high risk working environment	0.1	X66	Lack of fire suppression system	0.045
X27	Improper procedures to clean settled dust	0.067	X67	Malfunction of fire suppression system	0.1
X28	Lack of isolation devices	0.055	X68	Work permit not issued	0.033
X29	Failure of isolation devices	0.08	X69	Work permit/rules not strictly performed	0.045
X30	Collapse of equipment	0.085	X70	Standard defect	0.067
X31	Lack of inert gas device	0.045	X71	Ignition of settled dust	0.005
X32	Inadequate inert gas device	0.067	X72	Poor dissipation of heat	0.067
X33	Failure of inert gas device	0.08	X73	Bad contact	0.02
X34	Overloading operation of	0.01	X74	Combustion	0.3

	processing equipment				
X35	Lack of surface shielding/isolation for high temperature equipment	0.067	X75	Lack of separation device to prevent burning dust from entering process system	0.045
X36	Incorrectly specified electrical equipment	0.045	X76	Improper enclosure	0.045
X37	Mechanical failure of equipment such as bearings or blowers	0.04	X77	Calm	0.002
X38	Lack of excessive temperature controlling system	0.045	X78	Lack of dust suppressants	0.1
X39	Failure of excessive temperature controlling system	0.08	X79	Equipment erosion	0.0078
X40	Insufficient, excessive or impure lubricant	0.05			

Table 5.2 Intermediate events and undeveloped events of generic fault tree in Figure 5.1

Symbol	Description	Symbol	Description	Symbol	Description
IE1	Explosible concentration of dust	IE17	Misoperation causing collision of objects	IE32	Unwanted horizontal surfaces are designed
IE2	Dust is suspended in air	IE18	Electrical arc/ sparks	IE33	Dust emission from process equipment
IE3	Settled dust is lofted	IE19	Electrostatic discharges	IE34	Inadequate dust-tight system
IE4	Dust accumulation	IE20	Field intensity exceeds 3MV/m	IE35	Heat accumulation leads to temperature higher than auto-ignition temperature
IE5	Lofting event	IE21	Self-ignition	IE36	Gas/temperature detection system malfunction
IE6	Improper operation to activate dust layers	IE22	Open flame	IE37	Inert gas device malfunction
IE7	Shockwave from primary dust explosion	IE23	Confinement	IE38	Fire suppression system failure
IE8	Oxidant concentration> LOC	IE24	Cramped space	IE39	Fire
IE9	Ignition source energy>MIE and MIT	IE25	Inefficient ventilation	IE40	Violation of open flame standard
IE10	Heated surfaces	IE26	Insufficient air volume	IE41	Electrical equipment fire
IE11	Excessive temperature control system malfunction	IE27	Deficiency in design	IE42	Burning dust
IE12	Friction, impact or other sparks	IE28	Ventilation equipment malfunction		

IE13	Friction sparks	IE29	Improper reconstruction of ventilation system		
IE14	Impact sparks	IE30	Poor housekeeping		
IE15	Sparks from engines and motor-driven equipment	IE31	Lack of awareness of combustible dust hazard		
IE16	Sparks produced from collision of objects				

5.3.2 Generic event tree

Dust explosions are able to cause severe consequences, giving rise to significant human losses and/or damages to facilities. Based on the severity and likelihood, dust explosion consequences can be divided into five categories: near miss, mishap, minor damage, significant damage and catastrophic damage. The severities of five consequences are in an increasing manner depending on the functions of common used safety barriers in mitigating dust explosions. However, their probabilities are decreasing accordingly. For example, the severity of *Near miss* is the least comparing with other consequences but its probability is the greatest among them. A brief definition of each category is presented below.

- Near miss: the dust explosion is controlled at its initial stages, and the system can be recovered quickly.
- Mishap: the process is interrupted, and more time is needed to recover the system compared to that of a Near miss. However, no damage is caused to apparatus/equipment or operators.
- Minor damage: equipment may be damaged, and superficial injuries are expected.
- Significant damage: equipment is damaged along with the possibility of serious injury or death.

- Catastrophic damage: major facility damage is caused, and several fatalities are expected.

Several safety barriers can be applied to prevent, reduce or control damage if a dust explosion takes place: explosion suppression, explosion venting, explosion containment, explosion isolation and evacuation (Eckhoff, 2003). The generic ET for dust explosions is developed in Figure 5.2.

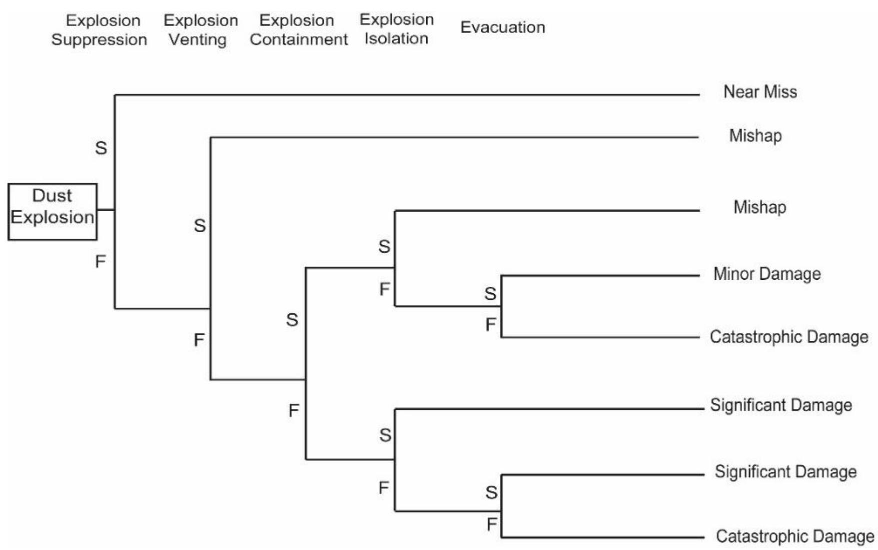


Fig. 5.2 Generic event tree of dust explosion.

The explosion suppression is activated when the pressure rises beyond a threshold due to a dust explosion. If the explosion suppression functions successfully, further development of the dust explosion can be prevented, and no damage would be caused. In this situation, the outcome is classified as a near miss. A fast-response flame or pressure detector is an essential component of a suppression system. The membrane pressure detector is an example of these barriers (Eckhoff, 2003).

However, if the explosion suppression system fails to operate, and the explosion overpressure proceeds further in the unit, the explosion venting barrier can be counted on to relieve the pressure to a safe space. In this case, the equipment and operators will not be seriously threatened by the overpressure. However, sufficient time will be needed to recover the system to operating condition (e.g., overhauling the explosion suppression system). This type of consequence is considered as a mishap.

If the venting system fails, the safety of the system will depend on explosion containment and isolation. Explosion containment refers to the units involving high risk materials or processes. These units are designed to withstand the maximum pressure or heat caused by dust explosions. Explosion isolation, on the other hand, refers to the safety measures to prevent the propagation of overpressure and fire (e.g., fire walls). When explosion containment and explosion isolation function, the pressure and fire will be restricted to the original unit and will not spread to nearby units. Thus, the system will suffer less damage, and can be recovered after the explosion source fails. The outcome can be deemed as a mishap. Otherwise, when the isolation system fails, the pressure and fire can spread to adjacent units. In this case, if the operators are well trained and successfully evacuate, fatal injuries are likely to be reduced, and the consequence can be classified as a minor damage. However, in the case of the failure of this barrier, fatal injuries and even death could occur, giving rise to catastrophic damage.

5.3.3 Generic bow-tie

After the generic FT and ET are developed, the generic BT can be constructed. As depicted in Figure 5.3, the BT shows the possible events contributing to a dust explosion as well as its potential consequences. The generic BT can also be used to implement a wide variety of safety measures to help minimize the risk.

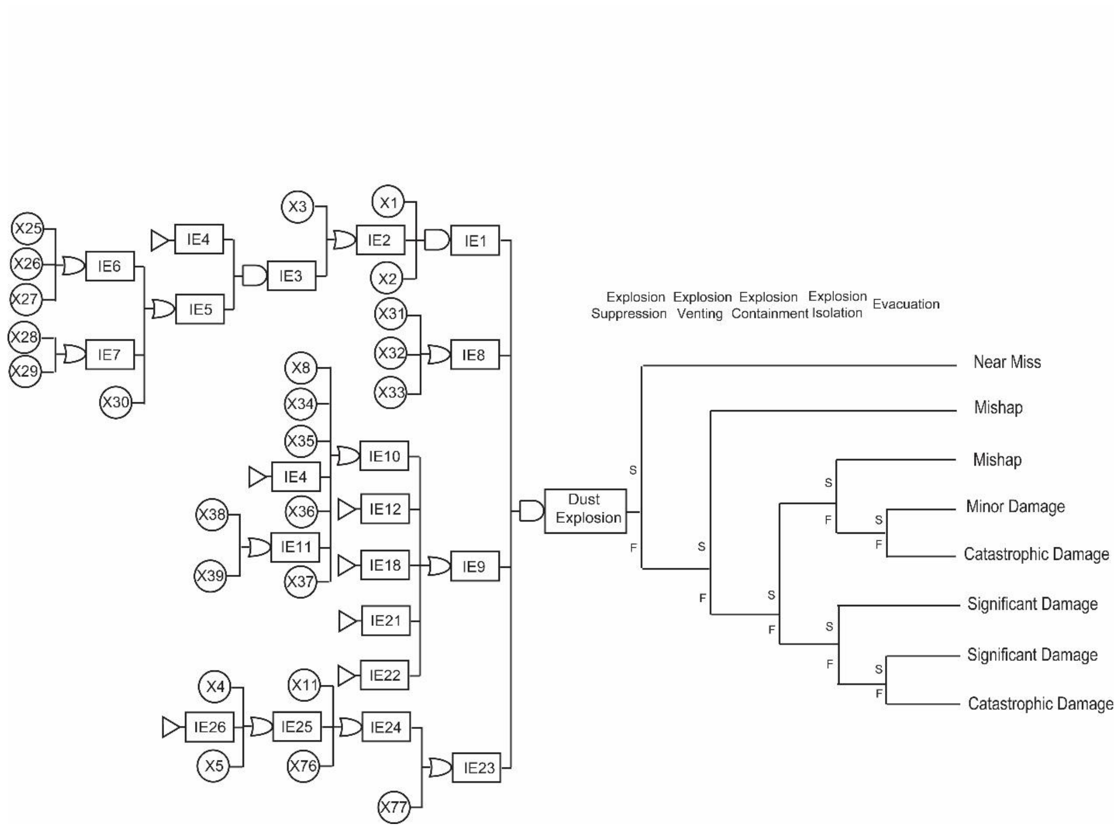


Fig. 5.3 Generic bow-tie of dust explosion. The main fault tree of Fig. 5.1 is shown for brevity.

5.4 Dust explosion safety assessment

5.4.1 Inventory of safety measures

As previously mentioned, safety measures are divided into inherent, engineered and procedural categories. In this study, the potential safety measures to reduce the probability of dust explosions are discussed in accordance with the aforementioned categories. The aim is to provide useful guidelines for safety measure implementation during different stages of a process design and operation. The basic events contributing to a dust explosion and the relevant safety measures are presented in Table 5.3 (Eckhoff and Amyotte, 2010).

Table 5.3 Safety measures in the context of dust explosion

Basic Event	Safety Measures	Inherent Safety Measures				Engineered		Procedural
		Minimizati-on	Substitution	Moderation	Simplific-ation	Passive	Active	
X1	Add inert dust			●				
X2	Increase the particle size			●				
X3	Install filter system or timely maintenance					●		●
X4	Follow latest ventilation construction code							●
X5	Timely maintenance							●
X6	Enact documented procedures for housekeeping							●
X7	Proper supervision and training							●
X8	Ensuring regular inspection							●
X9	Enact proper design codes, such as reducing unwanted horizontal surfaces, ventilation system, and so on.				●			●
X10	Improve design codes							●
X11	Proper supervision and training							●
X12	Timely maintenance							●
X13	Inspection/sealing							●
X14	Regular cleaning							●
X15	Safety training							●
X16	Supervision/Safety training							●
X17	Establish integrated management system for raw materials							●
X18	Systematic hazard identification techniques such as HAZOP or HAZID and effective use of Material Safety Data Sheets				●			●
X19	Supervision/ training/written							●

	communication rather than oral communication							
X20	Safety training							●
X21	Safety training							●
X22	Installation of coverings if needed					●		
X23	Regular inspection/ timely maintenance							●
X24	Install dust-tight system	●				●		
X25	Enact written procedures for housekeeping							●
X26	Safety training							●
X27	Improve operation procedures of settled dust							●
X28	Install isolation devices					●	●	
X29	Regular inspection/timely maintenance							●
X30	Improve design codes to reduce collapse of equipment				●			●
X31	Add inert gas						●	
X32	Ensure adequate inert gas supply						●	
X33	Install stand-by inert gas device and timely maintenance						●	●
X34	Supervision/ Training							●
X35	Install shielding/isolation for high temperature equipment					●		
X36	Choose correct electrical equipment		●					
X37	Regular inspection/timely maintenance							●
X38	Install excessive temperature controlling system						●	
X39	Regular inspection/timely maintenance							●
X40	Use proper		●					

	lubricant							
X41	Supervision/Training							●
X42	Improve design codes to substitute with safer equipment		●					●
X43	Regular inspection/timely maintenance							●
X44	Install magnetic separators at the inlet to remove tramp metal					●		
X45	Workplace training							●
X46	Choose materials with lower potential for spark generation		●					
X47	Regular inspection/timely maintenance							●
X48	Enact daily operation procedures							●
X49	Improve daily operation procedures							●
X50	Install spark arresters					●		
X51	Regular inspection/timely maintenance							●
X52	Install arc control device					●		
X53	Regular inspection/timely maintenance							●
X54	Install circuit breaker						●	
X55	Regular inspection/timely maintenance							●
X56	Install lightning protection device					●		
X57	Safety training							●
X58	Choose proper conductive equipment		●					
X59	Install grounding devices					●		
X60	Regular inspection/timely maintenance							●

X61	Control the breakdown voltage below 4KV						●	
X62	Install gas/temperature detection system						●	
X63	Regular inspection/ timely maintenance							●
X64	Rolling of bulk material from one silo to another							●
X65	Choose suitable storage methods for hazardous dust		●					●
X66	Install fire suppression system						●	
X67	Regular inspection/timely maintenance							●
X68	Safety training							●
X69	Safety training							●
X70	Improve work permit system							●
X71	Proper and timely housekeeping	●						●
X72	Install cooling equipment						●	
X73	Regular inspection/ timely maintenance							●
X75	Install separation device to prevent burning dust entering system					●		
X76	Safety training of design to avoid forming cramped space							●
X78	Add suppressants						●	
X79	Anti-corrosion measures, regular inspection					●		●

For example, for the basic event *Particle size in explosive range*, one possible safety measure is to *Increase the particle size*, which is aimed at making the size of particles beyond their explosive threshold. In other words, the process is modified to produce particles larger in size than those which could cause a dust explosion. This safety measure satisfies the characteristics of the inherent safety principle *Moderation*. Meanwhile, if additional devices and mechanisms, such as humidifiers, are used to combine smaller particles to form larger ones, the safety measure can also be classified as a passive safety measure. Another example is *Proper and timely housekeeping*, which is meant to remove dust layers from the workplace by correct methods. As smaller quantities of combustible dust would be involved in processes, this safety measure can be attributed to *Minimization*. Since the performance of this safety measure relies on the actions of operators, it can also be classified as a procedural safety measure.

5.4.2 Implementation of safety measures to bow-tie

As previously mentioned, in the context of accident modeling and risk analysis, safety measures can further be classified according to four guide words: avoid, prevent, control and mitigate. Examples for each guide word and the effective location of each safety measure regarding the BT of dust explosion are given in Table 5.4.

Table 5.4 Examples of Safety Measures

	Fault Tree	Event Tree
Avoid	If the explosiveness of particles is reduced, the dust explosion will be avoided. This is why in some cases inert dust is added to raw materials to decrease their explosiveness.	N/A
Prevent	To prevent sparks produced in high risk places, magnetic equipment can be installed in inlets to prevent tramp metal from entering the system.	Explosion suppression system is used to prevent further development of fire.

Control	Ventilation system can be used to control the airborne dust concentration below MEC (Minimum Explosible Concentration).	Fire walls are used to control fire.
Mitigate	N/A	Venting system is used to release overpressure to safe areas.

Similarly, all potential safety measures which can be applied to reduce hazards and improve the performance of existing safety means are categorized. Figure 5.4 illustrates how these safety measures are implemented into the BT.

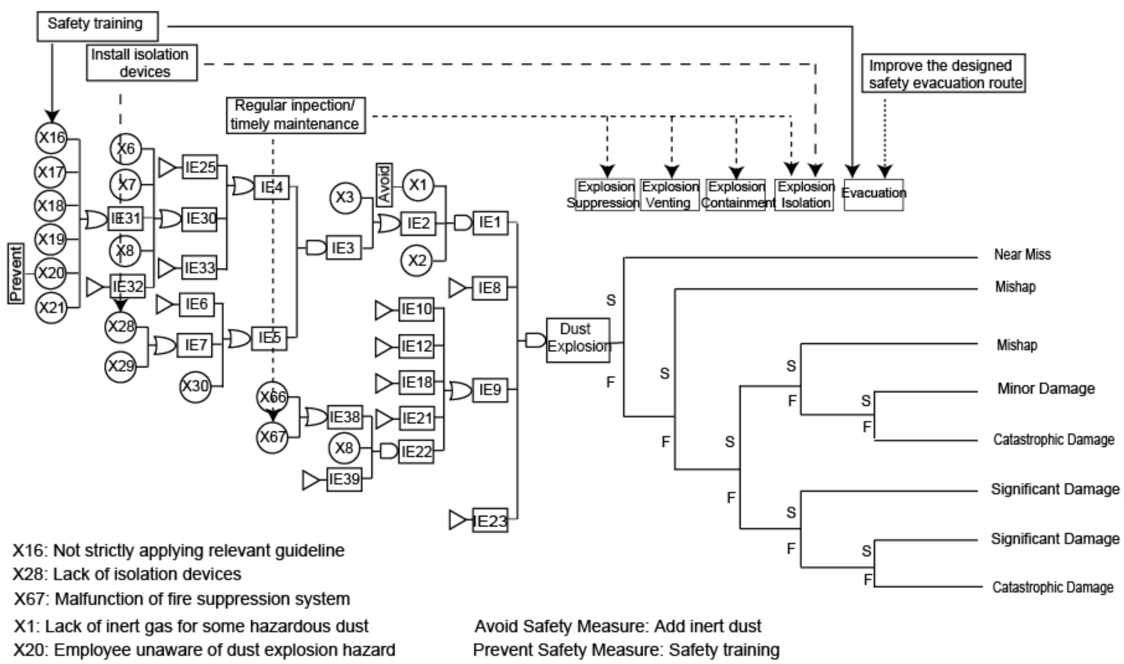


Fig. 5.4 Effects of safety measures on bow-tie

As can be seen from Figure 5.4, the effects of some safety measures are twofold. For instance, the safety measure *Install isolation devices* can not only avoid the basic event *Lack of isolation devices*, but also adds a safety barrier *Explosion Isolation* into the system to mitigate the damage caused by explosions. Likewise, *Safety training* and *Regular* *inspection/timely maintenance* are able to reduce the occurrence probability of basic events and improve the performance of safety measures (Figure 5.4). However, it should be noted that some safety measures only have an effect on basic events or on specific safety measures. For example, *Improve the designed safety evacuation route* only improves the reliability of *Evacuation*.

5.5 Application of the methodology to a case study

5.5.1 Case study

To demonstrate the efficacy of the generic BT developed in Section 5.3, a dust explosion in a wool factory in Vigliano Biellese, Biella, Italy on 9 January, 2001 was selected as the case study. This accident caused five injuries, three deaths and considerable damage to the factory (Piccinini, 2008). The wool processing facility included washing, carding, and combing of wool. The burrs and noils, separated in the process, were conveyed by pneumatic system and collected in storage cells. The possible ignition source of the primary explosion was identified as the flames or embers, triggered by sparks from the electrical equipment or the overheating of a component. The collapse of the net separating two cells caused the formation of a dust cloud (i.e., dust dispersion) which was ignited and gave rise to a primary dust explosion. When flames and overpressure of the primary explosion reached nearby dust layers, more dust became suspended and the secondary explosion resulted.

5.5.2 Bow-tie development

Based on the accident details (Piccinini, 2008), the generic BT of Figure 5.3 was tailored to model the accident scenario as shown in Figure 5.5. The basic events and intermediate events in Figure 5.5 have already been described in Table 5.1 and Table 5.2.

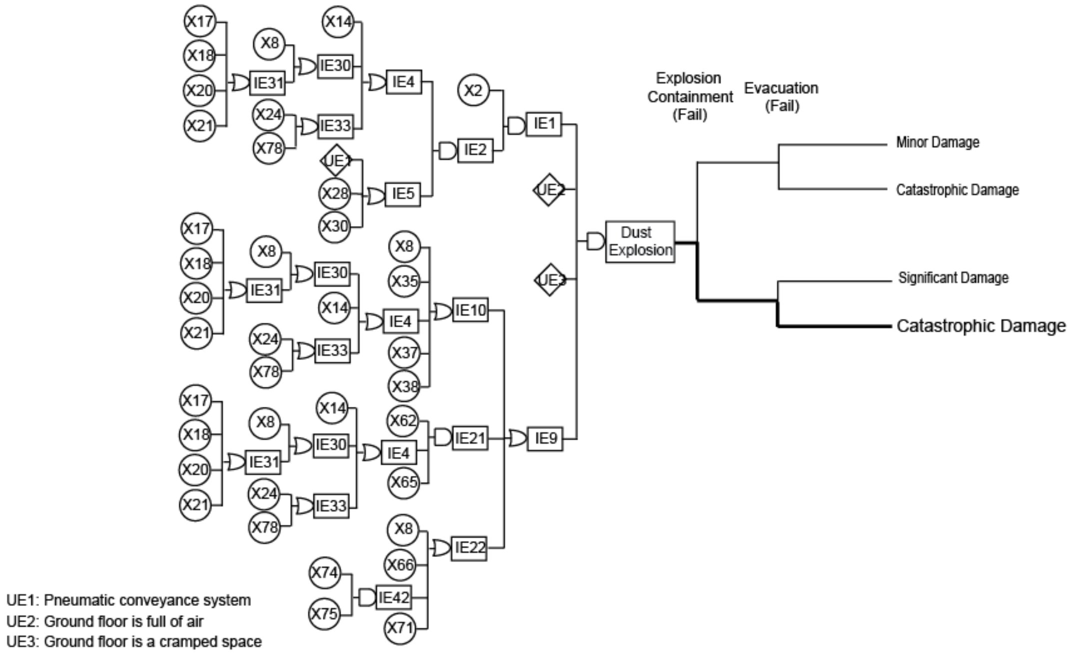


Fig. 5.5 Bow-tie of the dust explosion in the wool factory in Vigliano Biellese.

It should be noted that UE_i (i=1, 2, 3) stands for undeveloped events which do not need further resolution. For example, pneumatic conveyance of the burr is one of the reasons leading to dust dispersion and suspension in air. As a normal working condition for this case, it could be considered as an undeveloped event.

As shown in Figure 5.5, only two safety measures were installed in the facility, both of which failed after the dust explosion had occurred. The path to the consequence *Catastrophic Damage* is depicted in bold. The probabilities of the basic events used in the analysis are obtained from Table 5.1; using these data the probability of the dust explosion is calculated as 2.49E-02. Similarly, the occurrence probabilities of other consequences are estimated, and detailed results are presented in Table 5.5 (the second column).

Table 5.5 Probabilities of consequences

	Factory with existing safety measures	Factory with additional safety measures
Dust explosion	2.49 E -02	0.99 E -03
Near miss	N/A	0.89 E -03
Mishap (Suppression fails and Venting succeeds)	N/A	0.91 E -04
Mishap (Suppression and venting fail, other safety barriers succeed)	N/A	0.71 E -05
Minor damage	2.06 E -02	0.59 E -06
Catastrophic damage (Evacuation fails)	2.28 E -03	0.31 E -07
Significant damage (Containment fails & Isolation succeeds)	N/A	0.46 E -06
Significant damage (Containment fails & Evacuation succeeds)	1.86 E -03	0.38E -07
Catastrophic damage	2.07 E -04	0.2 E -08

5.5.3 Recommendation of safety measures

To reduce the risk, additional safety measures are recommended and implemented to the BT (Figure 5.6). As can be seen, these safety measures help to avoid or prevent most of the basic events and also improve the performance of existing safety measures. Further, some of the suggested safety measures, in the generic BT, are also considered to mitigate the damage caused by the accident. For example, an explosion suppression device is recommended as the first safety measure.

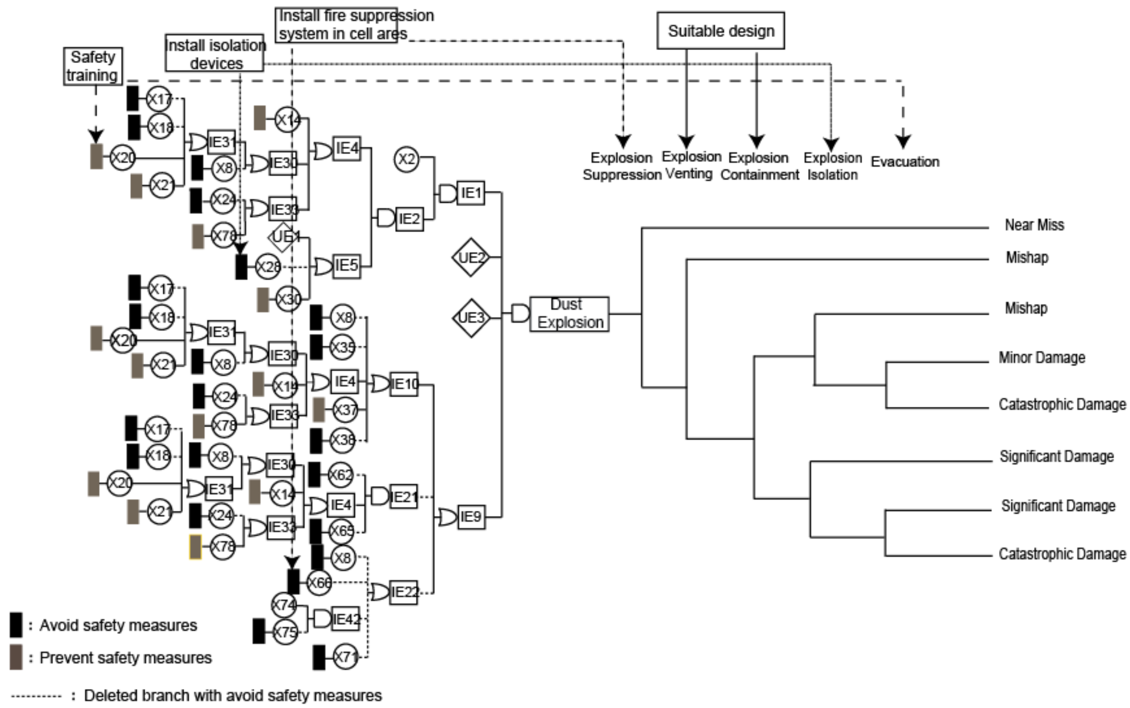


Fig. 5.6 Effects of additional safety measures in reducing the risk of explosion in the wool factory.

More examples illustrating how safety measures can improve the system's safety are given in Tables 5.6 and 5.7 for FT and ET, respectively.

Table 5.6 Effects of additional safety measures on basic events of FT of the bow-tie model

Guide word	Symbol	Safety Measures	Effects
Avoid	X_8	Ensuring regular inspection	After ensuring regular inspection, the situation of *lack of regular inspection* is avoided and the branch originating from X_8 could be deleted. The probabilities of related events "Poor housekeeping" and "Heat surface" can be calculated as: $P(IE30) = P(IE31) = 1 - \big(1 - P(X17)\big) * \big(1 - P(X18)\big) * \big(1 - P(X20)\big) * \big(1 - P(X21)\big) = 1 - (1 - 0.09) * (1 - 0.033) * (1 - 0.1) * (1 - 0.05)) = 0.248$ (compare with the prior value of 0.255) $P(IE10) = 1 - \big(1 - P(IE4)\big) * \big(1 - P(X35)\big) * \big(1 - P(X37)\big) * \big(1 - P(X38)\big) = 1 - (1 - 0.453) * (1 - 0.067) * (1 - 0.04) * (1 - 0.045)) = 0.532$ (compare with the prior value of 0.537)

Avoid	X_{17}	Establish integrated management system for burrs	By establishing an integrated management system for burrs, the branch including X_{17}, *Inadequate stewardship program of manufacturers of raw materials*, could be eliminated from BT. The probability of the relevant intermediate event, "Lack of awareness of combustible dust hazard", could be calculated as: $P(IE31) = 1 - (1 - P(X18)) * (1 - P(X20)) * (1 - P(X21)) = 1 - (1 - 0.033) * (1 - 0.1) * (1 - 0.05) = 0.173$ (compare with the prior value of 0.248)
Prevent	X_{14}	Regular cleaning (RC)	When "regular cleaning" is applied to prevent X_{14}, the probability of X_{14} could be calculated as: $P(X14) = P(X14 \mid RC) * P(RC) + P(X14 \mid \overline{RC}) * P(\overline{RC}) = 0.145 * 0.06 + 0.085 * 0.94 = 0.089$ (compare with the prior value of 0.145) Thus, the probability of IE4, "dust accumulation", would be as: $P(IE4) = 1 - (1 - P(X14)) * (1 - P(IE30)) * (1 - P(IE33)) = 1 - (1 - 0.089) * (1 - 0.256) * (1 - 0.1405) = 0.417$ (compare with the prior value of 0.424)
Prevent	X_{20}	Safety training (ST)	When safety training is taken to help operators increase their knowledge of dust explosion hazards, the failure probability of X_{20} will depend on safety training (ST), where: $P(X20) = P(X20 \mid ST) * P(ST) + P(X20 \mid \overline{ST}) * P(\overline{ST}) = 0.1 * 0.01 + 0.05 * 0.99 = 0.0505$ (compare with the prior value of 0.1) The probability P(IE31) of the relevant intermediate event "Lack of awareness of combustible dust hazard", would be as: $P(IE31) = 1 - (1 - P(X17)) * (1 - P(X18)) * (1 - P(X20)) * (1 - P(X21)) = 1 - (1 - 0.09) * (1 - 0.033) * (1 - 0.0505) * (1 - 0.05) = 0.206$ (compare with the prior value of 0.248)

Table 5.7 Effects of additional safety measures on the ET of bow-tie model

Existing Safety measure	Improvement	Effects
Lack of Explosion suppression	Install explosion suppression	Explosion suppression system can reduce the severity of consequences. For example, when fire is detected, the suppression devices will be activated. If this works, the

	system	consequence will become a near miss. Otherwise, more serious damage would be caused.
Failure of explosion containment	Suitable design (SD_1)	Explosion containment should be considered in the design stage. Therefore, taking suitable design could lessen the probability of flaws. The failure probability of explosion containment would be: $P(EC\|SD1) * P(SD1) + P(EC\|\overline{SD1}) * P(\overline{SD1}) = 0.085 * 0.01 + 0.06 * 0.99 = 0.06025$ (compare with the prior value of 0.085)

As may be seen from the examples given in Table 5.6, after implementation of "Avoid" safety measures to the FT, the basic events X_8 and X_{17} will not happen. That is, two contributory factors of the dust explosion are eliminated, and hence the probabilities of their upper events are reduced. "Prevent" safety measures are used to reduce the probability of relative basic events instead of avoiding them, as is the case for X_{14} and X_{20}. The probability of either X_{14} or X_{20} is decreased and accordingly the probabilities of their upper events are also reduced, which improves the safety of the system.

Aside from their effects on the FT, safety measures can be applied to the ET to mitigate potential damage of dust explosions and improve safety performances. For this case study, examples are shown in Table 5.7; via *installing explosion suppression system* to extinguish fires and by taking *proper supervision and training* to detect potential flaws of explosion containment, the damage caused by dust explosions is effectively mitigated.

Applying the above-mentioned safety measures to the facility, the occurrence probability of dust explosions could significantly have been reduced and the damage of dust explosions could thus have been lessened to a great extent. This helps to minimize the overall risk of a dust explosion.

5.6 Conclusion

In the present study, the basic events and likely consequences of dust explosions along with relevant safety measures are investigated and presented through a generic bow-tie. This bow-tie can be tailored to model a wide variety of dust explosions in different industries. A variety of safety measures are also suggested to reduce the probabilities of basic events. The practical application of these safety measures under inherent, engineering and procedural categories as well as avoid, prevent, control, and mitigate guide words are discussed, which provide suggestions for choosing most effective safety measures. Further, the efficacy of the generic bow-tie developed in this study is demonstrated via application to a case study, illustrating how effective it can be used for risk analysis of dust explosions with minimum complexity. The results also demonstrate the methodology presented in this study is able to effectively address most of the basic events contributing to dust explosions as well as to noticeably improve system safety.

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6 Risk Analysis of Dust Explosion Scenarios using Bayesian Network

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Preface

A version of this manuscript has been published in the Risk Analysis: an international journal. Under supervision of co-authors, Dr(s) Khakzad, Khan, and Amyotte, the principal author developed the dynamic risk analysis model for dust explosions and presented its application in dealing with common causes, diagnostics and information adaptation. The co-authors also reviewed the methodology and proposed valuable suggestions and corrections to improve the quality of the manuscript.

Abstract

In this study, a risk analysis model of dust explosion scenarios based on Bayesian networks is proposed. This model is directly transformed from a Bow-tie model of dust explosions taking advantage of the relationship between conventional risk estimation method and Bayesian networks. By this model, the risks of dust explosions are evaluated, taking into account common failure causes leading to dust explosions and dependencies among causes, and also probabilities of potential consequences are analyzed. The most critical events leading to dust explosions can be figured out by this model. According to posterior probabilities of primary events of dust explosions, studied using a diagnostic approach, the primary events related to dust particle properties, oxygen concentration and safety training are identified as the most critical factors for dust explosions. The probability adaptation concept is also used to learn from previous experience, which helps to dynamically revise the Bayesian network and prefigure risk by taking steps to design and implement additional safety barriers. This model is also applied to a case study that shows it can be used to depict the process of the accident, to estimate the risk of accidents and potential consequences, and, more importantly, to pick out the vulnerable parts of system for dust explosions.

Key words: Dust explosion; Risk analysis; Bow-tie model; Bayesian network

6.1 Introduction

Dust explosions are frequently reported industrial accidents. The earliest records of dust explosions date back to the late 1800s (Eckhoff, 2003). Dust explosions have caused huge damage to human beings and property. For example, a flax dust explosion caused 58 deaths and 177 injuries in Haerbin, China, in 1987 (Eckhoff, 2003). Therefore, better understanding of dust explosions mechanism is necessary to prevent dust explosions and reduce their effects. To this end, many experiments and simulations have been done (Eckhoff, 2003, 2009; Amyotte et al., 2005; Callé et al., 2005; Benedetto et al., 2007; Dufaud et al., 2009). However, due to the complexity of dust explosions, arising from a number of uncertain and interlinked primary causes, quantitative risk analysis (QRA) of such accidents has been limited (Voort et al., 2007; Khakzad et al., 2012).

Bow-tie (BT) is one of the widely used risk analysis tools. It integrates primary causes, potential consequences and safety measures of an accident scenario using a graphic approach. Dianous and Fiévez (2006) proposed a risk assessment methodology based on BT to evaluate the efficacy of risk control measures. Mokhtari et al. (2011) evaluated risk factors in sea ports and offshore terminals operation and management using BT. Celeste and Cristina (2010) proposed a semi-quantitative risk assessment methodology based on BT in the ship building industry. Yang (2011) used BT to evaluate risks of maritime security and proposed risk management strategies for maritime supply chains. However, due to its static characteristics, BT cannot easily be used in dynamic risk analysis unless equipped with extra models such as physical reliability models or Bayes' theorem (Khakzad et al., 2012).

The Bayesian network (BN) is able to perform both predictive (forward) analysis and diagnostic (backward) analysis. It also can consider common causes of failures, sequentially dependent failures, expert judgment, and structural and functional uncertainties (Khakzad et al., 2011). BN is widely used in modeling and risk analysis of a wide variety of accidents due to its flexible structure and robust reasoning engine (Khakzad et al., 2012; Cai et al., 2012; Khakzad et al., 2013a, b, c, d).

The parallels between conventional methods such as fault tree (FT), event tree (ET) and

BN have been discussed in previous work (Bobbio et al., 2001; Bearfield and Marsh, 2005; Khakzad et al., 2011). Further, Khakzad et al. (2013a) proposed an algorithm to transform a BT into the corresponding BN. This provides a bridge between static risk analysis and dynamic risk analysis by combining the features of BT and BN. The present study aims to establish a real-time risk analysis model for dust explosions using BN as an extension of a BT model. By this real-time model, risks of dust explosions and potential consequences resulted from dust explosions could be updated if new information is available. Also, the critical events for dust explosions in system could be picked out, which provides evidence for applying safety measures in systems to reduce risks of dust explosions in future.

This chapter is organized as follows: Section 6.2 briefly introduces mechanism of dust explosions, characteristics of BT, BN and the method of mapping BT into BN. In section 6.3, a generic BN is developed for accident modeling and risk analysis of dust explosions. To illustrate the efficacy and applicability of the developed BN, it is applied to a real dust explosion in Section 6.4. The conclusions drawn from this work are presented in Section 6.5.

6.2 Background

6.2.1 Dust explosion

Fuel (combustible dust), oxidants, ignition sources, dispersion of dust (mixing) and confinement have been proven to be five essential factors for a dust explosion to occur. These factors compose the dust explosion pentagon (Kauffman, 1982) and are indispensable in any dust explosion accident (Fig. 3.1). Fuel refers to combustible dust, the explosibility of which is mainly influenced by particle size, and combustible dust widely exists in various industrial areas such as aluminum products processing factories. Oxidants, usually in the form of oxygen in the air, affect the dust explosion process to a very large extent (Abbasi and Abbasi, 2007). Ignition sources, with minimal ignition temperature (MIT) or minimal ignition energy (MIE) for a specific dust, can be classified into various types such as hot surfaces and friction sparks. A dust cloud will be formed if dust is suspended in the air (mixing). Only if the dust concentration is within a certain limit, will an explosion happen. Confinement is another factor needed to build up the dust explosion energy to cause severe damage.

There are a number of primary events contributing to the aforementioned five essential factors, identified as indirect causes of dust explosions. In hazards assessment of industries prone to dust explosions, determining the primary events depends on a variety of factors such as the process flow diagram, the equipment and raw materials involved, layout of the work area, housekeeping and management. For example, the factor of *unsuitable cleaning methods* can refer to improper use of pressure air to clean depositing dust, which in turn can cause dust to disperse in the air, forming a combustible dust cloud. Other primary events such as the *collapse of equipment* can also result in dust clouds. However, in some process industries, dust suspensions are considered normal operating conditions. For example, pneumatic conveying technology, which is widely applied in bulk material handling systems, carries a mixture of powdery materials via a stream of air. Therefore, more attention should be paid to identifying hazards for such systems. In the present work, many factors are collected from accident reports (CSB, 2004, 2005, 2006), existing regulations (NFPA, 65, 68, 69, 91, 650, 654), and the literature (Piccinini, 2008; Abbasi et al., 2007).

As dust explosions could lead to severe consequences, safety barriers are applied to control and mitigate damage. Explosion suppression systems are among the commonly used barriers. When an explosion occurs, an explosion suppression system could be activated to prevent further development of the dust explosion. If the suppression system fails, pressure resulting from the dust explosion could be vented to outer spaces through venting systems to reduce risks. Otherwise, the dust explosion overpressure can be constrained in original units if the explosion containment and explosion isolation systems perform successfully. An explosion containment system is usually used in small-scale units such as grinding mills (Abbasi and Abbasi, 2007). An isolation system, on the other hand, is applied to block possible paths to prevent dust explosions spreading to nearby units or workshops.

6.2.2 Risk analysis methods

6.2.2.1 Bow-tie method

BT is a graphical method, composed of a critical event (CE) in the center, an FT on the left, and an ET on the right hand side of the critical event (Fig. 3.2). The CE is the top event of the FT, and the initiating event of the ET. A BT illustrates an accident scenario, beginning from the basic events (BE) and ending with the potential consequences (C). These consequences result from the CE and the failure of safety barriers (SB).

6.2.2.2 Bayesian Network

The Bayesian network is an inference probabilistic method. It is a directed acyclic graph (DAG) which is composed of nodes, arcs and conditional probability tables (CPT). Nodes represent random variables while arcs represent dependencies among linked nodes. The type and strength of these dependencies are defined via CPTs.

One of BN's advantages is probability updating when new information becomes available over time. This makes BN a robust tool in risk analysis of dynamic systems. Therefore, the probability of dust explosions, likelihood of consequences, and the envisaged risks can be updated as new operational and functional data become available through the system's operation. More importantly, the most critical basic events can be determined and proper safety measures can subsequently be applied to the weakest parts of the system.

Based on the conditional dependence of variables, the joint distribution $P(U)$ of a set of variables $U=(A_1, A_2, \ldots\ldots, A_n)$ can be expanded as the equation (3.2). In probability updating, prior probabilities of variables are updated (posterior probabilities) through Bayes' theorem given the observation of variables E, called evidence and can be represented as the equation (3.4).

6.2.2.3 Mapping Bow-tie to Bayesian Network

In order to consider dependencies and common causes of undesired accidents, a risk analysis model based on BT needs to be transferred into dynamic risk analysis based on BN, which has advantages in risk updating and sequential learning. Using the algorithm proposed by Khakzad et al. (2013a), shown in Figure 6.1, a BT can be mapped into the corresponding BN model.

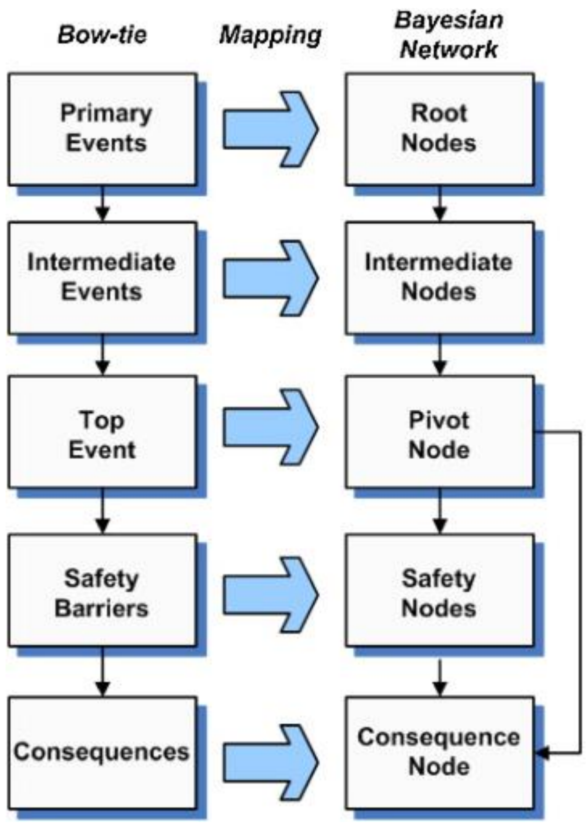


Fig. 6.1 Mapping BN from BT (Khakzad et al., 2013a)

6.3 Risk analysis of dust explosions

6.3.1 Dust explosion Bow-tie

In previous research (Yuan et al. 2013), detailed bow-tie analysis of dust explosion scenarios is established (a part of the bow-tie shown in Figure. 5.3). Descriptions and probabilities (Column 3 and 6) of basic events are listed in Table 5.1. Intermediate events, safety barriers and potential consequences are also listed in Table 5.2. The probabilities of a critical event and its potential consequences are calculated and listed in Table 6.1. (Column 2).

Table 6.1 Probability of critical event and consequences

Consequences	Probability (Without considering common causes)	Probability (Considering common causes)
Dust Explosion	0.49E-2	0.6E-2
Near Miss	0.44E-2	0.54E-2
Mishap (Venting success)	0.4E-3	0.5E-3
Mishap (Isolation success)	3.43E-5	4.19E-5
Minor Damage	2.69E-6	3.28E-6
Catastrophic damage	2.99E-7	3.64E-7
Significant Damage (Isolation Success)	3.11E-6	3.79E-6
Significant Damage (Evacuation Success)	2.43E-7	2.97E-7
Catastrophic Damage	2.7E-8	3.29E-8

As inherent limitations of BT, common cause failures and dependency cannot be considered. For example, X_9 (Lack of design codes), X_{10} (Improper design codes) and X_{11} (Failure to follow design codes) are basic events of IE_{27} (Deficiency in design of ventilation system). Meanwhile, all of them also cause the intermediate event of improper reconstruction of ventilation system (IE_{29}). In the BT of Figure 5.1 (a), these basic events have been considered twice; that is, once for IE_{27} and once for IE_{29}. As is shown in the next section, this lack of modeling can result in unrealistic probabilities for both the dust explosion and its consequences. Compared to BT, however, common causes and dependencies can be easily modeled in a BN.

6.3.2 Dust explosion Bayesian network

The BN model of dust explosion scenarios is developed as shown in Figure 6.2. For example, if the suppression system successfully functions at the beginning stage of a dust explosion, a *Near miss* will result (Figure 6.2). In the Bayesian network model of Figure

6.2, arcs are pointed to the consequence node *Near miss* from the safety measure node *Explosion Suppression* and critical event node *Dust Explosion* representing the influence of the safety measures and the critical event nodes on the consequence node. Similarly, other consequences can be mapped into the Bayesian network of Figure 6.2 from the BT of Figure 5.3.

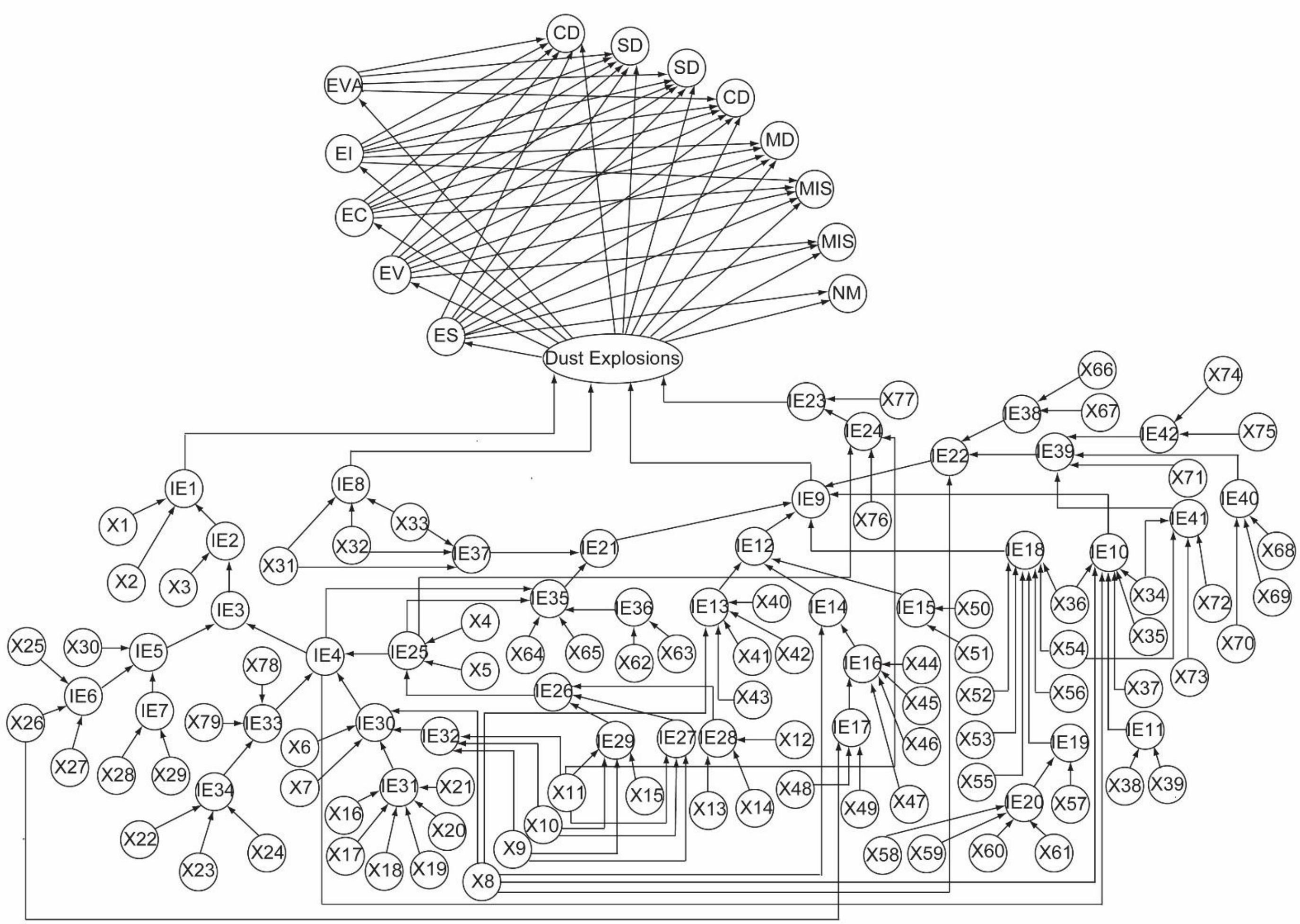
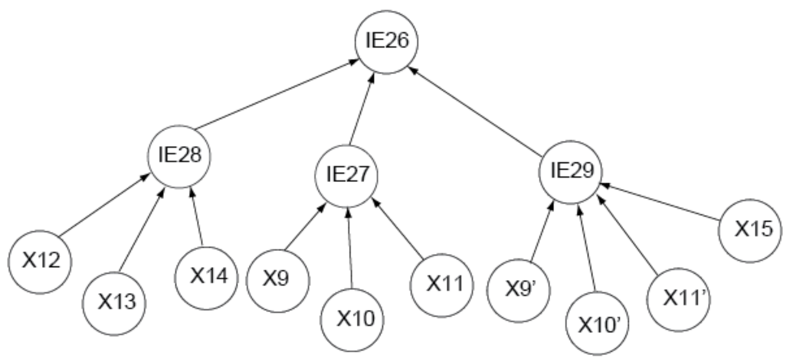


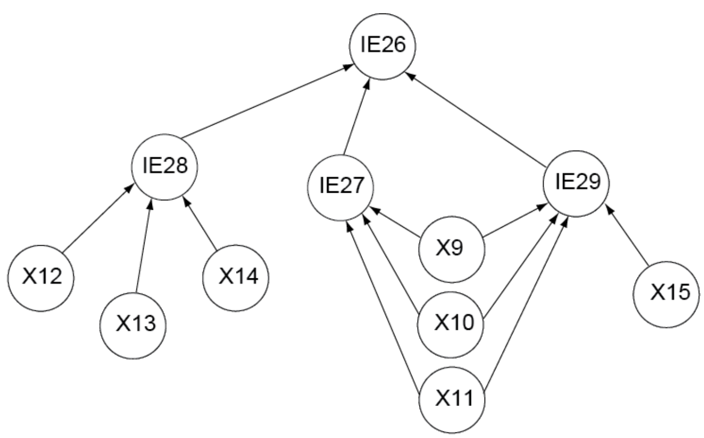
Fig. 6.2 Bayesian network model of dust explosions

6.3.3 Predictive analysis

BN can be applied to perform predictive analysis to obtain the probability of a dust explosion and its potential consequences (www.hugin.com). Results from the BN model are shown in Table 6.1. (column 3). It is worth noting that there are some differences between the results of the BN and those of the BT. The reason is whether common cause failures are considered in the model or not. As an example, Figure 6.3 illustrates how considering such dependency affects the results; for this purpose, the intermediate event IE_{26} and its basic causes have been selected (Figure 6.3).



(a) Ignoring dependencies



(b) Considering dependencies

Fig. 6.3 BN of IE_{26}

X_9, X_{10} and X_{11} are the common failure causes of IE_{27} and IE_{29}. In Figure 6.3 (a), when ignoring the dependencies between IE_{27} and IE_{29} (as in the BT model), the probability of IE_{26} can be calculated as 0.4484, which is the same as the result from the BT model. However, when X_9, X_{10} and X_{11} are considered as common parent nodes, the probability of IE_{26} differs from the above result. As shown in Figure 6.3 (b), when X_9, X_{10} and X_{11} are seen as common causes of IE_{27} and IE_{29}, the probability of IE_{26} is obtained as 0.3778. Thus, as can be seen, ignoring dependencies for this special case results in an overestimation of probabilities.

6.3.4 Risk updating

One of the main applications of BN is backward analysis or probability updating given new information (evidence), which is difficult performed using the BT without being coupled with other techniques (Khakzad et al., 2012). In risk updating, given that an accident has occurred, the probabilities of the basic causes along with the potential consequences of the accident can be revised to obtain updated probabilities. This is helpful particularly when the most probable configuration of basic causes of the accident is to be determined to allocate preventive safety measures. Likewise, knowing the most probable consequences of the accident, mitigation and/or control safety measures can be applied to alleviate the risk.

In dust explosion risk analysis, if a dust explosion or a certain consequence is observed, it could be considered as new information in the corresponding BN model to update probabilities.

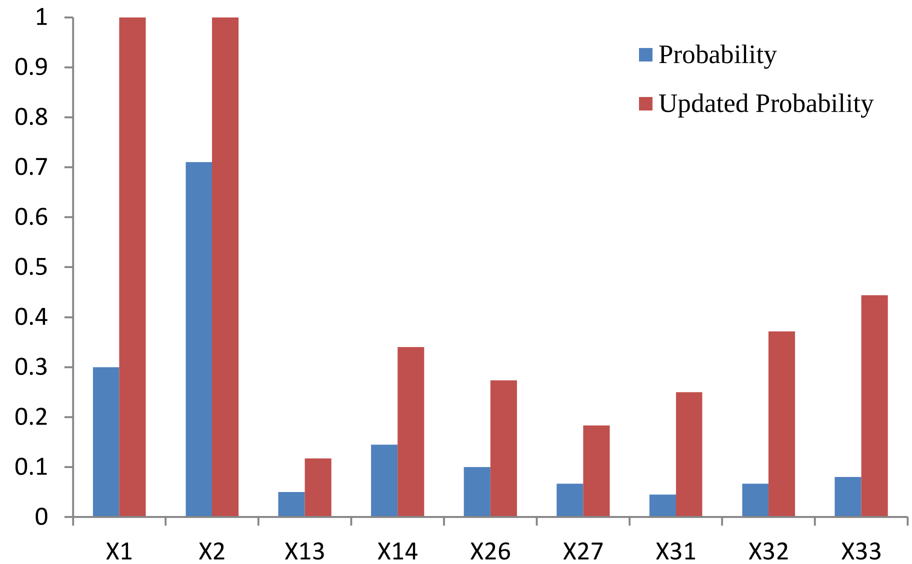


Fig. 6.4 Probability Changes of critical events of dust explosions

Figure 6.4 shows the posterior probabilities of some critical nodes contributing to the dust explosion (i.e., conditional probabilities of primary events in a dust explosion). As can be seen, the probabilities of nodes X_1 (*Lack of inert dust for explosible dust*) and X_2 (*Particle size in explosive range*) have increased to 1.0, emphasizing the critical role of combustible dust in dust explosions. Other important factors include the nodes pertinent to the ventilation system, i.e., X_{14} (*Blockage in ventilation system*) and X_{13} (*Leakage of air from ventilation system*), related to safety training, i.e., X_{26} (*Inadequately safety trained operators in high risk working environment*) and X_{27} (*Improper procedures to clean settled dust*). Also, X_{31} (*Lack of inert gas device*), X_{32} (*Inadequate inert gas device*) and X_{33} (*Failure of inert gas device*), which are related to the control of oxidant concentration in a dust explosion, become more important for dust explosions according to the updated probabilities.

According to the most probable configuration technique of BN, the most probable set of basic events leading to a dust explosion is determined as the occurrence of X_1, X_2, X_{14}, X_{26} and X_{33} and the nonoccurrence of other primary events. Considering this, priority will be given to the most probable configuration of the basic events to reduce the probability of a dust explosion and thus lower the envisaged risk.

6.3.5 Sequential learning

Another important application of BN is sequential learning, experience learning, or probability adapting. Using sequential learning, the probabilities can be updated with information accumulated over time (Jensen and Nielsen, 2007). This information can be in the form of accident precursors, near misses, mishaps, and incidents occurring during an operation.

In risk analysis of dust explosions, sequential learning can be implemented considering the previous dust explosions, occurrence of basic events from the system of interest. For example, it is assumed that the basic events X_5 (*Equipment failure of ventilation system*), X_{34} (*Overloading operation of processing equipment*), X_{43} (*Malfunction of equipment such as belt slip*), X_{45} (*Use unsuitable tools*), and X_{73} (*Bad contact*) have been observed and recorded over a 6-week period as shown in Table 6.2.

Table 6.2 Records of abnormal events in 6 weeks

Week	1	2	3	4	5	6
Equipment failure of ventilation system	_	1	_	1	1	_
Overloading operation of processing equipment	1	_	2	_	1	1
Malfunction of equipment such as belt slip	2	1	_	1	_	1
Use of unsuitable tools	_	1	1	_	1	_
Bad contact	1	_	2	2	_	1

According to Table 6.2, probabilities of *Equipment failure of ventilation system*, *Overloading operation of processing equipment*, *Malfunction of equipment such as belt slip*, *Use of unsuitable tools* and *Bad contact* are adapted by using relative records in Table 6.2. Using these new probabilities, the posterior probabilities of a dust explosion and the potential consequences can be calculated at the end of each time interval (week). Figure 6.5 shows posterior probabilities of dust explosions and the catastrophic damage probability over 6 weeks of the system's operation.

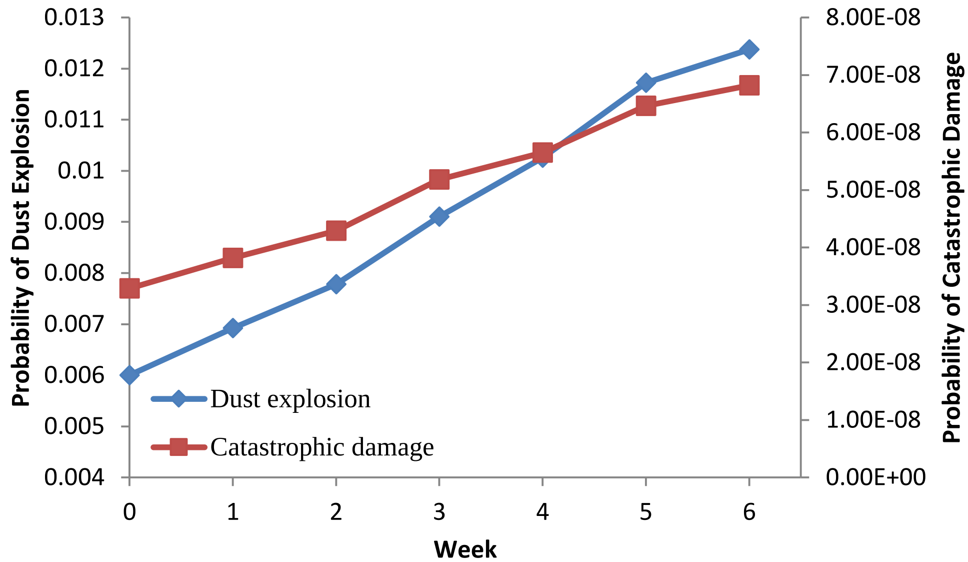


Fig. 6.5 Probabilities of dust explosion and catastrophic damages

As Figure 6.5 shows, the probabilities of dust explosion and catastrophic damage have increased more than two times at the sixth week, compared with week 0: the probability of dust explosion ascends from 0.06 in week 0 to 0.0124 in week 6 and the probability of catastrophic damage rises from 3.29E-08 in week 0 to 6.82E-08 in week 6. Although only the trend of catastrophic damage is shown here, other consequences' probabilities also show a rising trend with time (weeks).

6.4 Application of the methodology

To illustrate the application of the BN developed for dust explosions, it is applied to risk analysis of a dust explosion accident in a wool factory in Vigliano Biellese, Biella, Italy on January 9, 2001 (Piccinini, 2008). According to the accident report (Piccinini, 2008), the generic BN model in Figure 6.2 is tailored to model the accident scenario (Figure 6.6).

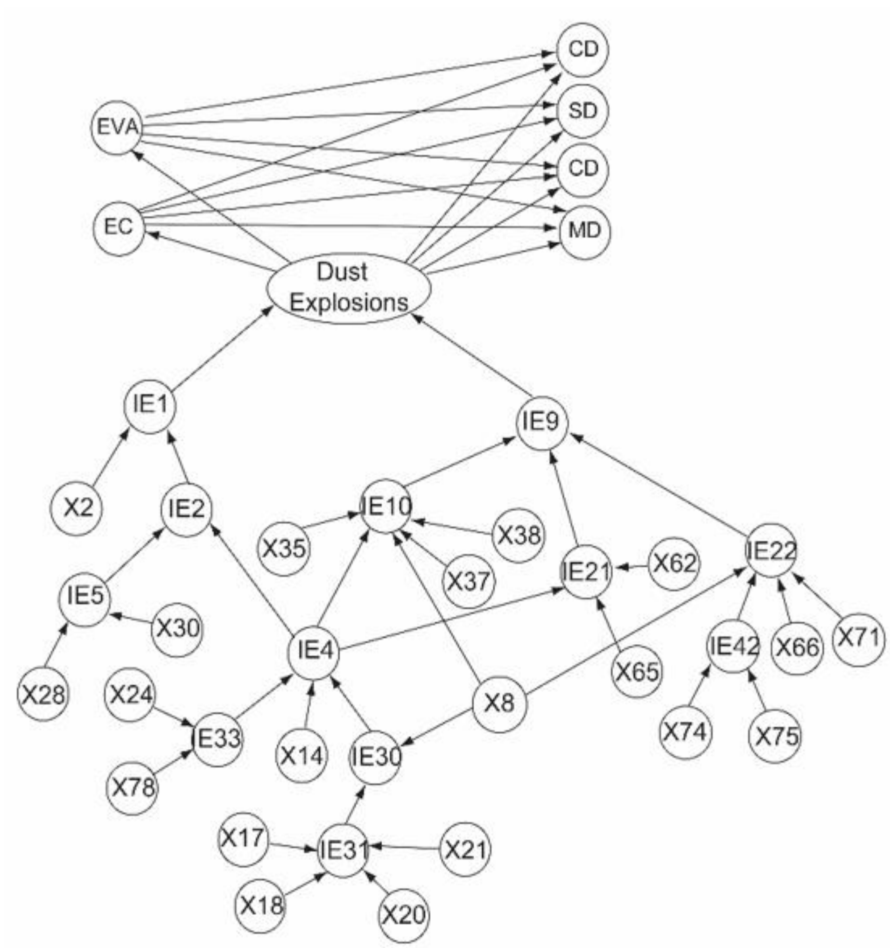


Fig. 6.6 BN Model of Wool Dust Explosion

In Figure 6.6, all the node indices are the same as those in Table 5.1.

The probability of a dust explosion in the wool factory is calculated as 4.35E-02 (compared with 2.49E-02 obtained from the BT model). Also, the probabilities of the different consequences are presented in Table 6.3.

Table 6.3 Probabilities of Consequences

	BT model	BN model
Dust explosion	2.49 E -02	4.35E-02
Minor damage	2.06 E -02	3.59E -02
Catastrophic damage (Evacuation fails)	2.28 E -03	3.99E-03
Significant damage (Containment fails & Evacuation succeeds)	1.86E -03	3.25E-03
Catastrophic damage	2.07E -04	3.61E-04

Given the dust explosion, the updated probabilities of the basic events (descriptions of basic events are shown in Table 5.1.) are shown in Table 6.4.

Table 6.4 Probabilities and updated probabilities of basic events

Symbol	Description	Probability	Updated Probability	Symbol	Description	Probability	Updated Probability
X2	Particle size in explosive range	0.71	1.0	X35	Lack of surface shielding/isolation for high temperature equipment	0.067	0.067
X8	Lack of regular inspection	0.01	0.022	X37	Mechanical failure of equipment such as bearings or blowers	0.04	0.04
X14	Blockage in ventilation system	0.145	0.32	X38	Lack of excessive temperature controlling system	0.045	0.045
X17	Inadequate stewardship program of manufacturers of raw materials	0.09	0.20	X62	Lack of gas/temperature detection system	0.045	0.045
X18	Lack of methods to identify hazards	0.033	0.73	X65	Unsuitable storage methods	0.045	0.045
X20	Employee unaware of dust	0.1	0.22	X66	Lack of fire suppression	0.045	0.043

	explosion hazard				system		
X21	Inadequate safety training about combustible dust hazard	0.05	0.11	X71	Ignition of settled dust	0.005	0.005
X24	Lack of dust-tight system	0.045	0.099	X74	Combustion	0.3	0.3
X28	Lack of isolation devices	0.055	0.41	X75	Lack of separation device to prevent burning dust from entering process system	0.045	0.045
X30	Collapse of equipment	0.085	0.63	X78	Lack of dust suppressants	0.1	0.22

According to the updated probabilities of Table 6.4., the most critical events are X_2, X_{18}, X_{30}, X_{28}, X_{14}, X_{20}, X_{78}, X_{17} and X_{21}, showing the highest increase in their probabilities. *The particle size of burrs and noils in explosion range* (X_2) is an essential factor for this accident. The explosivity of dust, sticking to the nets of the burr cells or gathering in an air conditioning system, have been proven to be high according to the accident report of Piccinini (2008). Further, *the stewardship program of burrs is inadequate* (X_{17}*)* in this wool factory; there is *a lack of methods to identify hazards* (X_{18}). Also, *employees being unaware of dust explosion hazards* (X_{20}) and *inadequate safety training about burrs hazard* (X_{21}) are some reasons for *a lack of awareness of a combustible dust hazard* (IE_{31}) causing *poor housekeeping* (IE_{32}). Small smouldering combustion events occurred almost daily, according to the accident report (Piccinini, 2008). As one of the injured technicians described, “the underground is a kingdom of dust” due to *the lack of dust suppressant* (X_{78}) and the application of the pneumatic conveying system. *Collapse of the net that separated the two cells* (X_{30}) was considered by Piccinini (2008) as the likely cause of cloud dust formation. After the primary explosion happened, the dust accumulated at bag filters of the air conditioning system, resulting from *the blockage in the ventilation system in storage cells* (X_{14}), was aroused by pressure waves caused by the primary explosion and *the lack of isolation devices between cells and bag filters* (X_{28}) leading to the pressure transmission from cells to bag filters. According to Piccinini (2008), at least 400-500kg flammable fibers, mainly on the ground floor equipment, such as bag filters of air conditioners, were involved in this deflagration. Further, based on the most probable configuration analysis, *the particle size of burrs and noils in explosion range* (X_2), *blockage in the ventilation system in storage cells* (X_{14}), and *collapse of the net that separated the two cells* (X_{30}) are determined as the most probable causes of the accident. All these events are the essential components of the dust explosion pentagon as are oxygen underground and complex ignition sources in this case. Therefore, the results obtained from the BN model in this study are in agreement with those of the accident report (Piccinini, 2008). Also, the most critical events for this dust explosion have been explored through Bayesian model analysis, illustrating the priority of safety measures for this wool factory.

6.5 Conclusions

In the present research, a risk analysis model of dust explosions was developed based on the Bayesian network. Probabilities of dust explosions and potential consequences were calculated using the BN compared with BT developed in a previous study. The differences between the results of BT and BN highlight the importance of considering common failure causes and dependencies in complex accident scenarios such as dust explosions.

Taking advantage of probability updating and sequential learning of BN, a dynamic risk analysis of dust explosions was also conducted. The critical basic events as well as the most probable configuration of basic events leading to a dust explosion were identified. These are particle properties, oxygen concentration and safety training. The current study also demonstrated the value of experience learning when accident related data over time is available. The model is tested and verified using the study of a past accident.

Acknowledgments

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7 Risk-based Optimal Safety Measure Allocation for Dust Explosions

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Preface

A version of this manuscript has been published the journal of Safety Science. Under supervision of co-authors, Dr(s) Khakzad, Khan, and Amyotte, the principal author developed the research on the entitled topic. The co-authors also reviewed the methodology and proposed valuable and necessary suggestions and corrections to improve the quality of the manuscript.

Abstract

Optimal allocation of safety measures in order to reduce threats of dust explosions is very challenging, particularly when all potential accident contributors and various safety measures are to be taken into account. In this paper, we have proposed a risk-based optimal allocation of safety measures while considering both available budget and acceptable residual risk. The methodology is based on a Bayesian network (BN) to model the risk of dust explosions, which in turn helps to identify key contributing factors, assess performances of relative safety measures, and decide on those safety measures to most efficiently control the risks of dust explosions within a limited budget. The Bayesian network also facilitates the implementation of diagnostic analysis to determine vulnerable parts in the system to which special attention should be paid in safety measure allocation. The Net Risk Reduction Gain (NRRG) for each relevant safety measure is also used to simultaneously account for both the cost of a safety measure and the respective risk reduction. Accordingly, the risk-based optimal allocation of safety measures will be achieved by maximizing the sum of the NRRG of all relevant safety measures under limited budgets, which is regarded as a knapsack problem. We applied the methodology to the aluminum dust explosion that occurred at Hayes Lemmerz International, Huntington, Indiana, US in October 2003. The result shows the efficacy and applicability of the proposed methodology for optimal risk reduction within a limited budget.

Key Words: Risk analysis model, dust explosions, safety measures, optimization, Bayesian network

7.1 Introduction

Dust explosions have been reported as a wide-ranging threat to industrial safety in recent decades (Blair, 2007; Zheng et al., 2009; Giby and Luca, 2010), having caused huge losses in terms of operators, shareholders, assets and the environment (CSB, 2004, 2005a, b, 2006). According to previous work (Abbasi, 2007), fuel, oxidant, ignition source, suspension, and confinement are five essential elements for every dust explosion. Accordingly, safety measures proposed to avoid or prevent dust explosions are mainly aimed at eliminating one or more of these essential factors. For example, the use of an explosion-proof vacuum to remove accumulated dust layers is usually intended to eliminate the possibility of suspension in areas with high explosion risks (Amyotte et al., 2009). In real cases, each essential element might be provided or triggered by a series of factors. For example, settled dust might be suspended by various causes such as incorrect methods of housekeeping or pressure waves from nearby explosions, to form a combustible dust cloud. Since each causation factor could further result from other lower level root causes, a large number of factors, directly or indirectly, could contribute to industrial dust explosions. Further, there are numerous relevant safety measures to prevent and control dust explosions, ranging from inherent to engineering to procedural safety measures, each with their own specific characteristics and applications. The complexities of potential dust explosions on one hand, and the versatility of pertinent safety measures on the other, introduce significant challenges in optimal allocation of safety strategies for dust explosions. Ideally, safety measures should be assigned to all dust explosion contributing factors in a process plant; however, the available budgets for system safety improvements are usually limited in reality. Therefore, decision-makers often face the dilemma of balancing risk reduction with the costs of safety measures.

Recently, there have been attempts to develop probabilistic models for risk analysis and safety assessment of combustible dust (Hassan et al., 2013) and dust explosions (Van der Voort et al., 2007; Yuan et al., 2013; Yuan et al., 2014). Van der Voort et al. (2007) proposed a quantitative risk analysis tool for the external safety assessment of industrial plants prone to dust explosion hazards. Yuan et al. (2013, 2014) developed a generic risk model for likelihood modeling and safety analysis of dust explosions based on the bow-tie and Bayesian network (BN). In their model, an attempt has been made both to consider as many dust explosion root causes as possible and to collect and categorize pertinent safety barriers. Since the present work is based on the work of Yuan et al. (2014), the BN and the explanation of its components are shown in Figure 6.2 and Tables 5.1 and 5.2, respectively. Caputo et al. (2013) proposed a multi-criteria "knapsack" model to select safety measures via a balancing between risk reduction (benefit) and cost of safety measures. In a similar approach, Reniers and Sörensen (2013) proposed an optimization model based on a risk matrix. However, the lack of risk models in the foregoing methods means that the risk of accidents and the effects of safety measures on estimated risk are based mainly on subjective judgments of decision-makers. The current paper proposes a risk-based optimization method for allocation of safety measures to avoid or prevent dust explosions based on dynamic risk analysis with the advantage of identifying the most critical factors when assigning the safety measures.

The paper is organized as follows. The fundamentals of the risk analysis model for dust explosions and the functions of relevant safety measures are recapitulated in Section 7.2. The developed methodology for risk-based optimal allocation of safety measures is then presented in Section 7.3. To verify the efficacy of the model, it is applied to a case-study in Section 7.4 while the main conclusions are summarized in Section 7.5.

7.2 Background

7.2.1 Bayesian networks

BN are directed acyclic graphs used to represent random variables and dependencies among them by means of chance nodes and directed arcs. Accordingly, the type and strength of such dependencies are modeled via conditional probability tables. Like conventional risk analysis methods such as fault tree and bow-tie, BN can be used to perform prognostic (forward) analysis. However, the main advantage of BN over fault tree and bow-tie is its ability to perform diagnostic (backward) analysis or probability updating when new information becomes available. Compared to prior probabilities, posterior (updated) probabilities are more reliable and reflect the real-time situation of the system of interest, as the newest information and operational data are taken into account (Khakzad et al., 2011). Therefore, the most critical factors contributing to an accident can be defined based on a comparison between prior and posterior probabilities if the occurrence of the accident is set as the evidence.

According to the local conditional dependence of variables, the joint distribution P(X) of a set of variables $X=(X_1, X_2, \dots, X_n)$ can be factored as the equation 3.2.

Using Bayes' theorem, prior probabilities of variables can be updated given the evidence E, as the equation 3.4.

The following case is a simplified evacuation model by using a free-fail boat and a rescue boat in an offshore system (Eleye-Datubo et al., 2006). The explanations of the symbols are shown in Figure 7.1.

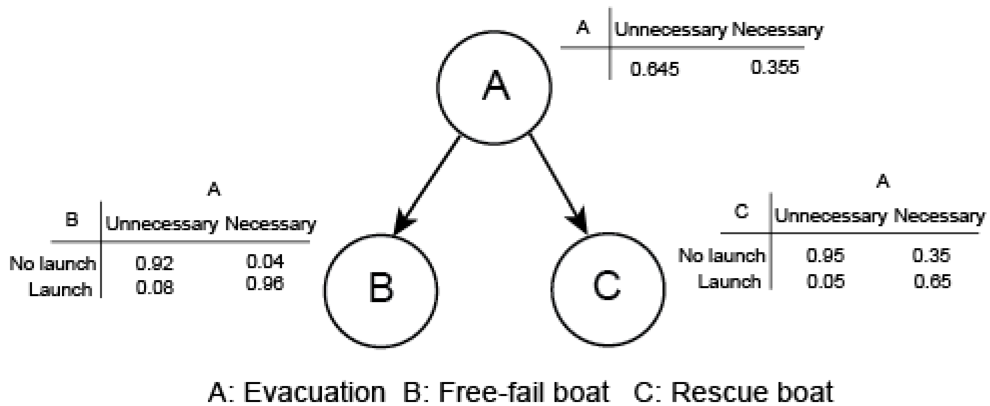

Fig. 7.1 Simplified BN showing a marine evacuation scenario (Eleye-Datubo et al., 2006)

Based on equation 7.1, the probability of free-fail boat launch, P(B), and the probability of rescue boat launch, P(C), can be calculated as:

$$P(B) = P(B|A)P(A) + P(B|\bar{A})P(\bar{A}) = 0.96 * 0.355 + 0.08 * 0.645 = 0.392$$

$$P(C) = P(C|A)P(A) + P(C|\bar{A})P(\bar{A}) = 0.65 * 0.355 + 0.05 * 0.645 = 0.263$$

Assuming the launching of free-fail boat already happened, which is set as the evidence, the prior probabilities of A and C can be updated respectively as:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} = \frac{0.96 * 0.355}{0.392} = 0.869$$

$$P(C) = P(C|A)P(A) + P(C|\bar{A})P(\bar{A}) = 0.65 * 0.869 + 0.05 * 0.131 = 0.571$$

7.2.2 Safety measures

Based on risk management principles, safety measures can be divided into three types: inherent, engineered, and procedural. Inherent safety measures eliminate hazards by focusing on the properties of materials or making improvements in the design stage without additional equipment. Minimization, substitution, moderation and simplification are the four key principles in inherent safety (Amyotte et al., 2007, 2009; Kletz, 1978, 2003). For example, the removal of deposited combustible dust via good housekeeping can effectively reduce the concentration in a potentially combustible dust cloud. Therefore, it can be considered as minimization in the context of inherent safety measures, with strong overtones of procedural safety (Amyotte et al., 2009). However, engineered safety measures rely on additional safety equipment. According to their method of operation, they are further classified into passive or active devices. Unlike active safety measures, passive safety measures do not depend on an external activator, actuator or human intervention, making them more reliable than active safety measures. For procedural safety measures (e.g., safety training), however, the focus is mainly on system management to improve human performance (e.g., reducing human response time) or eliminate human errors.

In safety decision making, inherent safety measures are usually given priority, compared to the other types of safety measures. Aside from inherent safety measures, passive safety measures are preferred next as they do not depend on external controlling or activating systems. Next to passive are active safety measures while the last option would be procedural safety measures. The recommended order of safety measures selection is shown in Figure 7.2 (in the direction of the arrowhead).

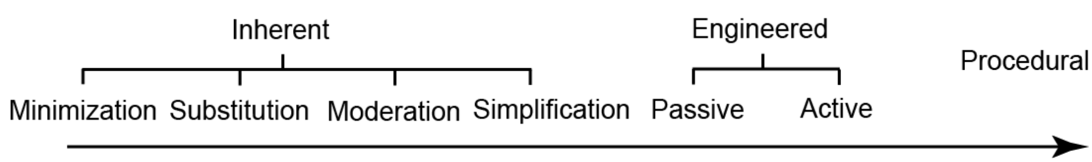

Fig. 7.2 Recommended preference of safety measures

In terms of the influence safety measures have on risk, they can be further labeled according to four keywords: avoid, prevent, control and mitigate. To be labelled using the avoid and prevent keywords, a safety measure should be applied before an accident occurs. After application of an avoid safety measure, the abnormal event will not happen. However, a prevent safety measure reduces the occurrence probability of a certain event. Classifying the control and mitigate keywords, these safety measures are mainly employed after an accident occurs in order to control or reduce the resulting damage (Dianous et al., 2006). Depending on the functioning or malfunctioning of safety measures, their impacts on the likelihood of abnormal events can be derived using the "Law of Total Probability". For example, if magnetic equipment (SM_{me}) is installed in an inlet to prevent tramp metal from entering the system to prevent impact sparks, then the probability of tramp metal entering the system, P(TM) is:

$$P(TM) = P(TM|SM_{me}) * P(SM_{me}) + P(TM|\overline{SM_{me}}) * P(\overline{SM_{me}}) \quad (7.1)$$

In the above equation, $P(SM_{me})$ stands for the failure probability of magnetic equipment; $P(TM|SM_{me})$ refers to the conditional probability of tramp metal entering the system given the failure of magnetic equipment. Similarly, $P(TM|\overline{SM_{me}})$ is the conditional probability of tramp metal entering the system given the functioning of the magnetic equipment. Further information about the classification and function of safety measures can be found in Dianous et al. (2006) and Yuan et al. (2013).

7.2.3 Potential losses from accidents

To calculate the risk of an accident scenario, the essential information needed is the potential damage resulting from the accident along with the probability of the accident. Usually, accidents result in damage to either tangible assets such as equipment or intangible assets such as market value or company reputation. Compared to tangible losses, the intangible damages are more difficult to assess and are thus often ignored in risk assessments. For example, Capelle-Blancard and Marie-Aude (2010) discussed the loss of market value caused by accidents and found that shareholders suffer a significant loss of about 1.3% in the two days following an accident.

In the current research based on the severity of dust explosions, potential consequences are classified as: near miss, mishap, minor damage, significant damage and catastrophic damage. Category definitions were given in our previous work (Yuan et al., 2013), and are also listed in Table 7.1.

Table 7.1 Classification of consequences

Consequence	Description
Near miss	Dust explosion is controlled at its initial stages, and the system can be recovered quickly.
Mishap	Process is interrupted, and more time is needed to recover the system compared to that of a near miss. However, no damage is caused to apparatus/equipment or harm to operators.
Minor damage	Equipment may be damaged, and superficial injuries are expected.
Significant damage	Equipment is damaged along with the possibility of serious injury or death.
Catastrophic damage	Major facility damage is caused, and several fatalities are expected.

The damage of different consequences can be weighted by equivalent economic losses as shown in Table 7.2, which is adopted from the consequence severity matrix proposed by Kalantarnia (2009).

Table 7.2 Consequence severity matrix (adopted from Kalantarnia, 2009)

Consequence	Dollar value equivalent	Asset loss	Human loss	Environment loss	Reputation
Near miss	0.01K-1K	Short term production interruption	No injury	Around the operating unit, easy recovery and remediation	Get noticed by the operation line workers/line supervisor
Mishap	1K-50K	Medium term production interruption	No injury	Around the operating line, easy recovery and remediation	Get noticed in plant
Minor damage	50K-0.5M	Equipment damage of one or more units requiring repair/long term production interruption	Superficial injuries	Within plant, short term remediation effort	Get attention in the industrial complex, information shared with neighboring units
Significant damage	0.5M-50M	Loss of major portion of equipment/product	Multiple major injuries, potential disabilities, potential threat to life, or one fatality	Minor offsite impact	Local media coverage or regional media coverage, brief national media note
Catastrophic damage	>50M	Loss of all equipment/product	Multiple fatalities	Community evacuation	National media coverage, brief note on international media

7.3 Approach for optimal safety strategies for dust explosions

The main steps for risk-based optimization of safety measures are expressed in Figure 7.3. The protocol is a combination of a risk analysis model for dust explosions and an optimization method to help decision-makers search for the most efficient safety strategy. Explanation of these steps can be found in the following subsections.

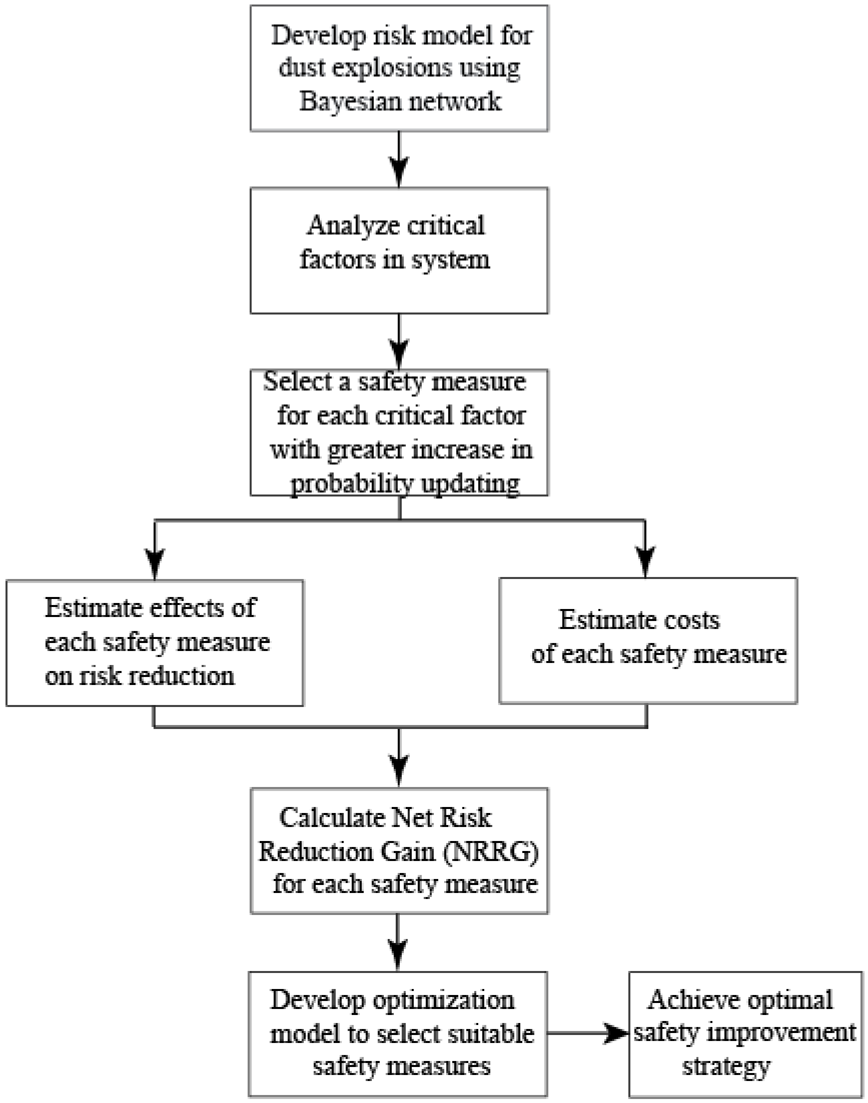

Fig. 7.3 Flow chart of the proposed optimization method

Step 1-Development of risk analysis model for dust explosions using Bayesian network:

Considering a specific case study, the generic BN developed in Figure 6.2 for risk analysis of dust explosions will be tailored by adding or eliminating factors to fit the case study of interest.

The dust explosion accident at CTA Acoustics, Inc. in Corbin, USA, in 2003 (CSB, 2005a) caused seven deaths and 37 injuries, and is chosen as an example to illustrate the methodology. According to the accident report provided by CSB (2005a), the phenolic resin dust was identified as the contributor for this accident. The dust explosion was triggered by the fire escaping through an open oven door and occurred in the area near the oven in line 405. It the risk model of the dust explosion is developed as shown in Figure 7.4.

Fig. 7.4 Risk model of CTA dust explosion

Most of the symbols appearing in Figure 7.4 are the same as those used in the generic model. Some alteration, however, is required to better represent the case study under consideration. For example, in the CTA Acoustics case, the ignition source might have been the fire caused by combustible materials in the oven of line 405. At the same time, as the oven door was improperly opened, the fire would have propagated from the oven to nearby spaces. To accurately depict this process, IE_{43}, standing for *Fire propagated from oven in line 405*, is added to the risk model as shown in Figure 7.4. This modification and other specific nodes for this case and their corresponding descriptions are listed in Table 7.3.

Table 7.3 Specific intermediate events added to the risk model of Figure 6.4

Symbol	Description
IE_{43}	Fire propagated from oven in line 405
IE_{44}	Accumulated combustible materials caught fire in oven
IE_{45}	Door of oven was improperly opened

Step 2- Analyze critical factors in system: As mentioned above, one of the advantages of BN is to utilize the latest known information (evidence) of some nodes to renew the probabilities of other nodes of a system. In this step, the occurrence of the critical event, i.e., dust explosion, is set as evidence. Then the probability of all contributing factors can be updated accordingly to yield posterior probabilities. Among these posterior probabilities, the factors with the highest values are considered as more important contributors to the dust explosion than others. Therefore, they should be given priority in safety improvement design. For this reason, the posterior probabilities of the CTA Acoustics dust explosion have been calculated, and the most important contributing factors are presented in Figure 7.5 and their descriptions are shown in Table 7.4 (column 2).

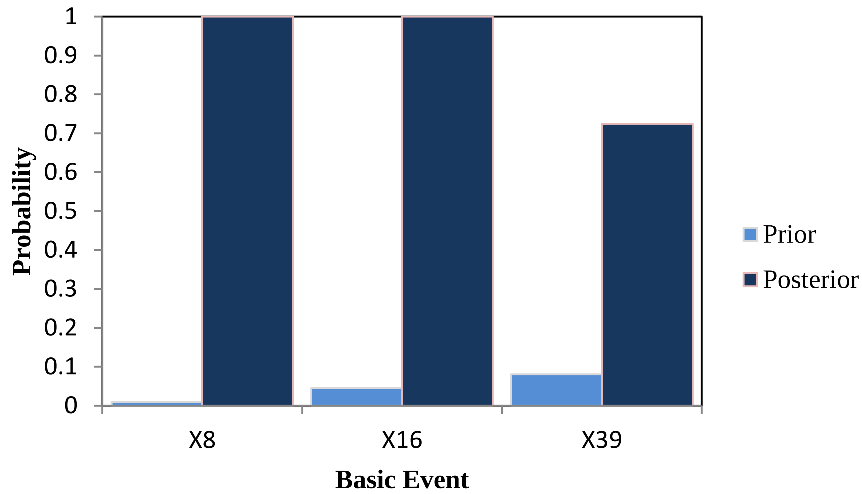

Fig. 7.5 Critical factors of CTA Acoustics dust explosion

Step 3- Selection of safety measures for critical factors: After obtaining the critical factors for the system, individual safety measures should be proposed according to suggestions made by experts. Some safety measures for each factor of the generic model of dust explosions have been recommended in our previous work (Yuan et al., 2013). In the case that more than one safety measure is suggested for a critical factor, the safety measures should be categorized first according to risk management principles. Priority should then be given to inherent, engineered and procedural safety measures in that order.

For the CTA Acoustics case, potential safety measures for each critical factor and the relevant categories are listed in Table 7.4:

Table 7.4 Safety measures for critical factors

Symbol	Description	Safety Measures	Category
X_8	Inadequate regular cleaning	Ensure combustible materials could be removed from oven in time	Inherent, Procedural
X_{16}	Not strictly applying relevant guideline	Strictly follow NFPA 654, NFPA 86 and CTA Acoustics incident investigation program	Procedural

X_{39}	Failure of excessive temperature controlling system	Install excessive temperature controller with higher reliability	Inherent
		Install new excessive temperature controller (same type)	Active Engineered
		Repair broken excessive temperature controller in time	Procedural

As shown in Table 7.4, three possible safety measures have been proposed for basic event X_{39} and classified into inherent, engineered and procedural safety, respectively (shown in dashed box). According to the recommended order of preference, the inherent safety measure, *Install excessive temperature controller with higher reliability*, is chosen as the safety measure for X_{39} together with the safety measures for X_8 and X_{16} as presented in Table 7.4.

Step 4- Estimate effects of safety measures on risk reduction: Risk can be defined as:

$$\text{Risk} = \sum_{i=1}^{n} P_i * L_i \qquad (7.2)$$

where P_i refers to the probability of the i-th consequence, and L_i stands for the corresponding losses, which are usually converted into equivalent financial losses.

Risk Reduction Index (RRI) is defined to represent the effect of a safety measure on the system risk:

$$RRI_i = {(R_b - R_{ai})}/{R_b} \qquad (7.3)$$

where R_b is the risk of the system before application of safety measures; R_{ai} is the risk of the system after the application of the i-th safety measure.

Thus, RRI_i must fall between 0 and 1. The closer to 1, the more efficient the i-th safety measure is with respect to risk reduction.

To obtain the RRI of each safety measure in the CTA Acoustics case, safety measure effects on either the probabilities of the basic events (Table 7.5) or those of the accident and potential consequences (Table 7.6) should be calculated.

Table 7.5 Probabilities of basic events with and without safety measures

Safety Measure	Without safety measure	With safety measure
X_8	0.010	$P(X8) = P(X8\|SM_{X8})P(SM_{X8}) + P(X8\|\overline{SM_{X8}})P(\overline{SM_{X8}})$ $= 0.01 * 0.01 + 0.005 * 0.99 = 0.005$
X_{16}	0.045	$P(X16) = P(X16\|SM_{X16})P(SM_{X16}) + P(X16\|\overline{SM_{X16}})P(\overline{SM_{X16}})$ $= 0.045 * 0.01 + 0.025 * 0.99 = 0.025$
X_{39}	0.080	$P(X39) = 0.040$ (new controller with higher reliability)

Table 7.6 Probabilities of critical events and consequences with and without safety measures

	Without safety measure	With SM_{X8}	With SM_{X16}	With SM_{X39}
Dust Explosion	4.97E-5	2.63E-5	2.78E-5	3.23E-5
Near Miss	*	*	2.50E-5	*
Significant Damage(Isolation Success)	4.57E-5	2.42E-5	2.56E-6	2.97E-5
Significant Damage(Evacuation Success)	3.58E-6	1.90E-6	2.00E-7	2.32E-6
Catastrophic Damage(Evacuation failure)	3.97E-7	2.11E-7	2.22E-8	2.58E-7

To calculate the RRI of each safety measure, the potential financial losses caused by the dust explosion are also estimated according to Table 7.2. For example, according to the description of a near miss in Table 7.2, the losses are mainly from the short term production interruption. Here, we assume the time for recovering a unit is one hour and the loss resulting from the production interruption is $850/hour. Therefore, the loss of a near miss equals $850. Similarly, the other losses for different categories of damage can be estimated for the CTA Acoustics case and the results are listed in Table 7.7.

Table 7.7 Potential losses of CTA Acoustics dust explosion

	Near Miss	**Significant Damage (Isolation success)**	**Significant Damage (Evacuation success)**	**Catastrophic Damage (Evacuation fail)**
Dollar value equivalent ($)	850	7 000 000	50 000 000	170 000 000

Then, based on Equation (7.4), the risk before application of safety measures can be calculated as:

$$R_b = 4.57e-5*7000000+3.58e-6*50000000+3.97e-7*170000000=566.320$$

Similarly, the risk after the application of a certain safety measure and the corresponding RRI can be obtained (Table 7.8).

Table 7.8 Risk after application of safety measures and RRI

Safety measure	**Risk after application of safety measure**	**RRI**
SM_{X8}	300.270	0.470
SM_{X16}	31.715	0.944
SM_{X39}	367.760	0.351

Step 5- Estimate cost of each safety measure: In this research, fixed cost and regular operation cost are estimated to form an Operation and Fixed Cost (OFC) index as expressed by Equation (7.4):

$$\mathrm{OFC} = \text{fixed cost} + \text{regular operation cost} \qquad (7.4)$$

For safety measures requiring additional equipment, such as installation of fire extinguishing equipment in the system, the fixed cost refers to the expense for purchasing equipment and regular operation cost mainly includes the costs of installation, personnel training for new equipment, and regular maintenance.

For different types of safety measures, expenditure on equipment and on operation presents different characteristics. For example, for safety measures relying on management, the majority of the cost is due to regular operation. For example, the cost of the safety measure *taking safety training to enforce consciousness for combustible dust hazards* is mainly used for organizing safety training and hiring safety trainers. However, for safety measures involving additional equipment, the fixed cost might be much higher than the operation cost. Compared to the fixed cost of equipment, the cost of operation will accompany each operation and maintenance procedure. A typical example is the installation of suppression systems. After purchasing the equipment, maintenance and training might continue throughout the equipment's lifetime. The fixed cost of equipment can usually be readily obtained from suppliers. Operation cost should be further analyzed for individual cases.

Cost potential index (C_i) of safety measure i can be expressed as:

$$C_i = OFC/C_B \qquad (7.5)$$

where C_B stands for the budget allocated for the safety strategy.

According to this definition, C_i of a suitable safety measure should be between 0 and 1. If $C_i>1$; then, the cost of a given safety measure is beyond the budget, which means the safety measure must be excluded from the potential safety measure list. The closer to 0, the less amount of the budget the safety measure costs.

To better represent the usage of the methodology, assuming the budget for safety improvement at CTA Acoustics is $23000 (because of less than this number, this optimal problem will be simplified as an either-or question, either SM_{X8} and SM_{X39} or SM_{X16} and SM_{X39}.). Then OFC and C_i for each safety measure can be calculated respectively (Table 7.9).

Table 7.9 OFC and C_i of safety measures

Safety Measure	Fixed cost	Operation cost	OFC	C_i
SM_{X8}	0	$8000	$8000	0.348
SM_{X16}	$2000	$13000	$15000	0.652
SM_{X39}	$1500	$3000	$4500	0.196

Step 6- Calculate Net Risk Reduction Gain of each safety measure: Net Risk Reduction Gain (NRRG) index of safety measure i is also defined in this work as:

$$NRRG_i = \omega_1 * RRI_i - \omega_2 * C_i \qquad (7.6)$$

Where ω_i is a weighting factor indicating the importance of a particular objective estimated by decision makers. It should be noted that $\omega_1 + \omega_2 = 1$.

The net gain of risk reduction brought about by safety measure i will be reduced, because the high cost of safety measure i might make an analyst hesitate to apply the safety measure.

In the CTA Acoustics case, assuming that both risk reduction and cost are of the same importance would result in ω_1=ω_2=0.5. Table 7.10 presents the results for NRRG calculation.

Table 7.10 NRRG of safety measures

	SM_{X8}	SM_{X16}	SM_{X39}
NRRG	0.061	0.146	0.078

Step 7- Develop optimization model to select suitable safety measure: The objective is to maximize the sum of $NRRG_i$; that is, the net gain of risk reduction should be the greatest after the application of the optimal safety strategy under the constraint of the limited available budget, which appears to be a typical knapsack problem. So the objective and constraint functions can be established as:

$$\text{Max}Z = \sum_{j=1}^{n} NRRG_j x_j \qquad (7.7)$$

$$\text{s.t.} \begin{cases} \sum_{j=1}^{n} C_j x_j \leq C_B \\ x_j = 0 \text{ or } 1 \qquad (j = 1, \ldots, n) \end{cases}$$

where C_j is the cost of safety measure j, and C_B is the budget for safety improvement. When safety measure j is chosen, x_j equals 1. Otherwise, x_j equals 0.

The objective and constraint functions can be developed for the CTA Acoustics case as:

$$\text{Max}Z = \sum_{j} NRRG_j x_j \text{ for j=8, 16, and 39} \qquad (7.8)$$

$$\text{s.t.} \begin{cases} \sum_{j} C_j x_j \leq 23000\$ \\ x_j = 0 \text{ or } 1 \qquad (\text{for } j = 8, 16, \text{and } 39) \end{cases}$$

Solving the above set of equations, the results will be x= (0, 1, 1), which means SM_{X8} will not be considered while SM_{X16} and SM_{X39} should be taken into account in an optimal safety strategy. As a result, the maximum net risk reduction 0.2235 will be gained while satisfying the financial constraints.

7.4 Case study

7.4.1 Introduction

To further illustrate the application of the methodology, the dust explosion at Hayes Lemmerz International-Huntington, Inc. Indiana, USA, in 2003 (CSB, 2005b) is considered. According to the investigation report, this accident "occurred in the scrap reprocessing area, destroyed the dust collection system outside the building, lifted a portion of the building roof above one furnace and ignited a fire for several hours"(CSB, 2005b). CSB (2005b) concluded this explosion might have originated in the dust collector and propagated to the drop box, then traveled to Furnace 5 and ignited accumulated dust in the vortex box. The layout of the equipment is shown in Figure 7.6.

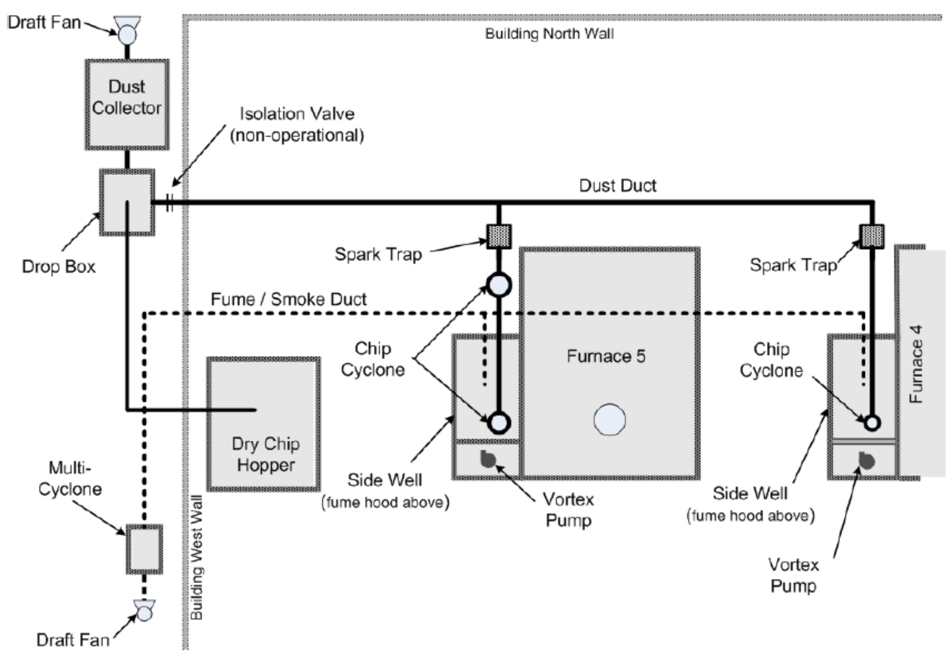

Fig. 7.6 Layout of equipment (CSB, 2005b)

7.4.2 Optimal safety measures allocation for Hayes Lemmerz dust explosion

The risk analysis model given in Figure 7.7 for the dust explosion at Hayes Lemmerz was established using the generic model and using the details in CSB (2005b). The corresponding symbols appearing in this model and their descriptions can be found in

Tables 5.1 and 5.2.

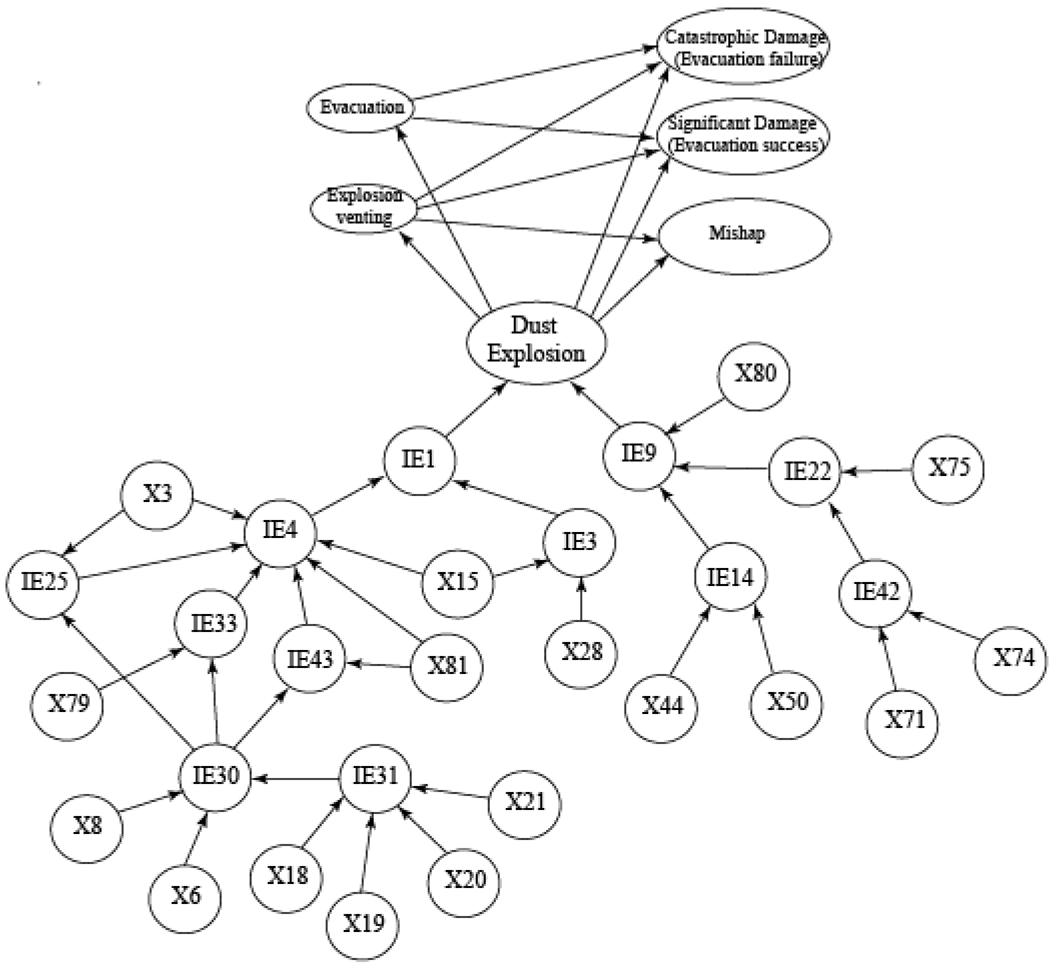

Fig. 7.7 Risk analysis model of dust explosion for Hayes Lemmerz

Most of the symbols in Figure 7.7 are the same as those presented in the generic model in Figure 6.2. However, some new nodes have been added, and small changes have been made to tailor the generic model to fit this specific case study. For example, the basic event *chemical reaction between rusty tramp metal and aluminum dust* is suspected as one of the likely ignition sources for this accident (CSB, 2005b). Therefore, this event is added to the model as X_{80} as shown in Figure 7.7. Likewise, *lack of vibratory separator at dryer outlet*, X_{81}, which leads to *dust accumulation on surfaces inside vortex box, side well and fume* *hood*, IE_{43}, are added to the model accordingly.

Based on the above risk analysis model for Hayes Lemmerz, the occurrence of the dust explosion is set as evidence to update prior probabilities of all the basic events (Columns 3 and 7 in Table 7.11).

The increased ratio can be simply calculated as: $\text{Increased ratio} = (\text{Posterior} - \text{Prior}) / \text{Prior}$. Results are listed in Columns 4 and 8 of Table 7.11.

It can be seen that all posterior probabilities are greater than the respective prior probabilities. Basic events with the highest increased ratios and higher posterior values are assumed to have made a greater contribution to the dust explosion and are thus selected as critical factors that need to be improved (shown in bold type in Table 7.11).

Table 7.11 Prior and Posterior Probabilities of Basic Events

Symbol	Prior	Posterior	Increased Ratio	Symbol	Prior	Posterior	Increased Ratio
X3	**0.010**	**0.01428**	**0.428**	**X44**	**0.050**	**0.08077**	**0.615**
X6	0.033	0.03308	0.002	**X50**	**0.045**	**0.07594**	**0.688**
X8	0.010	0.01002	0.002	X71	0.005	0.00728	0.456
X15	**0.100**	**0.95547**	**8.555**	**X74**	**0.300**	**0.43694**	**0.457**
X18	0.033	0.03308	0.002	**X75**	**0.045**	**0.23496**	**4.221**
X19	0.090	0.09022	0.002	X79	0.0078	0.00873	0.119
X20	0.100	0.10024	0.002	**X80**	**0.050**	**0.76825**	**14.365**
X21	0.050	0.05012	0.002	**X81**	**0.083**	**0.11856**	**0.428**
X28	**0.055**	**0.09708**	**0.765**				

Having identified the critical factors, relevant safety measures for each critical factor are proposed, as listed in Table 7.12.

As can be seen from Table 7.12, there could be more than one potential safety measure allocated to critical event X_{28} (shown in dashed box). Based on the proposed risk management principles, the safety measure *Install new isolation equipment* belongs to the category of active engineered safety measures. Thus, compared to the other two procedural safety measures, i.e., *Conduct safety training to ensure correct installation of isolation devices* and *Conduct regular inspection*, the engineered safety measure is given priority, and is selected as the potential safety measure for X_{28}. Further, it can be observed that if a magnetic separator is installed in the system, probabilities of impact sparks caused by tramp metal and chemical reaction between rusty tramp metal and aluminum powders could be reduced at the same time. Thus, for these two critical events, the same safety measure is adopted.

Table 7.12 Safety measures for potential optimization objects

Symbol	Safety Measure	Symbol	Safety Measure
X_3	Clean up accumulated dust at filter	X_{74}	Enforce housekeeping or maintenance of fume hood to reduce deposits
X_{15}	Improve structure of dust collector system and ensure it meets NFPA requirements	X_{75}	Install proper covers to reduce ingress of embers
X_{28}	**Install new isolation equipment** Conduct safety training to ensure correct installation of isolation devices Conduct Regular inspection	X_{80}	Install magnetic separators at inlet to remove rusty tramp metal
X_{44}	Install magnetic separators at inlet to remove tramp metal	X_{81}	Install vibratory separator at dryer outlet
X_{50}	Install spark box		

To seek the effect of chosen safety measures on the critical events (see Table 7.13), probabilities of these critical events are considered before and after implementation of the safety measures, as shown in Table 7.13.

Table 7.13 Effects of safety measures on critical events

Safety Measure	Probabilities without safety measures	Probabilities of basic events with safety measures
X_3	0.010	$P(X_8) = P(X_3\|SM_{X3}) * P(SM_{X3}) + P(X_3\|\overline{SM_{X3}}) * P(\overline{SM_{X3}})$ $= 0.01 * 0.06 + 0.005 * 0.94 = 0.005$
X_{15}	0.100	$P(X_{15}) = P(X_{15}\|SM_{X15}) * P(SM_{X15}) + P(X_{15}\|\overline{SM_{X15}}) * P(\overline{SM_{X15}})$ $= 0.1 * 0.01 + 0.02 * 0.99 = 0.021$
X_{28}	0.055	$P(X_{28}) = 0.05$ (Equal to the reliability of new isolation equipment)
X_{44}	0.050	$P(X_{44}) = P(X_{44}\|SM_{X44}) * P(SM_{X44}) + P(X_{44}\|\overline{SM_{X44}}) * P(\overline{SM_{X44}})$ $= 0.05 * 0.08 + 0.02 * 0.92 = 0.022$
X_{50}	0.045	$P(X_{50}) = P(X_{50}\|SM_{X50}) * P(SM_{X50}) + P(X_{50}\|\overline{SM_{X50}}) * P(\overline{SM_{X50}})$ $= 0.045 * 0.05 + 0.03 * 0.95 = 0.031$
X_{74}	0.300	$P(X_{74}) = P(X_{74}\|SM_{X74}) * P(SM_{X74}) + P(X_{74}\|\overline{SM_{X74}}) * P(\overline{SM_{X74}})$ $= 0.3 * 0.06 + 0.1 * 0.94 = 0.112$
X_{75}	0.045	$P(X_{75}) = P(X_{75}\|SM_{X75}) * P(SM_{X75}) + P(X_{75}\|\overline{SM_{X75}}) * P(\overline{SM_{X75}})$ $= 0.045 * 0.2 + 0.03 * 0.8 = 0.033$
X_{80}	0.050	$P(X_{80}) = P(X_{80}\|SM_{X80}) * P(SM_{X80}) + P(X_{80}\|\overline{SM_{X80}}) * P(\overline{SM_{X80}})$ $= 0.05 * 0.08 + 0.02 * 0.92 = 0.022$
X_{81}	0.083	$P(X_{81}) = P(X_{81}\|SM_{X81}) * P(SM_{X81}) + P(X_{81}\|\overline{SM_{X81}}) * P(\overline{SM_{X81}})$ =0.083*0.04+ 0.04*0.96=0.042

Comparing the probabilities (columns 2 and 3 in Table 7.13), the influence of each safety measure on the reduction of both dust explosion likelihood and potential consequences can be calculated and is presented in Table 7.14.

Table 7.14 Probabilities of dust explosion and potential consequences with and without safety measures

	Without SM	With SM_{X3}	With SM_{X15}	With SM_{X28}	With SM_{X44}/ SM_{X80}	With SM_{X50}	With SM_{X74}	With SM_{X75}	With SM_{X81}
Dust Explosion	6.81E-3	6.80E-3	1.68E-3	6.78E-3	3.84E-3	6.74E-3	5.98E-3	6.45E-3	6.68E-3
Mishap	6.23E-3	6.24E-3	1.54E-3	6.22E-3	3.52E-3	6.18E-3	5.48E-3	5.92E-3	6.13E-3
Significant damage (Isolation success)	-	-	-	5.35E-4	-	-	-	-	-
Significant damage (Evacuation success)	5.08E-4	5.08E-4	1.26E-4	2.53E-5	2.87E-4	5.04E-4	4.47E-4	4.82E-4	4.99E-4
Catastrophic damage	5.64E-5	5.64E-5	1.40E-5	2.82E-6	3.19E-5	5.60E-5	4.96E-5	5.35E-5	5.55E-5

Besides the likelihood reduction, another consequence with less damage, *Significant damage (Isolation success)*, is added to the model as a potential consequence when SM_{X28} is implemented.

In order to calculate the risk reduction index (RRI), the potential financial loss of each consequence is estimated according to CSB (2005b) (Table 7.15).

Table 7.15 Losses of consequences

	Mishap	Significant Damage (Isolation Success)	Significant Damage (Evacuation Success)	Catastrophic Damage (Evacuation Fail)
Dollar Valve Equivalent ($)	1000	500 000	1 000 000	50 000 000

Then, the risk of the dust explosion without the safety measures can be calculated as:

$$\text{RISK} = \sum_{i=1}^{n} P_{ci} * L_i = 6.23E-3*1000 + 5.08*10E-4*1000000 + 5.64E-5*50000000$$
$$= 3334.230$$

It should be noted that the risk of an accident could be reduced not only by adding safety barriers into the system to reduce the probabilities of the consequences (using preventive safety measures such as X_{28}) but also by reducing the severities of the potential consequences (using mitigative safety measures). For example, if SM_{X3}-*Clean up accumulated dust at filter*- functions, the amount of accumulated dust at the filter will decrease. Thus, even if a dust explosion occurs in the filter, its damage to the dust collector and to the entire dust collecting system will be reduced. This could decrease the severity of Mishap and Significant damage (Evacuation success). For illustrative purposes, assume 60% of damage of the consequences Mishap and Significant damage (Evacuation success) can be reduced by decreasing the amount of accumulated dust. Therefore, the risk after applying SM_{X3} can be calculated as:

$$\text{RISK} = \sum_{i=1}^{n} P_{ci} * L_i$$

$$= 6.23E - 3 * 1000 * 0.4 + 5.08 * 10E - 4 * 1000000 * 0.4 + 5.64E - 5 * 50000000$$

$$= 3026.614$$

Similarly, the risk after application of other safety measures can be calculated as presented in Table 7.16.

Table 7.16 Risk of dust explosion with and without safety measures

Without SM	**With SM_{X3}**	**With SM_{X15}**	**With SM_{X28}**	**With SM_{X44}/Smx80**	**With SM_{X50}**	**With SM_{X74}**	**With SM_{X75}**	**With SM_{X81}**
3334.230	3026.614	749.438	440.011	1885.524	3307.182	2664.580	3164.715	2978.267

According to the Risk Reduction Index (RRI) equation, RRI of SM_{X3} can be calculated as:

$$RRI_{SM_{X3}} = \frac{3334.230 - 3026.614}{3334.230} = 0.092$$

Thus, the RRI for each safety measure can be calculated (Figure 7.8).

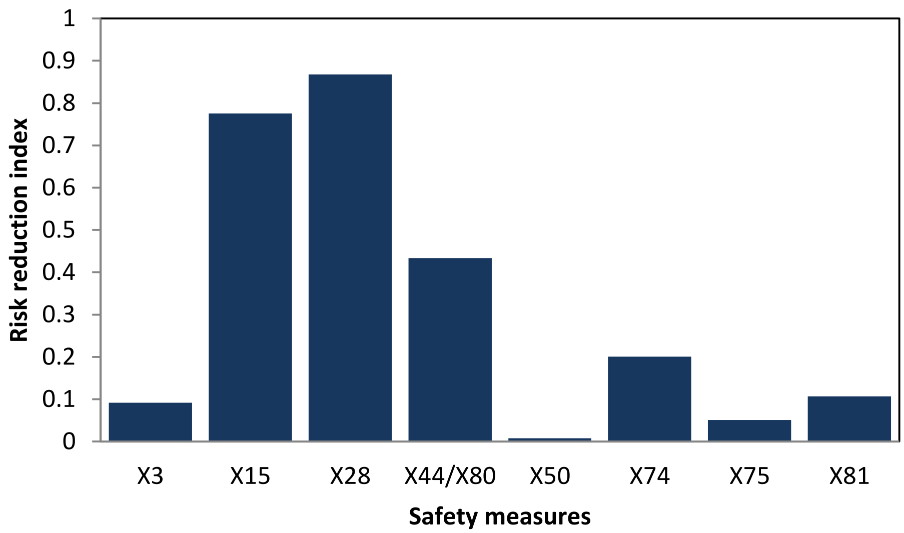

Fig. 7.8 Risk reduction index of various safety measures

The next step is to estimate the cost of each potential safety measure (Table 7.17), including fixed cost and regular operation cost, according to suppliers and experts. Based on the definitions of Operation and fixed cost (OFC) and cost potential index (C_i), both parameters can be calculated for each safety measure (Columns4 and 5of Table 7.17) when the budget for safety improvement is assumed as $80,000.

Table 7.17 Operation and fixed cost of safety measures

Safety Measure	Fixed Cost	Operation Cost	OFC	C_i
SM_{X3}	0	$5760	$5760	0.072
SM_{X15}	$20000	$30000	$50000	0.625
SM_{X28}	$2000	$1000	$3000	0.038
SM_{X44}	$10000	$1000	$11000	0.138
SM_{X50}	$400	$400	$800	0.010
SM_{X74}	0	$1920	$1920	0.024
SM_{X75}	$10000	$300	$10300	0.129
SM_{X81}	$10000	$1000	$11000	0.138

In this case, risk reduction caused by application of a safety measure is assumed to be as important as its cost when selecting a safety measure. Therefore, $\omega_1=\omega_2=0.5$. Then, NRRG of each safety measure can be calculated (Table 7.18).

Table 7.18 NRRG of safety measures

SM_{X3}	SM_{X15}	SM_{X28}	$SM_{X44/X80}$	SM_{X50}	SM_{X74}	SM_{X75}	SM_{X81}
0.011	0.075	0.415	0.149	0.000	0.089	-0.038	-0.014

Thus, the objective and constraint functions for this case can be established as:

$$\mathrm{Max}\,z = \sum_j \mathrm{NRRG}_j x_j$$

$$\text{s.t.}\begin{cases} & \sum_j C_j x_j \leq \$80000 \\ x_j = 0 \ or \ 1 & (j = 3, 15, 28, 44/80, 50, 74, 75, 81) \end{cases}$$

The optimal solution is calculated as: X=(1,1,1,1,1,1,0,0).

This means SM_{X3}, SM_{X15}, SM_{X28}, $SM_{X44/X80}$, SM_{X50} and SM_{X74} should be considered as required safety measures in the safety strategy under this pre-defined budget. By this safety strategy, the net risk reduction gain for this system can be maximized.

7.4.3 Sensitivity analysis

An optimal safety strategy is decided by various factors, such as budget and weighting factors. As a result, this methodology can be applied to a variety of situations to search for optimal safety strategies. A higher budget means more financial resources are available and this could affect the NRRG index of each safety measure. Therefore, a safety strategy decision is inevitably influenced by the amount of the budget. In this work, changes in risk with different safety strategies under different budgets are analyzed (Figure 7.9).

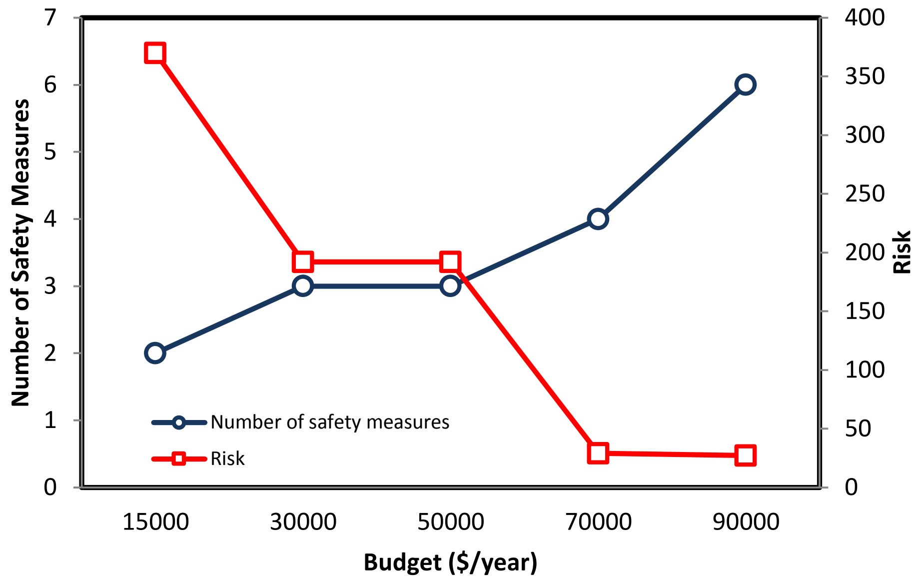

Fig. 7.9 Number of safety measures and risks under different budgets

As can be seen from Figure 7.9, with an increase in budget, the number of safety measures in the safety strategy can also increase. For example, the safety measures number in the safety strategy increases from 2 to 6 when the budget increases from \$15000/year to \$90000/year. The role of a budget increase is twofold: firstly, the higher budget can lead to lower C_i, which means a less negative influence is caused by the cost of safety measures in calculation of the NRRG index, and secondly, the higher budget implies the relaxation of financial constraints. For example, when the budget is \$20000/year, the safety measure of X_{15} is obviously excluded. However, when the budget increases to \$80000/year, the safety measure X_{15} is considered as an alternative safety measure in the safety strategy. At the same time, risks under different safety strategies are decreased with increases in budget. However, it also can be seen that this decreasing tendency of risk does not mean that the larger the financial investment, the better. As shown in Figure 7.9, risk decreases from 29 to 27.1 with increasing the budget from

$70000/year to $90000/year. Compared with the increased amount of financial investment, the risk slightly declined, which means that it may not be economically justifiable to go beyond a $70000/year budget for a lower risk.

Besides the influence of a budget on the selection of safety measures, the cost of safety measures will also affect the process of decision-making. For example, increasing the frequency of cleaning of the dust collector, safety measure for X_3, will lead to higher expenditure in terms of human resources. Considering that the costs of SM_{X3} with different cleaning frequencies will increase from $5760/year to four hypothetical costs of $6260/year, $6760/year, $7260/year and $7760/year, via the safety measures optimization method, optimal safety strategies under these different costs are calculated for SM_{X3} (Table 7.19),

Table 7.19 Safety strategy with different costs of SM_{X3}

Cost (per year)	SM_{X3}	SM_{X15}	SM_{X81}	SM_{X28}	$SM_{X44/X80}$	SM_{X50}	SM_{X74}	SM_{X75}	SM_{X80}
$ 5760	×	×		×	×	×	×		×
$ 6260	×	×		×	×	×	×		×
$6760	×	×		×	×	×	×		×
$7260	×	×		×	×	×	×		×
$7760		×		×	×	×	×		×

When the cost of SM_{X3} increases from $7260/year to $7760/year, SM_{X3} is excluded from the optimal safety strategy and the risk increases from 27.1 to 27.6. This shows that estimation of the cost of safety measures will influence the safety strategy decision and also the risk level of the system. The reason is the higher cost could bring a higher value of C_i and thus reduce the NRRG of the safety measure.

RRI is another important factor influencing safety strategy decision-making. According to the above analysis, it is already known that SM_{X3} is included in the safety strategy under a budget of $80000/year. Now, considering five different values for the RRI of SM_{X3} as 0.094, 0.085, 0.080, 0.075 and 0.070 (only for the purpose of representing the influences of different RRIs on the allocation of safety strategy), the optimal safety strategy is obtained by using the optimization method (Table 7.20).

Table 7.20 Safety strategy with different risk reduction index of SM_{X3}

RRI	SM_{X3}	SM_{X15}	SM_{X28}	$SM_{X44/X80}$	SM_{X50}	SM_{X74}	SM_{X75}	SM_{X80}	SM_{X81}
0.094	×	×	×	×	×	×		×	
0.085	×	×	×	×	×	×		×	
0.080	×	×	×	×	×	×		×	
0.075	×	×	×	×	×	×		×	
0.070		×	×	×	×	×		×	

As shown in Table 7.20, SM_{X3} is removed from the safety strategy when the respective RRI decreases to 0.070, showing the role of the RRI index in the final decision. This also results from the lower NRRG caused by the smaller RRI.

As mentioned earlier, the weighting indices ω_1 and ω_2 are introduced into the calculation of the NRRG index of safety measures to represent decision-makers' estimation of the importance of RRI and C_i, respectively. Therefore, the emphasis of analysts on RRI or C_i could also impact the decision about the optimal safety strategy. Safety strategies under different combinations of the weighting index are presented in Table 7.21.

Table 7.21 Safety strategy of different estimation of weighting index

	Category	SM_{X3}	SM_{X15}	SM_{X28}	$SM_{X44/X80}$	SM_{X50}	SM_{X74}	SM_{X75}	SM_{X81}
1	$\omega_1=0.9, \omega_2=0.1$		×	×	×	×	×		×
2	$\omega_1=0.7, \omega_2=0.3$	×	×		×		×		×
3	$\omega_1=0.5, \omega_2=0.5$	×	×	×	×	×	×		
4	$\omega_1=0.3, \omega_2=0.7$			×	×		×		
5	$\omega_1=0.1, \omega_2=0.9$			×					

It should be noted that the number of safety measures decreases with increasing the weighting index ω_2. For example, when ω_2 increases from 0.1 to 0.9, the number of safety measures in the optimal strategy decreases from 6 (category 1) to 1 (category 5). Moreover, the changes of importance indices can greatly influence compositions in safety strategy. For example, although the number of safety measures under category 1 and 3 both equal 6, their corresponding members are different. For category 1, the safety strategy is constituted by SM_{X15}, SM_{X28}, $SM_{X44/X80}$, SM_{X50}, SM_{X74} and SM_{X81}. However, the members of the safety strategy change to SM_{X3}, SM_{X15}, SM_{X28}, $SM_{X44/X80}$, SM_{X50}, SM_{X74} when both $\omega_1$and ω_2 are estimated as 0.5. The higher ω_2 implies that decision makers treat C_i as a more important factor than RRI in calculation of the NRRG index. Hence, the higher cost could notably depress the desire of a safety engineer to apply the respective safety measure. The effects of weighting factors on NRRG of the same safety measure are shown in Table 7.22 (the second row). One extreme situation is the case in which only the risk reduction is considered by decision makers, i.e., $\omega_1 = 1.0$ and $\omega_2 = 0.0$. Then the optimization model is simplified to maximize the risk reduction brought by safety measures under the budget constraint.

Table 7.22 NRRG of $SM_{X3}$and Risks under different estimations of importance indices

	ω_1=0.9,ω_2=0.1	ω_1=0.7,ω_2=0.3	ω_1=0.5,ω_2=0.5	ω_1=0.3,ω_2=0.7	ω_1=0.1,ω_2=0.9
NRRG	0.077	0.044	0.011	-0.022	-0.055
Risk	25.739	303.082	27.265	173.079	440.021

Finally, dust explosion risks can be affected by different safety strategies under different combinations of importance indices (Table 7.22, the third row). The results show that the risk reduction of the system brought about by an optimal safety strategy depends on the estimation of importance indices by decision makers.

7.5 Conclusions

When considering the safety improvement of process plants, the most efficient allocation of limited financial resources to available safety measures becomes very challenging. The issue becomes even more complicated in the case of dust explosions due to the large number of contributing factors and interlinked correlations. To efficiently utilize budgets for risk reduction of dust explosions, a risk-based optimization approach for optimal allocation of safety measures has been proposed in this paper. In this approach, the most critical factors contributing to dust explosions can be identified using a Bayesian network generic risk model developed for this purpose. This way, not only a smaller number of potential factors would need to be considered in safety improvement strategies, but also an efficient allocation of limited financial resources to the most vulnerable parts of the system would be possible. Further, the dust explosion generic Bayesian network facilitates the quantification of the safety measures' effects on risk reduction, relaxing the need for experts' estimations or qualitative risk ranking methods such as a risk matrix. In the present work we applied a knapsack–based formulation in optimization so that the optimal safety strategy can be easily obtained using conventional solvers. Applying the developed methodology to a dust explosion that occurred at Hayes Lemmerz International, US, in 2003, it was demonstrated that the developed optimal safety strategy is able to efficiently reduce the risk of dust explosions under a limited budget. However, since our methodology relies on a generic Bayesian network risk model developed for dust explosions, minor changes would be made to tailor the generic risk model to a dust explosion of interest, demanding knowledge by the analyst of the dust explosion under consideration as well as constraints.

Acknowledgments

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8 Domino Effect Analysis of Dust Explosions Using Bayesian Networks

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Preface

This manuscript about domino effects of dust explosions has been submitted to the journal of Reliability Engineering & System Safety. Under supervision of co-authors, Dr(s) Khakzad, Khan, and Amyotte, the principal author developed the model and relevant research on the entitled topic. The co-authors also reviewed the methodology and proposed valuable and necessary suggestions and corrections to improve the quality of the manuscript.

Abstract

In most dust explosion accidents, a series of explosions constituting a primary (dust) explosion and one or more subsequent secondary dust explosions has been reported. Such chains of related dust explosions can be referred to as dust-explosion domino effects. Dust-explosion domino effects are capable of causing severe damage to humans, assets, and the environment both on-site and off-site. Thus, a detailed understanding of the causes, consequences, probabilities, and escalation of such domino effects is of great importance for protecting humans and assets. In this research, we have proposed a methodology for modeling and probability estimation of a chain of dust explosions based on Bayesian networks. The application and efficacy of the proposed methodology have been demonstrated via a real case study, CTA Acoustics, in the U.S. in 2003.

Keywords: Dust explosion; Domino effect; Bayesian network.

8.1 Introduction

A domino effect is a chain of unintended events in which a primary event triggers secondary events, the total consequences of which are much more severe than the primary event in terms of human and asset losses (Reniers and Cozzani, 2013). In most process plants, a number of major hazardous installations (MHIs) are located and are operating in a limited space. Because of the flammability and explosibility of the contained chemical substances which are usually stored, processed or transported under high pressure and high temperature conditions, a primary accident is likely to lead to a domino effect. The presence of numerous flow conduits and conveying systems in chemical plants further facilitates the propagation of accidents and ensuing physical effects such as fire, flames and overpressure among separate MHIs, thus increasing the probability of domino effects. A variety of safety measures such as internal safety distances has been proposed to reduce the likelihood of domino effects (National Fire Prevention Association (NFPA), 2012); however, in many cases, the implementation of such safety barriers would be difficult due to the inherent restrictions of complex industrial processes such as limited land available.

Among domino effects, dust-explosion-induced domino effects (hereafter called dust domino effects) have drawn less attention due to either complex cause-consequence relationships or the complicated escalation probabilities involved. Combustible dust is widely involved in process industries either as raw production materials or byproducts. It can be found in the form of raw materials such as cotton in textile mills, intermediate products such as synthetic resin powders in plastic product manufacturers, or as byproducts such as aluminum dust in casting forges. Combustible dust can be easily suspended in the air and cause a dust explosion if ignited. Reports on dust explosions and the huge harm and damage to humans, assets and the environment are commonly seen in the media (Eckhoff, 2009; Ebadat and Prugh, 2007; Piccinini, 2008; Wang and Li, 2001). Recently, a metal dust explosion at AL Solutions, U.S. in 2010 resulted in three deaths and one injury (U.S. Chemical Safety Board (CSB), 2011).

The mechanisms of dust explosions have widely been studied (Eckhoff, 2003; Amyotte et al., 2005; Cashdollar and Zlochower, 2007; Pilão et al., 2006; Di Benedetto, et al., 2010) and a variety of preventive and mitigating safety measures has been proposed (Amyotte et al., 2009; Amyotte et al., 2010; Myers, 2008; Holbrow, 2013; Liu et al., 2013). Recently, methods of quantitative risk assessment (QRA) have been applied to estimate the risk of dust explosions (van dert Voort et al., 2007; Yuan et al., 2013, 2015; Khakzad et al., 2012).

Nevertheless, the attempts made to assess dust domino effects have been very few (van dert Voort et al., 2007). The present work aims to develop a methodology for modeling and estimating the probability of dust domino effects using the Bayesian network (BN). BN has successfully been employed to model domino effects triggered by fires and explosions (other than dust explosions) (Khakzad et al., 2013, 2014, 2015). However, to the best knowledge of the authors, the present study is the first work devoted to the application of BN for modeling dust domino effects.

This paper is organized as follows: Section 8.2 briefly explains the mechanism of dust explosions and introduces the basis of dust domino effects. In Section 8.3, a BN methodology is developed to model and assess the likelihood of dust domino effects. The application of the methodology is demonstrated using a case study in Section 8.4. The conclusions drawn from this work are presented in Section 8.5.

8.2 Background

8.2.1 Dust explosion mechanism

Combustible dust, oxidant, mixing, ignition and confinement are determined as essential factors for a dust explosion as shown in Figure 3.1 (Eckhoff, 2003, 2009; Pilão et al, 2006; Abbasi and Abbasi, 2007; Amyotte and Eckhoff, 2010; Kauffman, 1982). When all these factors coexist, a dust explosion will happen.

Combustible dust in Figure 3.1 can be produced from natural organic materials (e.g., grain, coal and peat), synthetic organic materials (e.g., plastics), or metals (e.g., aluminium powder) (Eckhoff, 2003). Oxidant mainly refers to the oxygen in the air. Mixing refers to the deposited combustible dust suspended in the air by, for example, improper housekeeping methods or pressure waves from falling objects or explosions. Ignition source includes but is not limited to impact sparks, flames, and hot surfaces (Abbasi and Abbasi, 2007). For a rapid and violent combustion and energy build-up, confinement is an essential factor in dust explosions. In summary, a dust explosion will occur when combustible dust which has been suspended in a confined space meets an adequate ignition source. Nevertheless, dust explosibility can be influenced by various factors such as the minimum ignition temperature (MIT) and the minimum ignition energy (MIE). MIT is the temperature above which a combustible dust cloud be ignited. A higher MIT (°C) indicates the mixture of combustible dust and oxygen is more difficult to ignite and thus less likely to cause a dust explosion. MIE (mJ), likewise, expresses the minimum energy required to ignite a combustible dust suspension. The severity of a dust explosion can be represented using the maximum explosion pressure (P_{max}) or the normalized maximum rate of pressure rise (K_{St}) (Hassan, 2014).

Compared to other types of explosion, a dust explosion usually leads to greater damage because of higher pressure and temperature generated (Eckhoff, 2003). For example, the experimental results of dust explosions with various combustible dusts in the standard 1m^3 ISO vessel or in the 20-L Siwek sphere show the value of P_{max} ranging from 8.0 bar(g) to 10.4 bar(g) (Hassan et al., 2014). However, similar experiments for methane-air explosions show the values of P_{max} around 8.0 bar(g) (Razus et al., 2006). Aside from more destructive overpressures generated by dust explosions, toxic gases produced from dust explosions can cause even more casualties. For example, in polyvinylchloride dust explosions, hydrogen chloride gases can be produced, leading to pulmonary edema in exposed workers (Eckhoff, 2003).

8.2.2 Domino effects of dust explosions

The mechanism of a dust domino effect is shown in Figure 8.1. The dust explosion chain originates from a primary explosion (not necessarily a dust explosion). If the blast wave generated by the primary explosion is able to suspend settled dust layers and form a combustible dust cloud, it is very likely that a secondary dust explosion will take place. As mentioned earlier, the occurrence likelihood of such a secondary dust explosion also depends on the presence of an ignition source with adequate MIT or MIE. Compared to the primary dust explosion, the secondary dust explosion(s) can cause more severe consequences due to larger quantities of combustible dust involved (Lees, 2005).

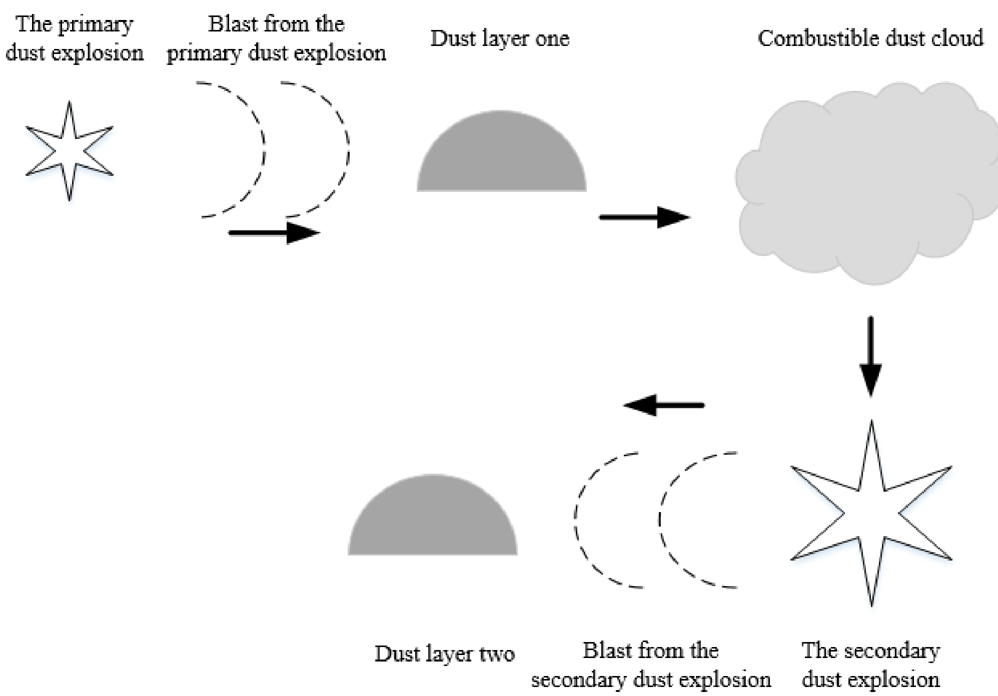


Fig. 8.1 Dust domino effects mechanism

As the primary and secondary dust explosions could occur in different units of a process plant, safety barriers are difficult to implement between different hazardous units to block the propagation of pressure and flames in different units in case of a primary explosion. A typical example is the phenolic resin dust explosion at CTA Acoustics, Inc., U.S. in 2003 (CSB, 2005a). The initial dust explosion occurred at production line 405 while another dust explosion took place at line 401, more than 80 ft (24.38 m) away from the initial explosion. Another case is the aluminum dust explosion at Hayes Lemmerz International-Huntington, Inc., U.S., where a primary dust explosion in the aluminum dust collector located outside of the building propagated through ducts and caused a secondary dust explosion around furnace 5 in the workshop (CSB, 2005b), due to the lack of an explosion isolation device between the dust collector and the connected units.

For illustrative purposes, consider a process plant in Figure 8.2 where A_1, A_2, and A_3represent the units susceptible to dust explosions whereas B_1 and B_2 are the units for which a pool fire and vapor cloud explosion (VCE), respectively, have been determined as dominant accident scenarios. It should be noticed that potential accidents in B_1 and B_2 are not limited in listed above and should be determined according to individual process.

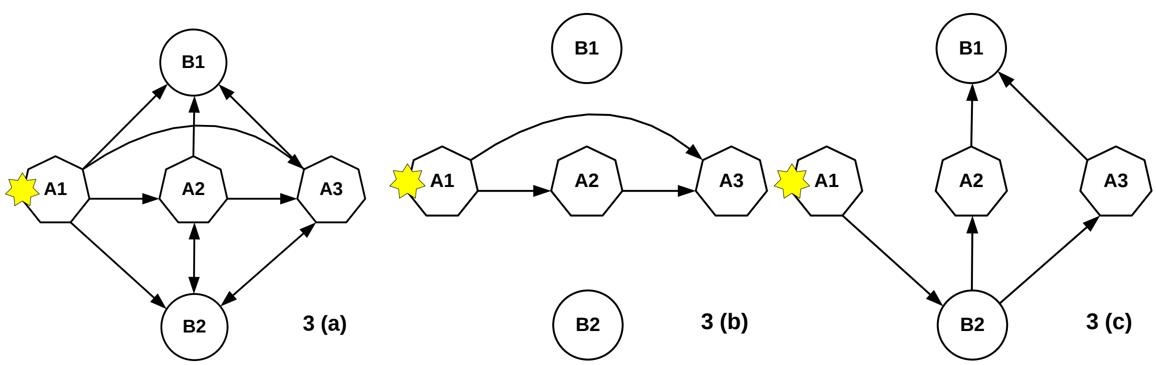


Fig. 8.2 Schematic of possible domino effects given a primary dust explosion in A_1. A_1, A_2, and A_3 are units where dust explosions can occur. Dominant accident scenarios for B_1 and B_2 are determined as pool fire and VCE, respectively.

With a primary dust explosion in A_1, several domino effects can be envisaged (Figure 8.2(a)). The first one is a chain of dust explosions. For example, in Figure 8.2(b), the primary dust explosion in A_1 could trigger a dust explosion in A_2 which in turn could cause a dust explosion in A_3 without causing credible damage to B_1 or B_2. Thus, the dust explosions in A_2 and A_3 can be considered as secondary and tertiary dust explosions, respectively. However, it is worth noting that the dust explosion in A_1 could directly cause a dust explosion in A_3 depending on the magnitude of overpressure received by A_3 from A_1. In this case, A_2 and A_3 are both considered as secondary dust explosions. As another chain of accidents in Figure 8.2(c), the primary dust explosion in A_1 can result in a VCE in B_2; the overpressure and flame caused by VCE can then trigger simultaneous dust explosions in A_2 and A_3. As a result of these dust explosions, B_1 can be heavily damaged, leading to a release of chemical containment and a subsequent pool fire. Therefore, each domino effect depicted in Figure 8.2 could occur. To determine which domino effects are likely to take place, the magnitudes of overpressures and escalation probabilities have to be calculated. This issue is discussed in more detail in the next section.

8.2.3 Escalation probabilities

Generally speaking, for a primary accident to cause significant damage to a target unit, the magnitude of the physical effects – also known as escalation vectors – such as heat flux and explosion overpressure should be higher than some threshold values. These threshold values are usually determined using experimental data and regression methods for a number of atmospheric and pressurized units as well as auxiliary equipment (e.g., pumps) and pipelines (Gledhill and Lines, 1998; Contini et al., 1996; Pettitt et al., 1993; Cozzani, 2001; Cozzani and Salzano, 2004). An escalation vector that is greater than the respective threshold value is likely to cause significant damage to a target unit, leading to loss of containment of the target unit. Based on the type of loss of containment (catastrophic, major or minor) and type of the released chemical substance (flammable, explosible or both) a secondary accident could occur. There are several methods to estimate the probability of damage to a target unit – the so-called escalation probability – among which probit functions are very popular due to their flexibility and applicability to a wide range of equipment and escalation vectors (Cozzani et al., 2005).

In the case of target units or installations that are prone to secondary dust explosions, most of the afore-mentioned threshold values and probit functions cannot be employed. As stated earlier, to have a secondary dust explosion in a target unit, the magnitude of the overpressure received by the target unit from a primary explosion should be able to suspend layers of dust settled on the floor, ceiling, or equipment. In addition, the density of suspended dust, presence of an ignition source, and confinement should effectively have been taken into consideration as influential factors. For the sake of clarity, the event tree in Figure 8.3 illustrates different accident scenarios likely to occur in a target unit given a primary explosion.

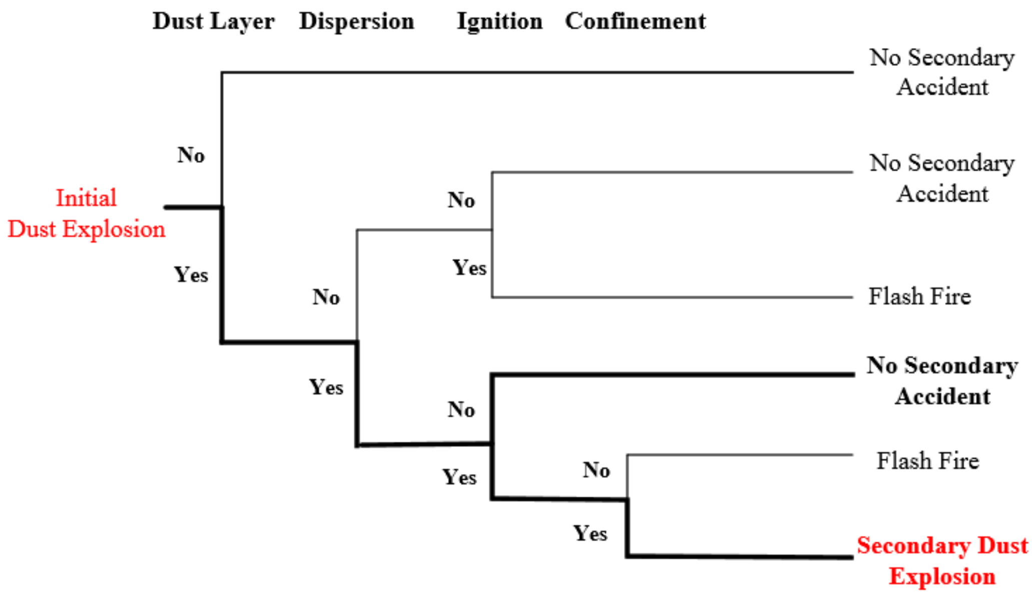


Fig. 8.3 Secondary dust explosion triggered by a primary explosion

In the event tree of Figure 8.3, the essential factors for a secondary dust explosion, i.e., the dust layer, dispersion, ignition and confinement, are depicted. As can be seen, a secondary dust explosion will occur only if all contributing factors coexist. It should be noted that the essential factor, oxygen, is not included in the event tree, since it has been assumed the oxygen would be present in most units involved in the process industries. In Figure 8.3, an initial dust explosion (or other types of explosion such as VCE and BLEVE) can cause two different secondary accidents in a dust-containing unit, that is, a flash fire or secondary dust explosion, depending on the presence/absence of essential factors. Knowing the occurrence probabilities of the initial dust explosion and essential factors, the probability of a secondary dust explosion can be estimated using the event tree in Figure 8.3.

For confinement, the probabilities of 0 and 1 are given to the situations of no-confinement and complete confinement, respectively, based on the type of target units. For example, if the target unit is a dust collector, the probability of confinement is considered as 1.0 whereas in the case of dust settled on the roof of a warehouse the probability of confinement is taken as 0.0. Since flames are observed in most dust explosions, a probability of 0.3, is assumed for the ignition in Figure 8.3. For the probability of a dust layer, $P(DL)$, an exponential equation can be used, considering both the mass of accumulated dust in a target unit or area and the threshold of accumulated dust mass:

$$P(DL) = 1 - \exp(-AM/M_{th}) \tag{8.1}$$

where AM is the mass of accumulated dust in the unit, and M_{th} is the corresponding threshold value.

M_{th}can be calculated according to relevant regulations, such as NFPA 654 (2000):

$$M_{th} = 0.004 * A_{floor} * H \tag{8.2}$$

where $A_{floor} = \min(enclosure\ floor\ area, 2000\ m^2)$;

$H = \min(enclosure\ ceiling\ height\ , 12\ m)$. The unit of M_{th} is kg.

AM can be conveniently calculated based on observation of the real situation:

$$AM = D * A_d * C \tag{8.3}$$

In Equation (8.3), D (m) is the depth of the dust layer in the target area or unit; $A_d(m^2)$ means the area of dust layer; C (kg/m^3) is the bulk density of the dust layer. The values of D and A_d can be identified by inspection while the value of C can be estimated by experiments.

When the overpressure from a primary dust explosion reaches the dust layer, the accumulated dust can be dispersed and result in a combustible dust cloud if the magnitude of the overpressure is greater than some threshold value. Because the overpressure will decay along the distance from the location where the primary explosion occurs, the magnitude of overpressure reaching a dust layer can be estimated by the equation listed in the German standard VDI 3673 (2002):

$$P_r = P_{MAX} * (R_s/r)^{1.5} \tag{8.4}$$

where P_{MAX} is the maximum pressure generated from a dust explosion; R_s is the distance of the blast center from the vent (m); r is the distance of the target (dust layer in this study) from the vent (m). Note that R_s could also be considered as the distance from the blast center to the connections with other units if no venting system is installed. An overpressure (P_r) with the value of 1.0 psig (7.0 kPa) can lead to partial demolition of houses and make them uninhabitable (National Oceanic and Atmospheric Administration). An overpressure at this level is thus assumed to be able to disperse the dust layer in the form of a combustible dust cloud. Thus, in this study the probability of dispersion, $P(Dp)$ is considered as 1.0 when the magnitude of overpressure equals or is higher than 1.0 psig. For overpressures magnitudes lower than 1.0 psig Equation (8.5) can be employed to estimate P(Dp).

$$P(Dp) = 1 - 0.2 * (7 - P_r) \tag{8.5}$$

A secondary dust explosion would be able to trigger other tertiary accidents. However, if the primary dust explosion results in a flash fire (see event tree of Figure 8.3), the probability of tertiary accidents triggered by the flash fire can be ignored (Cozzani et al., 2014).

8.2.4 Bayesian network and its application in domino effect analysis

The Bayesian network (BN) is a directed acyclic graph (DAG) (Neapolitan, 2003; Jensen and Nielsen, 2007), in which nodes stand for random variables and arcs between nodes refer to the direct dependency between them. The type and strength of dependencies are determined by conditional probability tables (CPTs). One of the main applications of BN is probability updating by taking advantage of the latest information so that the accuracy of predictions can be improved.

The joint distribution P(U) of a set of variables $U=(X_1, X_2, ... , X_n)$ can be expanded in equation (3.2) according to the conditional dependence of variables.

Similarly, if the latest information is observed, called evidence E, the posterior probabilities can be estimated based on Bayes' theorem as shown by the equation (3.4).

Due to its flexibility and robust probabilistic reasoning engine, BN has been widely used in risk analysis and safety assessment (Khakzad et al., 2013b, 2013c, 2013d; Zhao et al., 2012; Holický et al., 2013; Eleye-Datubo et al., 2006; Nordgård and Sand, 2010; Donald et al., 2009). Further, applications of BN to risk analysis of dust explosions (Yuan et al., online) and domino effects (Khakzad et al., 2013a, 2014, 2015) have been examined. In the current work, the risk of dust explosions with respect to domino effects is assessed using BN, with a main focus on a chain of dust explosions (e.g., $A_1\rightarrow A_2\rightarrow A_3$ in Figure 8.2(b)).

8.3 Development of domino effects model of dust explosions

The developed methodology for dust domino effects analysis is composed of several steps as follow:

Step 1: Locate areas or units with potential risk of dust explosions.

According to the characteristics of the process equipment, the units and the areas where combustible dust can be generated, either as a cloud or as settled layers, are identified as potential units and areas for dust explosion. For example, at Hayes Lemmerz International-Huntington, Inc. (Hayes, hereafter) (CSB, 2005b), the whole chip-processing system, including the chip mill and dry chip hopper, and the dust collection system including drop box and dust collector can be considered as areas where dust explosions might occur.

Step 2: Identify the most critical unit/area for the location of primary dust explosions.

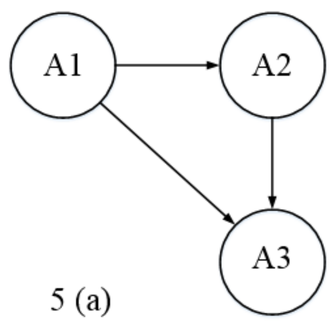
As can be noted from Hayes, more than one unit can be determined as a potential location for a dust explosion. In this step, among the units identified in Step 1, the unit with the highest risk is determined as the location of the primary dust explosion. The presence and intensity of essential factors for a dust explosion (Figure 3.1) are used to further screen the equipment/areas. The more the necessary elements of a dust explosion coexist in a unit, the higher the likelihood of a dust explosion; such a unit can be considered as the initiating unit in a domino effect (such as A_1 in Figure 8.2). For example, at Hayes, the dryer burner is excluded as the primary unit due to the incomplete combustion process involved, though it was identified as a potential unit for dust explosion in Step 1. Historical data and accident records can be effectively used to identify the most critical units for dust explosion occurrence.

Step 3: Calculate the strength of escalation vectors and identify target units.

For the escalation vector of dust explosions, the maximum pressure caused by the primary dust explosion can be obtained from relevant sources (Eckhoff, 2003; ASTM E1226-09). After calculating the magnitude of overpressure reached at target dust layers using equation (8.4), the probabilities of dispersion can be determined by equation (8.5).

Step 4: Estimate escalation probabilities and develop the BN.

Based on the methodology proposed by Khakzad et al. (2013a), a potential domino effect can be illustrated and modeled using a BN. The domino effects of dust explosions, 3(b) and 3(c), in Figure 8.2 are represented by 5(a) and 5(b) respectively in Figure 8.4. The units/locations with a risk of an accident triggered by a primary dust explosion in A_1 are represented by respective nodes. The influence relationship among nodes can be represented by directed arcs, i.e. $A_1 \rightarrow A_2$. It should be kept in mind that this research focuses on the chain of dust explosions, shown as $A_1 \rightarrow A_2 \rightarrow A_3$. The occurrence probability of a dust explosion in nodes A_i (i=1, 2, 3) can be calculated using a QRA method, i.e. fault tree (Yuan et al., 2013). In the current work, a developed generic risk analysis model for a dust explosion based on BN (Yuan et al., 2015), being tailored to various cases, is recommended.



5 (a)

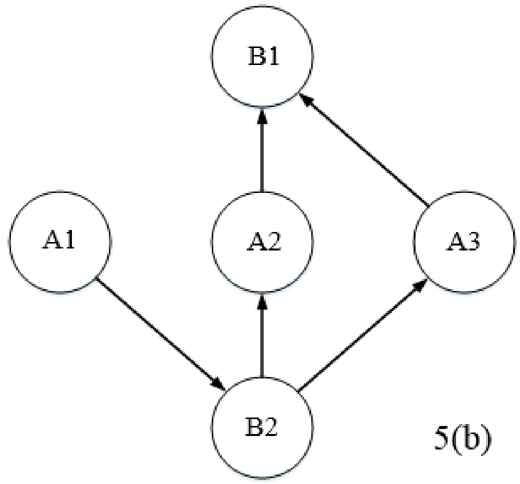


Fig. 8.4 Domino effects of dust explosion based on BN

The conditional probability table (CPT) of each node in the BN can be calculated using the event tree developed in Figure 8.3 once all the probabilities of essential factors are obtained in step 2. For illustrative purposes, the probabilities of dust explosion in node A_1 and A_2 and the probability of each essential factor in the event tree shown in Figure 8.3 are demonstrated in Table 8.1.

Table 8.1 Probabilities of initial dust explosion and safety barriers in event tree

	Initial Dust Explosion in A_1	Dust Explosion in A_2	Dust Layer	Dispersion	Ignition	Confinement
Probability	0.50E-5	0.40E-6	0.20	0.10	0.30	1.0

Like unit A_1, unit A_2 is also determined to have a dust explosion risk in step 1, which means a dust explosion could occur even if unit A_2 is not affected by a dust explosion in A_1. This is called the inherent probability of A_2 (Khakzad et al., 2013a).

Based on the assumed data used in Table 8.1, the probabilities of potential consequence categories in unit A_2 triggered by the initial dust explosion in A_1 can be calculated and listed in Table 8.2.

Table 8.2 Probabilities of different situations in A_2 resulting from initial dust explosion in A_1

Outcome	No Secondary Accident	Flash Fire	Secondary Dust Explosion
Probability	0.41E-5	2.70E-7	0.30E-7

Thus, the CPT of A_2 can be represented in Table 8.3:

Table 8.3 CPT of node A_2

		No Secondary Accident		Flash Fire		Secondary Dust Explosion	
		Yes	No	Yes	No	Yes	No
Initial Dust Explosion	Yes	0.41E-5	0.999	2.7E-7	0.999	0.30E-7	0.999
	No	0	1	0	1	0.40E-6	0.999

Repeating the above steps, the CPT for each node can be established and the model of domino effect analysis for dust explosions is developed using BN.

8.4 Case study

8.4.1 Introduction

On Feb. 20, 2003, a dust explosion occurred at CTA Acoustics, Inc., KY, U.S., causing 7 deaths and 37 injuries (CSB, 2005a). CTA manufactures acoustical and thermal insulation products involving fiberglass, phenolic resin powder and facing. According to CSB (2005a) the phenolic resin dust was the fuel for this explosion, and the primary dust explosion occurred near the oven in line 405 and led to a secondary dust explosion in the space above the blend room in line 405. Then the pressure wave and fireball from the secondary dust explosion propagated along the ceiling toward line 403, line 402 and line 401. In the southeast corner of the blend room on line 401, another dust explosion occurred and caused extensive damage. The layout of the facility is shown in Figure 8.5.

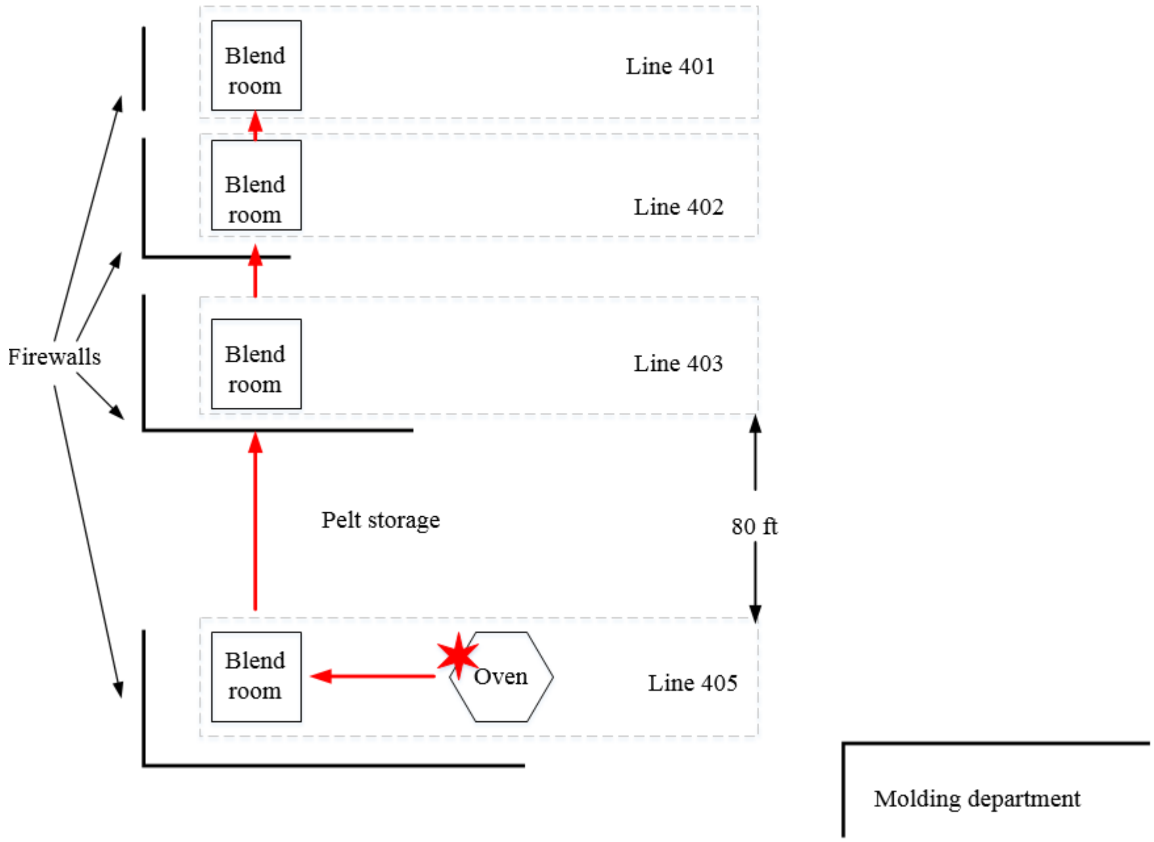


Fig. 8.5 Simplified layout of CTA facility

8.4.2 Domino effect of dust explosions analysis for CTA Acoustics

According to the descriptions of the production process and daily operations, the areas around the ovens, the blend houses and the spaces above the blend houses on production lines can be identified as the units/areas susceptible to dust explosions because combustible layers are often observed in these areas. Among them, the area around the oven in line 405 can be identified with the highest risk of a dust explosion (CSB, 2005a). One of the reasons is that the accumulated dust above the production lines cannot be effectively removed by the housekeeping program, and can even arise because of improper housekeeping methods (e.g., compressed air forming a combustible dust cloud around ovens in different lines). The other reason is that the fires ignited in the residual material in the oven with enough ignition energy for a dust explosion can propagate outside of the oven through the improperly opened oven door on line 405 to reduce the unexpected high temperature in the oven due to the malfunction of temperature control equipment. Therefore, tailoring the generic likelihood estimation model for dust explosions to this case, the occurrence probability of initial dust explosions around the oven on line 405 has been calculated in previous research (Yuan et al., 2015) and equals 4.97E-5.

Once a dust explosion occurred around the oven on line 405, the propagation routes of produced flames and pressure blast can be classified into two possible scenarios. One is spreading into the space above the blend room on line 405 (as shown in Figure 8.5), where accumulated dust layers on flat surfaces resulting from inadequate housekeeping could be dispersed to form a combustible dust cloud, and further lead to a secondary dust explosion. The other propagation path is to the outer spaces of line 405, where a fireball from the initial dust explosion is less likely to be further transferred. As the CSB found (2005a), when the fireball reached the molding department, it dissipated. Moreover, the semi-cured pelts stored between line 403 and 405 was ignited. Therefore, in domino effect analysis, the space above the blend room on line 405 is considered as the potential area where a secondary dust explosion could occur. Due to the similar production process and safety management in lines 403, 402 and 401 as in line 405, phenolic resin powders can easily accumulate on the flat surfaces in and above the blend rooms, which are able to be the fuel for fires and further dust explosions. Thus, the blend rooms on lines 403, 402 and 401 and their overhead spaces are also determined as the units with dust explosion risks. Based on above analysis about the production process, origins of dust explosions and potential propagation routes of dust explosions, the model for the domino effect of dust explosions can be established using BN and is shown in Figure 8.6.

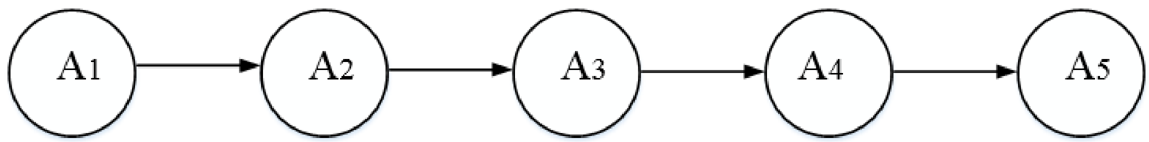


Fig. 8.6 Domino effect of dust explosions originating from area around oven on line 405

In Figure 8.6, A_1 and A_2 stand for the area around the oven and the space above the blend room in line 405, respectively. Similarly, the blend rooms on lines 403, 402 and 401 are represented by A_3, A_4, and A_5, respectively. Using the tailored occurrence probability model of dust explosions for unit A_2, the probability of a dust explosion in A_2 can be calculated as 5.31E-6. Due to the similar working circumstances and maintenance strategies as in A_2, the probabilities of dust explosions in A_3, A_4, and A_5 can be considered as equal to that in unit A_2.

Before obtaining the CPT of each node based on the event tree in Figure 8.3, the probability for each safety barrier should be calculated as discussed in section 8.2.3. For this case, the probability of a dust layer is first calculated using equations (8.1) to (8.3). According to the investigation report (CSB, 2005a), the area above the blend rooms can be calculated as 112 m^2 (listed in Table 8.4, column 1) and the mass threshold of combustible dust accumulating in the areas above the blend rooms can be calculated as 1.366 kg using equation (8.2) (Table 8.4, column 3).

Table 8.4 Values of Relevant Parameter

A_{floor} (m^2)	H (m)	M_{th} (kg)	AM (kg)	P_r (psi)
112	3.05	1.366	7.2	5.98

Further, the depth and area of the dust layer can be observed during the regular investigation and operation. However, due to the extensive fire and explosion damage, both parameters of the dust layer cannot be determined from CSB (2005a). For the purpose of analysis, 0.0008 m, recommended by NFPA above which the area needs immediate cleaning (NFPA654, 2000), is taken as the depth of accumulated dust layer and the area of dust layer is estimated as 20 m^2. The CSB report also revealed the test result for the diameters of phenolic resin samples from CTA ranged from 10 to 50 μm (CSB, 2005a). Thus, the bulk density of the dust layer can be estimated as 450 kg/m^3 according to Janès et al. (Janès et al., 2014). With equation (8.3), the mass of accumulated dust can be calculated as 7.2 kg (column 4 in Table 8.4) and the probability of the dust layer in this case can be calculated as 1.0 according to equation (8.1). Because of the similar operation processes and housekeeping in the blend rooms on lines 403, 402 and 401, the probabilities of dust layers in these units can also be considered as 1.0

For the estimation of the probability of dispersing dust layers, the strength of overpressure received by a dust layer should be first calculated. According to the test by CSB (2005) using ASTM E1226-09, the Standard Test Method for Pressure and Rate of Pressure Rise for Combustible Dust (ASTM, 2000), the P_{max} of combustible dust collected from CTA can be up to around 110 psig (7.59 bar(g)). According to the layout of the CTA facility (CSB, 2005a), the longest distance between two units is 80 ft (24.38m) between line 405 and line

403. Therefore, if the dust layer in the blend room in line 403 can be lifted by the overpressure from line 405, the dust layers in other production lines can also be dispersed by the overpressure from a nearby dust explosion. Using equation (8.4), the overpressure propagating from line 405 to line 403 (P_r) can be calculated as 5.98 psig (0.41 bar(g)) (column 5 in Table 8.4). This value is much greater than the threshold of overpressure with the ability of dispersing dust layers as discussed in 8.2.3. Therefore, in this case, the probability of dispersion can be considered as 1.0. Further, as the result of estimating the confinement of the space above the blend rooms and the blend rooms themselves, the probability of confinement can be considered as 1.0. Based on the event tree in Figure 8.3, the probabilities of two outcomes in node A_2, secondary dust explosion and no secondary accident (the paths are depicted in bold in Figure 8.3), given an initial dust explosion in node A_1, can be calculated. For example, the conditional probability of a secondary dust explosion, given an initial dust explosion, P (secondary dust explosion given initial dust explosion), can be calculated as 0.3. Thus, the CPT of node A_2 can be obtained as shown in Table 8.5. Following similar steps, the CPT of each node can be established.

Table 8.5 CPT of A_2 in Figure 7

		A_2	
		Secondary Dust Explosion	**No Secondary Accident**
A_1	**Dust Explosion**	0.30	0.70
	No Dust Explosion	5.31E-6	0.999

Note that the CPTs for node A_3, A_4 and A_5 are considered to be the same as for node A_2 due to their similar operating conditions and maintenance strategy in this case. Otherwise, the CPT of each node should be individually calculated by tailoring the event tree in Figure 8.3 to the units with different operating conditions and maintenance.

After obtaining the CPT of each node, the occurrence probability of dust explosions in each unit can be calculated taking advantage of HUGIN 8.0 (http://www.hugin.com) (2010). The results are given in Table 8.5. The occurrence probabilities of dust explosions in various units from A_1 to A_5 are decreasing, which reveals that the threats from dust explosions in different units are reduced along with domino effects of the primary dust explosion in unit A_1. However, due to the effects of the initial dust explosions, the occurrence probabilities of dust explosions in A_2, A_3, A_4 and A_5 increase in different degrees. For example, the occurrence probability of a dust explosion in A_2 increases from 5.31E-06 to 2.02E-05.

Table 8.6 Occurrence probabilities of dust explosions in different units

	A_1	A_2	A_3	A_4	A_5
Probability of dust explosion	4.97E-5	2.02E-5	1.14E-5	8.72E-6	7.93E-6

8.5 Conclusions

Domino effects of accidents are usually difficult to analyze especially in complex process industrial scenes. Due to the presence of multiple essential factors of dust explosions, the issue is more complicated in the analysis of the chain of dust explosions. In the current research, a methodology is proposed to analyze domino effects of dust explosions using BN.

In this methodology, the units or locations with risks of dust explosions are identified first according to the production processes in specific industries. Among them, the unit or location with the maximum number of essential factors for dust explosions is considered to have the highest risk of dust explosions and the dust explosion occurring in it is located as the primary one. Then, taking advantage of BN, the potential propagation routes of the escalation vectors, the overpressures, are represented considering facility layout. After developing an event tree to quantify the occurrence probabilities of different consequence categories triggered by an initial dust explosion, the CPT of corresponding nodes in the BN model can be calculated. By tailoring the developed risk analysis model of dust explosions to target units, the inherent probability of dust explosions in each node on the BN can be further estimated. Then, based on the developed domino effect analysis model of dust explosions, the occurrence probability of a dust explosion in each unit can be calculated. CTA Acoustics, Inc. was chosen to illustrate the usage of this method.

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9 Conclusions and Future Research

Dust explosions are commonly occurring accidents in process industries and cause severe financial losses to shareholders and insurance companies and physical damage to operators. The research about dust explosions mainly focuses on the occurrence mechanisms as well as prevention technologies and there are few risk estimations about dust explosions. At the same time, the domino effects of dust explosions are seldom seen due to the complex mechanisms and complex scenes. Therefore, a versatile QRA model for dust explosions, considering interlinks among contributors, still needs to develop. Further, the features of dynamic analysis should be integrated in this model to represent the dynamic characteristics in process industries. Moreover, the dust explosion chain should be analyzed, which can help to prevent accidents' propagation and mitigate severe consequences caused by dust explosions in a system.

9.1 Conclusions

The main conclusions of this study are as follows:

9.1.1 Investigation of dust explosion accidents worldwide

This study analyzed statistical characteristics of dust explosions worldwide. The huge differences among the statistical results in various countries, periods, and industries, shows the contributors to these accidents need to be further discussed, but usually have been ignored due to the limitations in data collection.

More than 2000 dust explosions cases are collected to overcome the limitation of insufficient samples. Also differences in developing and developed countries are compared and further discussed. However, note that the number of reported accidents is far lower than that of the actual occurrences, which limits the representativeness of this study. Moreover, the missing critical information (e.g. ignition source) and intentional underestimation of the casualties in some accident reports also limit the value of this study.

9.1.2 Developing generic risk analysis model for dust explosions

In this study, a generic risk analysis model of dust explosions is established based on BT. Due to the numerous factors contributing to dust explosions and their complex internal relationships, utilizing them in QRA is a big challenge, as is integrating various safety barriers with potential consequences.

Taking advantage of BT, the primary causes of dust explosions are integrated according to cause-effect relationships on the left side; at the same time, common applied safety barriers as well as potential consequences categories are presented on the right. After obtaining the probabilities of basic events, the reliabilities of safety barriers and loss of each consequence category, the risk of a dust explosion is calculated. The tailoring ability of this generic model is also illustrated through a case study which shows its adaptability. Moreover, a potential safety measure is recommended for each basic factor, and the implementation of the safety measures as well as their efficacies in risk reduction for dust explosions are discussed.

9.1.3 Developing dynamic risk analysis model for dust explosions

Although the risk of dust explosions can be obtained by tailoring this generic risk analysis model to specific cases, the limitation of ignoring the dependencies among basic events restricts its application. Moreover, since BT is composed of FT and ET, this also brings the static characteristic into BT.

To overcome these limitations, in this research, the BT model of dust explosions is transformed to BN, which enables analysts to perform dynamic risk analysis, including probability prediction, probability updating and sequential learning. In addition, the dependencies among primary causes of dust explosions are conveniently represented. Moreover, utilizing the latest information from a dynamic system in the risk analysis of dust explosions using a BN model leads to more accurate results compared to the conventional QRA (i.e. BT). These functions are represented by taking advantage of a case study.

9.1.4 Proposing a methodology of safety measures allocation

A risk-based optimal methodology of safety measures allocation for dust explosions is proposed in this research. The barrier in selecting suitable safety measures is to satisfy the risk control requirement within a limited budget. Moreover, considering various potential safety measures for a basic event, the selection priority should be determined.

Safety measures are proposed and categorized first according to risk management principles in this study. Further, the priorities of safety measures are recommended to follow inherent, engineered and procedural safety measures. To obviate the aforementioned dilemma in determining a safety strategy for dust explosions, optimization methods are introduced and integrated with the developed risk analysis model of dust explosions to establish the methodology for safety measures allocation. In this method, an index, NRRG, is also defined for each safety measure to account for the cost of a safety measure and its efficacy in risk reduction.

9.1.5 Analyzing domino effects of dust explosions

The chain of dust explosions is analyzed based on BN. Although the effects of blast waves and flames can be analyzed using conventional methods (i.e. probit method) in the academic area, discussion about the dust explosion chain is seldom seen due to the lack of comprehensive research in the propagating mechanisms of dust explosions.

To quantify the escalation probabilities of dust explosions, ET is resorted to in this study considering the five essential factors of dust explosions as safety barriers. After obtaining their occurrence probabilities, the probability of a secondary dust explosion given the primary one can be calculated, which is taken as the targeted escalation probability. Then, taking advantaging of the BN model, the occurrence probability of each dust explosion on the chain can be obtained.

9.2 Future research

The current research includes establishing a generic risk analysis model of dust explosions, overcoming its static characteristics by introducing BN, analyzing domino effects of dust explosions and developing optimal methodology to help decision makers to determine safety strategies. Distribution characteristics of dust explosion accidents worldwide are also discussed. Based on this research, the following recommendations for future research can be made.

9.2.1 Extending the scope of hazards identification

In this research, the contributors to dust explosions, involving defects in design, operations and management, and so forth, were drawn as comprehensively as possible from accident investigations, academic papers, and relevant regulations, and the total number of primary events is 79. However, due to the characteristics of individual industries and productions, some potential factors might be missed in the generic model. Though the defects can be overcome along with continuously tailoring the generic model to different cases to some extent, by which new basic events can be added, it is also recommended to expand the range of hazards identification based on the latest accident investigations, updated regulations and research.

9.2.2 Dealing with uncertainty

Though this research focuses on developing a risk model for dust explosions, a large amount of probability data of basic events is essential in risk estimation. The crisp values were obtained from academic papers, relevant handbooks and expert opinions. However, the arbitrary estimations from experts are usually questioned. In the future work, the fuzzy set theory, being available in the situation where complete or precise information is lacking, could be introduced to both the developed BT model and the BN model to improve the accuracy of estimation.

9.2.3 Settling multi-objective programming problem

In this research, an index of Net Risk Reduction Gain (NRRG) was defined to simplify the problem of safety measures allocation as a knapsack problem. However, in a more complex case, both the objectives of experts and constraint conditions could be multiple. For example, the cost of a potential safety strategy can be considered as the other objective in safety measures allocation, besides controlling the risk level of a system. Therefore, a multi objective programming model might be introduced to solve the complex issues.

9.2.4 Introducing risk analysis in domino effects of dust explosions

In this research, the domino effects of dust explosions are analyzed. However, the work focuses on estimating the occurrence probability of a dust explosion in the chain. In order to obtain the risks of dust explosions, the loss caused by an individual dust explosion should be further considered. Based on analysis of risks caused by dust explosions, the areas with a higher risk can be evaluated which will efficiently help to introduce safety measures to mitigate potential damage caused by dust explosions. For this purpose, loss functions, estimating the potential losses with the changes of process characteristics, could be introduced in the risk analysis of domino effects. By this method, both the probabilities of occurrence categories and their individual potential loss could be updated with dynamic processes.

Appendix A

A partial case of dust explosions around the world from 1785 to 2012

Date	Country	Material	Equipment Involved	Types of Industries	Dead/ Injured	Ignition Source	Reference
1785	IT	F	Warehouse	Food plant	2i	Flame and direct heat	Eckhoff, 2003
1866	UK	C	_	_	388d	Hot work	Mining-technology, 2014
1878	US	F	_	Mill	18d	_	Explosion Hazards Ltd
1906	FR	C	_	Coal mine	1099d	Flame and direct heat	Energy Liabrary
1911	UK	F	Store	Flour mills	5d/7i	Flame and direct heat	PAPERSPAST
1911	UK	F	_	Food and feed plant	39d/100i	Electrical sparks	Explosion Hazards Ltd
1911	UK	_	_	_	3d/5i	_	Abbasi & Abbasi, 2007
1916	US	F	Steel bin	Silo/elevator/warehouse	_	_	Vijayaraghavan, 2011
1919	US	F	_	Food and feed plant	43d	_	Explosion Hazards Ltd
1924	US	F	Starch powder house	Food and feed plant	42d/100i	Static electricity	GenDisasters, 2007
1930	UK	F	Silo	Food and feed plant	11d/32i	Self-heating and smoldering	Explosion Hazards Ltd
1936	US	In	Coal handling equipment	Chemical plant	2d	_	NFPA, 1957
1956	US	F	Elevator	Food and feed plant	1i	Hot work	NFPA, 1957
1960	CHN	C	Electric locomotive, tripper	Coal mine	684d	Electrical sparks	Wang & Li, 2001
1960	AUS	F	Elevator	Silo/elevator/warehouse	_	Hot work	Explosion Hazards Ltd
1963	JPN	C	Mining slope	Coal mine	458d/839i	Friction sparks	Hoshino et al., 1992
1963	CHN	M	Dust collector	Metal products plant	19d/24i	Impact friction	Wenku, 2012
1965	IN	C	Mining slope	Coal mine	375d	Flame and direct heat	Mining technology, 2014
1969	CHN	C	Electric locomotive	Coal mine	115d/108i	Electrical sparks	Wang & Li, 2001
1970	GER	F	Grain silo	Silo/elevator/warehouse	6d/17i	_	Eckhoff, 2003
1973	CHN	C	Switch/ cable	Coal mine	50d/10i	Flame and direct heat	Wang & Li, 2001
1975	IN	C	_	Coal mine	372d	_	Mining technology, 2014
1977	US	F	Tunnel connected to elevator	Silo/elevator/warehouse	18d/22i	Friction sparks	GenDisasters, 2009
1977	US	F	Elevator	Silo/elevator/warehouse	36d/10i	Static electricity	Bright Hub,2012
1978	CHN	M	Multiclone dust collector	Metal products plant	5d/6i	Impact sparks	Safehoo, 2011
1980	US	F	Bin, conveyor	Food and feed plant	8d/1i	_	CSB, 2006

1981	CHN	F	Store house	Silo/elevator/warehouse	7i	Flame and direct heat	MuYung Ltd
1985	CHN	C	Working surface	Coal mine	63d/3i	Hot work	Wang & Li, 2001
1985	US	IN	Electric equipment	Animal pesticide packaging plant	13d/1i	Flame and direct heat	CSB, 2006
1986	JPN	CH	Weighing hopper	Chemical plant	1i	Static electricity	Failure Knowledge Database
1986	CHN	F	_	Food and feed plant	2d/5i	_	Yan & Yu, 2012
1986	CHN	O	Dust collector	Textile mill	5d/15i	Friction sparks	Safethoo, 2009
1986	US	W	Incinerator, propane heater	Manufacturer of "smoke" flavoring for food products	4d	Flame and direct heat	CSB, 2006
1987	CHN	C	Working surface	Coal mine	3d/1i	Hot work	Wang & Li, 2001
1987	CHN	F	_	Food and feed plant	1i	_	Yan & Yu, 2012
1987	CHN	O	Dust collection system	Textile mill	58d/177i	Static electricity	Explosion Hazards Ltd
1987	CHN	F	_	_	1i	_	Yan & Yu, 2012
1987	US	M	Grinder, aluminum fuser rolls	Coating, Engraving, and Allied Services	5d/1i	_	CSB, 2006
1988	CHN	C	Working surface, ventilation	Coal mine	26d/3i	Hot work	Wang & Li, 2001
1989	US	M	Dust collection system, grinder/polisher	Metal products plant	2d/1i	Hot work	CSB, 2006
1989	US	W	Tyler model 2400 multi-spindle panel router s/n2984-87	Unsupported Plastics Profile shapes	2d	Hot surface	CSB, 2006
1990	CHN	C	Detonators, roadway	Coal mine	12d/4i	_	Wang & Li, 2001
1990	JPN	O	Storage	Chemical plant	9d/17i	_	Abbasi & Abbasi, 2007
1990	US	M	Magnesium batching hopper	Chemical plant	1d/2i	Impact sparks	CSB, 2006
1991	CHN	C	Roadway, cable	Coal mine	29d/14i	Electrical spark	Wang & Li, 2001
1991	CHN	C	Working surface	Coal mine	35d/1i	Hot work	Wang & Li, 2001
1991	CHN	C	Working surface	Coal mine	16d/7i	Hot work	Wang & Li, 2001
1991	US	IN	Granulator	Pharmaceutical preparations	1d/1i	_	CSB, 2006
1991	US	W	Conveyor belt	Wood products plant	2d/1i	_	CSB, 2006
1991	US	M	Machine press, acetylene torch	Plastic products factory	2d	Flame and direct heat	CSB, 2006
1992	JPN	M	Mixing operation	Firework manufacturing plant	3d/58i	Friction sparks	Explosion Hazards Ltd
1992	CA	C	_	Coal mine	26d	Flame and direct heat	GenDisasters, 2009
1992	US	W	Dust collection system	Wood products plant	2d	_	CSB, 2006
1993	CHN	C	Roadway	Coal mine	40d/4Si	Hot work	Wang & Li, 2001
1993	US	PR	Air arc gauge with Plasmarc and Mappgas; mixing tank	Plastic products factory	2d/2i	Electrical sparks	CSB, 2006

1993	US	F	_	Food and feed plant	9d	Flame and direct heat	CSB, 2006
1994	CHN	C	Coal lane	Coal mine	79d/129i	Friction sparks	Wang & Li, 2001
1994	US	C	Turbine generator hopper	Electric Services	22d	Flame and direct heat	CSB, 2006
1994	US	O	Metal duct	Metal products plant	6d/1i	Friction sparks	CSB, 2006
1994	US	W	Halogen light, Dust collection system	Facilities support services	2d	Hot surface	CSB, 2006
1996	US	PR	Blending Tote	Automobile brake pads and lining manufacturer	1d	_	CSB, 2006
1997	JPN	M	Bag filter dust-collecting device	_	1d/1i	_	Abbasi & Abbasi, 2007
1997	FR	F	Storage	Silo/elevator/warehouse	11d/1i	Impact sparks	Masson, 1998
1997	US	O	Dust collection system, welding device	Motor vehicle parts and assessories	5d	_	CSB, 2006
1998	US	C	Tripper, Vacuum	Electric Services	17d	_	CSB, 2006
1998	US	PR	Dust collector; air handling ducts	Sports equipment manufacturer	16d	_	CSB, 2006
1999	US	C	Boiler	Power station	30d/6i	Flame and direct heat	CSB, 2006
1999	US	PR	Oven; dust collection system	Grey and duct tile foundries	9d/3i	Flame and direct heat	CSB, 2006
1999	US	W	Silo	Wood products plant	4d	_	CSB, 2006
1999	US	PR	Machine that grinds plastic pellets	Plastic manufacturing	2d	Hot work	CSB, 2006
2000	CHN	W	Dust removal equipment	Wood products plant	4d/7i	_	Chinanews, 2008
2000	US	F	_	Food and feed plant	3d	Hot work	CSB, 2006
2001	CHN	C	Roadway	Coal mine	17d/23i	_	CSAWS
2001	IT	O	Storage	Wool factory	3d/5i	Electrical sparks	Piccinini, 2008
2001	CHN	W	Ventilation system	Wood products processes	6i	Static Electricity	Safehoo,2011
2001	CHN	O	Silo	Food and feed plant	1d/7i	Self-heating and smoldering	Chinanews, 2008
2001	US	W	_	Wood Products plant	10d/3i	_	CSB, 2006
2001	US	IN	Saw, vacuum cleaner	Rocket propellant/motor manufacturing plant	3d/1i	Hot work	CSB, 2006
2001	US	M	Dust collector	Metal products plant	2d	_	CSB, 2006
2002	CHN	F	Agitator	Food and feed plant	8i	_	Sina, 2002
2002	CHN	W	_	_	_	Flame and direct heat	Anquan
2002	CHN	F	_	Food and feed plant	6d/12i	_	Chinanews, 2002
2002	CHN	C	_	Coal mine	9d/14i	_	CSAWS
2002	CHN	F	Workshop	Maintenance	17i	Hot work	Sina, 2002
2002	US	PR	Tire bin	Tire recycling	13d	_	CSB, 2006
2003	CHN	C	_	Coal mine	3d	_	CSAWS

2003	US	PR	Milling equipment	Mechanical rubber goods	38d/6i	_	CSB, 2006
2003	US	W	_	_	2d	_	CSB, 2006
2003	US	PR	Oven	_	37d/7i	_	CSB, 2006
2003	US	W	_	_	9d/2i	_	CSB, 2006
2004	CHN	C	Coal lane	Coal mine	2d/16i	_	CSAWS
2004	UK	PR	LPG tank	Plastic products factory	9d/33i	Flame and direct heat	Explosion Hazards Ltd
2004	US	W	_	_	2d	_	CSB, 2006
2004	US	W	Dust collection system	Wood products plant	3d	Impact sparks	CSB, 2006
2004	US	F	Bag house	Tofu manufacturer	16d/1i	_	CSB, 2006
2005	CHN	C	Underground coal bin	Coal mine	171d	_	Chinanews, 2005
2006	CHN	C	_	_	7i	_	Yan & Yu, 2012
2006	CHN	C	_	Coal mining	14d	_	CSAWS
2007	CHN	W	Conveyor	Wood pelts manufacturer	4d/5i	_	Xinhuanews, 2007
2007	CHN	F	Workshop, pulverizer	Rice process factory	_	Hot surface	Wenku, 2010
2007	CHN	F	Hopper	Feed processing	5i	Self-heating and smoldering	Fire department, 2007
2007	CHN	W	Packing workshop	Wood products processes	1d/1i	Electrical sparks	Chinanews, 2007
2007	CHN	C	_	Coal mining	31d	_	CSAWS
2008	CHN	F	_	Starch/Candy	12i	_	Yan & Yu, 2012
2008	CHN	M	Dust collection system	Metal fabrication	10i	Electrical sparks	Chinanews, 2008
2009	CHN	M	Workshop	Aluminum products manufacturer	11d/20i	Self-heating and smoldering	Xinhua news, 2009
2009	CHN	W	_	Wood products plant	8i	_	Yan & Yu, 2012
2009	CHN	IN	Dust collection system	Chemical preparations	2i	_	Chinanews, 2009
2010	US	M	Silo	Titanium plant	3d	_	CSB, 2006
2010	CHN	M	Dust setting chamber	Metal polishing	2d/6i	Impact sparks	Chinanews, 2010
2010	US	C	Coal lane	Coal mine	29d/2i	Flame and direct heat	McAteer, 2011
2011	US	M	Pipes, furnace	Iron Powder plant	3d/2i	Impact sparks	CSB, 2011
2011	CHN	M	Polishing workshop	Aluminum products plant	5d/1i	Flame and direct heat	China news, 2011
2012	CHN	M	Polishing workshop	Metal polishing plant	13d/16i	Electrical sparks	Safehoo,2013
2012	CHN	M	Polishing workshop	Apple supplier factory	59i	_	NPR news, 2012
2012	CHN	C	_	Coal mine	6d	_	China news, 2012

M: Metal; W: Wood; F: Food; C: Coal; IN: Inorganic; PR: Plastic/Rubber; CH: Chemical; O: Others;