# A Predictive Model to Assess Dust Explosion Occurrence

by

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A Thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of

**Masters of Engineering**

**Faculty of Engineering and Applied Science**

Memorial University of Newfoundland

**May, 2014**

St. John's Newfoundland

# Abstract

The danger of a dust explosion is difficult to avoid in process facilities where combustible dusts are handled. To develop effective prevention and mitigation strategies, it is very important to understand the interaction among dust explosion controlling parameters and to assess the likelihood of an dust explosion occurrence. Six controlling parameters ( Particle Diameter, Minimum Ignition Energy, Minimum Explosible Concentration, Minimum Ignition Temperature, Limiting Oxygen Concentration and Explosion Pressure) are identified to model a predictive tool which can assess the likelihood of dust explosion in a given operating condition. Experiments have been conducted by the dust explosion researcher to understand the characteristics of these parameters and the generated data has a substantial scope in estimating dust explosion probability with the use of probabilistic approach. A conceptual framework is developed to use the existing experimental data on dust explosion parameter to assess the dust explosion prediction in a given facility. The model is further extended with considering dust classes and a detailed implementation in specific process industries are discussed with case studies. The proposed model can assess the dust explosion probability in a given operating condition at a specific process facility. The assessment can be very helpful to strategies effective prevention and mitigating measures in process industries. Three case studies are discussed in this study to demonstrate the real life application of the model.

# Acknowledgements

First and foremost, I would like to express profound gratitude to my supervisors, Dr. Faisal Khan, co-supervisor Dr. Paul Amyotte for their invaluable support, motivation, immense knowledge, encouragement, supervision and useful suggestions throughout the research work. Their extensive support and wise guidance helped me to complete my work successfully.

Besides my advisor, I would like to thank the dust explosion project team leader Dr. Refaul Ferdous for his continues encouragement, insightful comments and important questions. His knowledge and technical suggestions helped me to develop the model successfully.

I would also like to gratefully acknowledge the financial support provided by Natural Science and Engineering Research Council (NSERC) through Strategic grant.

I thank my fellow lab mates in Safety and Risk Engineering Group (SREG): Nima Khakzad, Muhammad Masum Jujuly, Yuan Zhi, Mashrura Musharraf, Raihan Mallick and Dan Chen for the stimulating discussions, valuable ideas, encouragements, helps in every means and for all the fun we have had in the last two years.

I would like to specially thank my parent for supporting and encouraging me to pursue this degree. I thank them for their love and support throughout the whole career.

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# Chapter 1

# Introduction

## 1.1 Overview of Dust Explosion

The dust explosion hazard continues to represent a constant threat to process industries that handles combustible dust. A dust explosion can occur when particular solid material is suspended in air and sufficient energetic ignition source present. Dust explosion is relatively less familiar to the gas explosion but the consequences are almost akin, if the impact on surrounding environment, industrial assets and monitory value are considered.

Unfortunately, dust explosion's causation and severity is less familiar compare to the gas explosion among industrial professionals [Amyotte and Eckhoff, 2010]. For gas explosion fuel, oxidant and ignition sources are necessary while dust explosion requires two more vital criteria: appropriate mixing and confinement. These five elements are termed as dust explosion pentagon (Figure 2.2).

Five parameters are identified as dust explosion influential parameter: particle diameter, minimum explosible concentration, minimum ignition energy, minimum ignition temperature and limiting oxygen concentration, whereas the maximum explosion pressure represents the severity of dust explosion. Five essential elements ( e.g. fuel, oxidant, ignition source, mixing and confinement) form a dust explosion pentagon [Kauffman, 1982]. These five elements are represented by five influencing parameters of dust explosion. When these parameter reaches to the explosible range, dust explosion occurs [Abbasi and Abbasi, 2007]. Explosion may not occur if all parameter do not reach the explosible range [NFPA, 2007]. The strength of the dust explosion is measured in terms of severity. In the study, the maximum explosion pressure is the indicator of the severity.

## 1.2 Motivation of Research

Dust explosion hazards are fatal for process facilities that deal with combustible materials. Research on safer plant design, safer work places and several standard safety codes is available in contemporary literature and books.

Different safety methods have been proposed and analysed with case studies to make process plants safer. Still, dust explosion is considered as a serious threat for industries dealing with dust materials.

In the process industry, major accidents are often initiated due to process upsets, mechanical and operational hazards. Traditional prevention and mitigation strategies are developed without considering facility condition. Existing safety models does not consider the quantification of explosion proneness of a process facility at normal operation condition. Thus, the models focusing on process hazards are not considering normal operating condition while formulating prevention and mitigation strategies. Industrial professionals and researchers are striving for more pragmatic and easily implementable solution to prevent dust explosion phenomena. However, in the context of quantitative assessment, a predictive tool to assess the explosion probability in a particular industry is absent.

In this study, an effort has been made to establish a probabilistic model to assess the dust explosion occurrence. The model is extended further to specific process industry and implemented with real life case studies. The model is applied for three dust classes: Food feed, plastic, resin and rubber and metal alloy.

## 1.3 Objectives of the Research

The main objective of this research is to develop a model that can be used to formulate effective strategies in dust explosion prevention and mitigation. A predictive model will help to improve system's safety at design as well as at operational phase of a process facility for a better and safer work place.

Based on this main objective, following sub-objectives are developed for this work:

- To develop a predictive model to assess the conditional probability for given operating conditions.
- To provide a quantitative probabilistic assessment at a specific process facility on dust explosion.
- To help in formulating effective prevention and mitigation strategies in the developed model.

- To develop a simplified tool called "nomograph" for easy and effective use of the model.

## 1.4 Novelty and Contribution

The contributions of this study are described below:

- The proposed model considers six key parameters of dust explosion and a vast amount of experimental data of these parameters are analyzed and their inherent distributions are identified.
- Dust explosion parameters are classified into two categories: influencing parameter and severity parameter. A conditional probabilistic approach is used to correlate these two parameters to understand the interaction between them.
- A probabilistic model is used to obtain the total probability of dust explosion at a given operating condition.
- A simplified tool called 'nomograph' is developed to analyze the facility condition easily. The nomograph provides an easy interpretation of the complex mathematical functions to understand the facility condition.

## 1.5 Organization of Thesis

This thesis is written in manuscript format (paper based). Outline of each chapter is explained below:

Chapter 1 is a brief introduction on the concept of dust explosion occurrence and prevention in process industries followed by the motivations and objectives of this research.

Chapter 2 presents the literature review pertinent to this thesis. The literature review mainly deals with the existing prevention and mitigation strategies in process facilities.

Chapter 3 introduces a conceptual model developed by the authors which uses conditional probabilistic approaches. The model focuses on six key parameter of dust explosion and based on the facility operating condition it can assess the likelihood of a dust explosion. This chapter is submitted to the *Journal of Hazardous Materials*.

Chapter 4 presents the application of the conceptual model developed earlier by the authors. Three case studies are discussed to demonstrate the implementation of the model in process facility. This chapter is submitted to the *Journal of Chemical Health and Safety*.

Chapter 5 concludes the study by a brief summary, conclusion and future scope of research in this area.

# Chapter 2

# Literature Review

## 2.1 Preface

Dust explosion is considered as a serious threat for the industry that use/handles dust of combustible materials. Dust explosion may lead towards a serious financial losses in terms of damage to the facility and personnel. To protect the industry from such catastrophic accidents, substantial advance have been made through diverse research and development. In dust explosion prevention and mitigation associated with other challenges, there is a continuous strive for a perfect solution [Eckhoff, 1995]. Industry always needs a practicable solutions which can be implemented easily to achieve a better safety measure. The importance of inherently safer process design, better understanding the mechanism of dust explosion, system safety and reliability systems are the prime concern of improvement. But these areas lack the analysis in terms of probabilistic modelling. A conditional probabilistic approach is discussed to better understand the dust explosion occurrence. In this study, a newly proposed model is described which can be used to asses the plant condition and hence taking safety precaution according to that.

## 2.2 Definition of Combustible Dust

According to the definition of BS2955 [BS1, 1958, Lees and Mannan, 2005], particles with a diameter of less than 1000 $\mu$m (microns) are defined as powder and when particles have a diameter less than 76 $\mu$m (200BS mesh size) they are referred to as 'dust'. As per NFPA (National Fire Protection Association) 'dust' is any finely divided solid, 420 $\mu$m or less in diameter. Though BS:2955 [BS1, 1958, Lees and Mannan, 2005] and NFPA 68 have different definitions for defining dust, Palmer [Palmer, 1973] proposed that a particle with a diameter coarser than 1000 $\mu$m is be called dust [Lees and Mannan, 2005]. The term dust used as per the NFPA 68 [NFPA, 2007] definition, which is considered potentially threatening for the process industries. As the range of the explosible particle size may be larger for a specific material, the particle size distribution is considered in addition to the median particle diameter [Amyotte and Eckhoff, 2010]. In this study, combustible dust is the prime focus. Any dust capable of creating violent explosion when it is suspended in air in ignitable concentrations, regardless of size, shape or chemical compositions is be called combustible dust [Amyotte and Eckhoff, 2010].

## 2.3 Dust and Gas Explosion

While most industrial practitioner are familiar with the mechanism of gas explosion (e.g., the requirement of fuel, oxidant and ignition source, known as fire triangle), the dust explosion is often considered less familiar [Amyotte and Eckhoff, 2010]. The primary difference between gas and dust explosion is the phase of the fuel. Dust particles are solid materials where the fuel is in gaseous state for gas explosion. According to Kauffman [Kauffman, 1982] a dust explosion will occur when the explosion pentagon is completed.

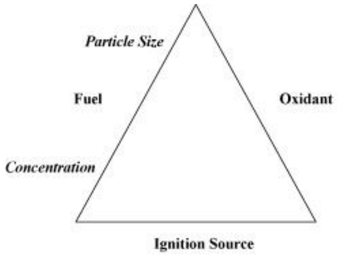

Figure 2.1: Fire triangle

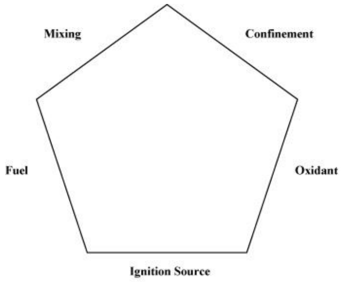

Figure 2.2: Dust explosion pentagon

This pentagon consists of mixing, confinement, fuel, oxidant and an ignition source. When these parameters reach a sufficient threshold limit (explosible range), dust explosion occurs [Abbasi and Abbasi, 2007]. In addition, explosion may not occur if all parameters do not reach the explosible range [NFPA, 2007]. Amyotte and Eckhoff [Amyotte and Eckhoff, 2010] made an comprehensive study on the basic difference between these two and conclusively stated the causation for dust explosion.

## 2.4 Dust Explosion Mechanism

Dust explosion is a rapid and simultaneous combustion of flammable suspended particles [Abbasi and Abbasi, 2007]. The strength of the combustion depends on burning speed and the degree of confinement of particle [Eckhoff, 2003]. Dust explosion often follows a domino effect: a secondary explosion followed by a primary explosion [Pickup, 2001, Lees and Mannan, 2005]. The first explosion may set a series of explosion called "domino effect" and leads toward a secondary explosion which are often violent than the primary one [Lees and Mannan, 2005]. A secondary explosion can be initiated due to entrainment of dust layers by the blast waves arising from a primary explosion [Amyotte and Eckhoff, 2010].

Five parameters are identified as dust explosion influential parameter: particle diameter, minimum explosible concentration, minimum ignition energy, minimum ignition temperature and limiting oxygen concentration, whereas the maximum explosion pressure represents the severity of dust explosion. Five essential elements ( e.g. fuel, oxidant, ignition source, mixing and confinement) form a dust explosion pentagon [Kauffman, 1982]. These five elements are represented by five influencing parameters of dust explosion. When these parameter reaches to the explosible range, dust explosion occurs [Abbasi and Abbasi, 2007]. Explosion may not occur if all parameter do not reach the explosible range [NFPA, 2007].

The outcome of the dust explosion is measured in terms of severity. In the study, the maximum explosion pressure is the indicator of the severity, as it is the most widely used indicator of the explosion scenario for a particular dust. A brief description of these six ( five influencing parameters and one severity parameter) parameters is given below:

- Particle Diameter (PD): Dust particles have different shapes and sizes. In this study, Particle median diameter is chosen as PD. The unit of the PD is micron, $\mu$m.

- Minimum Explosible Concentration (MEC): If the dust particles are accumulated in a certain volume then the concentration is a major factor in an explosion. A dust cloud must have to maintain a minimum concentration below which it will not be able to explode. MEC is measured in g/m$^3$.

- Minimum Ignition Energy (MIE): The dust particle, if exposed to a suitable condition which facilitates the explosion, must have a minimum ignition energy. If the minimum ignition energy requirement is not met the explosion will not take place. The unit of MIE is mJ.

- Minimum Ignition Temperature (MIT): The minimum temperature which is required to initiate the ignition process is called minimum ignition temperature, MIT. The unit used to measure MIT is °C.

- Limiting Oxygen Concentration (LOC): Limiting oxygen concentration is the availability of the oxidant. The LOC is measured by volume % of $O_2$ above which deflagration can take place [NFPA, 2008].

- Maximum Explosion Pressure ($P_{max}$): When the explosion takes place the parameter which measures the severity of the explosion is pressure. The unit of measurement for maximum explosion pressure is bar(g).

## 2.5 Dust Explosion Prevention and Mitigation

When selecting dust explosion prevention and mitigation, it is very helpful to employ a heuristic or framework for making appropriate choices [Amyotte et al., 2003]. The fire triangle in Figure 2.1 and the explosion pentagon in Figure 2.2 offer guidance to identify the explosion causation factors [Amyotte and Eckhoff, 2010]. For example, the triangle provides industrial practitioners several approaches to explosion prevention (e.g., removal of fuel by good housekeeping and removal of ignition sources by grounding). The use of the pentagon may help to visualize explosion requirements leads to identification of measures for explosion mitigation such as venting (in relief of the confinement criterion) [Amyotte and Eckhoff, 2010]. For further development of preventive and mitigatory methods, fundamental aspects in dust explosion research needs to focus on dust cloud formation, dust cloud ignition process, flame propagation process in dust clouds and blast wave generated by burning dust clouds [Eckhoff, 2005]. Some of widely used prevention and mitigation process are described below:

### 2.5.1 Explosion Venting

Explosion venting is one of the most widely used methods of mitigating dust explosion. The vital point of venting is area sizing [Eckhoff, 2005]. Tamanini and Valiulis [Tamanini and Valiulis, 1996] illustrated an improved model for sizing vents for the protection of equipment and buildings from dust explosions, rely on statistical regressions of test data. An effort based on this approach produced notable improvements in several aspects of explosion vent sizing, including: vent duct and panel inertia effects, partial volume deflagrations, venting of equipment inside buildings, and explosions at initial elevated pressure etc. A similar approach was discussed by Ural [Ural, 2001]. Different formulae have been used to size the explosion vents for strong and weak enclosure. The National Fire Protection Association (NFPA) 68 Committee has developed a simplified equation for strong and weak structures that may be subjected to full volume or partial volume internal explosions. Ural [Ural, 2001] proposed the simplified analysis which was used to develop the unified formula.

Venting provides a smooth way of emission of blast waves and flames to the surroundings which may present hazard. several works has been developed to eliminate hazards from the vent opening. Harmanny [Harmanny, 2001], Holbrow, Hawksworth and Tyldesley [Holbrow et al., 2000] reported various aspects of blast wave magnitude, vent sizing and hazards on surroundings. Li, Deng and Liu [Li et al., 1994] discussed about the quenching vending door (QVD) for dust and flame free venting. To predict the resultant reacting impulse on a process structure during vented explosion, Tamanini and Valiulis [Tamanini and Valiulis, 2000], Ural [Ural, 1993] presented a novel approach. It was a conceptual formulation of theoretical approach. Lunn [Lunn, 2001] studied some experiments on the impact of vent ducts at maximum explosion pressure during vented explosion. Crowhurst [Crowhurst, 1993] presented a conclusive summary on the special consideration for industrial buildings and venting arrangements for rooms/buildings $> 5000$ m$^3$ with walls which is able to withstand overpressure 0.2 bar. Tamanini [Tamanini, 2002] addresses two directions in which design methods can evolve to yield more advanced predictive tools for engineering applications. First, making use of simple models to identify parameters that better capture the features of the available data. Adopting this feature, modelling can also be used in a predictive mode. Second, the development and eventual adoption of more advanced techniques, to address aspects of explosion problems that are currently well beyond the capabilities of available methods. This last step will be necessary for the technology to model diverse explosion scenario [Tamanini, 2002].

### 2.5.2 Explosion Isolation

The objective of explosion isolation is to prevent spreading of dust explosions from the primary explosion location to other process units. Two approaches are widely adopted for isolation: using quick acting shut-off valves and material chokes [Abbasi and Abbasi, 2007].

Wingerden, Pedersen, Teigland and Eckhoff [Van Wingerden et al., 1995] worked experimentally on vented vessels interconnected via duct. To prevent dust explosion spreading from one portion to another, several methods of explosion isolations can be used. For example, fast-acting mechanical valves, rotary locks and diverters. Adoption of such process will make the system more safer and reliable. Holbrow, Andrews and Lunn [Holbrow et al., 1996] and Holbrow, Lunn and Tyldesley [Holbrow et al., 1999] recapitulated the outcomes of similar experiments in UK and described quantitative guidance during designing phase of interconnected process equipments.

### 2.5.3 Automatic Explosion Suppression (AES)

A system which gets activated as soon as the the explosion begin to take place, suppresses the the explosion by immediately adding inertants, and prevents it from rebuilding, is known as automatic explosion suppression system (AES). AES device aims to achieve four basic attributes [Abbasi and Abbasi, 2007]:

- Responds within minimum time delay with activation
- Adequate suppressant injection within short time to arrest the flame propagation
- To shut down the plant
- Prevent the plant getting restarted until complete explosion hazard mitigation

Moore [Moore, 1996], Chatrathi and Going [Chatrathi and Going, 1998] discussed about the suitable suppressant selection. Moore and Siwek [Moore and Siwek, 1998] recapitulate the extensive experimental work and provided significant modification on suppressant system. Chatrathi and Going [Chatrathi and Going, 2000] provided a comprehensive overview of recent technology and suggestion for implementing automatic suppression system in industrial aspect.

In contrary, this method of dust explosion mitigation is comparatively complex and costly to adopt, therefore, used when less expensive methods are not adequate [Eckhoff, 2005].

### 2.5.4 Inerting

Intering is comparatively a new but promising concept of dust explosion mitigation process. With the reduction of oxygen, both ignition sensitivity and combustion rate of the dust cloud decreases. This concept is applied for the inerting process. A moderate reduction in oxygen concentration can significantly reduce the explosion hazard [Amyotte and Eckhoff, 2010]. A modest reduction of oxygen can significantly increase the minimum ignition energy. In gaseous phase (mixture of nitrogen and oxygen) maximum rate of pressure rise ($K_{st}$) exhibits a liner relation with the percentage of oxygen concentration [Devlikanov et al., 1995]. Eckhoff [Eckhoff, 2004] proposed for extensive use of partial inerting as it a cost effective and efficient way of mitigating dust explosion.

### 2.5.5 Process Equipment Design

Design of process equipment for specific internal explosion load can significantly change the safety standard of the plant. Harmanny's [Harmanny, 1993] study delivers the insight to predict the response of the enclosure structure to the explosion load.

The limitation of the study was revisited by Harmanny [Harmanny, 1996, Harmanny, 1999] and it provides a conclusion that, the concept of pressure-shock-resistant design should be developed further to facilitate cost effective equipment design. Li, Chen, Deng and Eckhoff [Li et al., 2002] compared the elastic and plastic structural response of a simple mechanical structure determined experimentally with prediction from using a computational finite-element based approach.

# Chapter 3

# A Model to Assess Dust Explosion Occurrence Probability

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## Preface

A version of this manuscript is accepted in the *Journal of Hazardous Materials, January 2014 (Reference No: HAZMAT-D-13-03942R1).* The co-authors, Dr. Khan, Amyotte and Refaul supervised the principle author, Junaid, to develop the research on the entitled topic and helped him to conceptualize the techniques and theories available for this topic. Junaid conducted the dust explosion prediction modelling and associated statistical tests and necessary analysis while Dr. Khan, Amyotte and Refaul reviewed the manuscript and provided necessary suggestions.

## Abstract

Dust handling poses a potential explosion hazard in many industrial facilities. The consequences of a dust explosion are often severe and similar to a gas explosion; however, its occurrence is conditional to the presence of five elements: combustible dust, ignition source, oxidant, mixing and confinement. Experiments have been conducted by dust explosion researchers to study the characteristics of these elements and generate data for explosibility. These experiments are often costly but the generated data has a significant scope in estimating the probability of a dust explosion occurrence. This paper attempts to use existing information (experimental data) to develop a predictive model to assess the probability of a dust explosion occurrence in a given environment. The proposed model considers six key parameters of a dust explosion: Dust Particle Diameter ($PD$), Minimum Ignition Energy ($MIE$), Minimum Explosible Concentration ($MEC$), Minimum Ignition Temperature ($MIT$), Limiting Oxygen Concentration ($LOC$) and Explosion Pressure ($P_{max}$). A conditional probabilistic approach has been developed and embedded in the proposed model to generate a nomograph for assessing dust explosion occurrence. The generated nomograph provides a quick assessment technique to map the occurrence probability of a dust explosion for a given environment defined with the six parameters.

Keywords: Probabilistic approach, Probability distribution, Dust explosion, Dust explosion parameters, Nomograph.

## 3.1 Introduction

### 3.1.1 Dust explosion

Dust explosions pose a serious hazard in dust processing facilities. According to the definition of BS2955 [BS1, 1958, Lees and Mannan, 2005], particles with a diameter of less than 1000 $\mu$m are defined as powder and when particles have a diameter less than 76 $\mu$m (200BS mesh size) they are referred to as 'dust'. As per NFPA (National Fire Protection Association), 'dust' is any finely divided solid, 420 $\mu$m or less in diameter. Though BS:2955 [BS1, 1958, Lees and Mannan, 2005] and NFPA 68 have different definitions for defining dust, Palmer [Palmer, 1973] proposed that a particle with a diameter coarser than 1000 $\mu$m should be called dust [Lees and Mannan, 2005]. The term dust used as per the NFPA 68 [NFPA, 2007] definition, which is considered potentially threatening for the process industries. As the range of the explosible particle size may be larger for a specific material, the particle size distribution is considered in addition to the median particle diameter [Amyotte and Eckhoff, 2010]. In this study, combustible dust is the primary focus. Any particular material capable of exploding when suspended in air in ignitable concentrations, regardless of size, shape or chemical composition termed combustible dust [Amyotte and Eckhoff, 2010].

Dust explosion scenarios are not only restricted to coal mines or food industries; they may occur at a chemical process plant, in the wood and paper industry, in metal handling units, etc. Most dust handling plants are susceptible to dust explosions and thus require special safety measures and monitoring aids.

Combustible dust needs to achieve certain criteria to explode. Five factors are identified as triggers responsible for a dust explosion : particle diameter, minimum explosible concentration, minimum ignition energy, minimum ignition temperature and limiting oxygen concentration. To cause an explosion, five criteria ( fuel, oxidant, ignition source, mixing and confinement) need to be fulfilled. The five identified parameters cover the five essential elements of a dust explosion. A dust explosion is a rapid combustion of flammable dust particles in an environment that supports the initiation of the combustion.

A dust explosion is initiated when suspended flammable particles in the air are in close proximity with a proper ignition source. If the dust cloud is unconfined and the ignition source is present, it would typically produce a flash fire. For rapid and violent combustion, confinement is a necessary element. Likewise, four other conditions are also very important for an explosion to occur. According to Kauffman [Kauffman, 1982] a dust explosion will occur when the explosion pentagon is completed. This pentagon consists of mixing, confinement, fuel, oxidant and an ignition source. When these parameters reach a sufficient threshold limit (explosible range), a dust explosion occurs [Abbasi and Abbasi, 2007]. In addition, an explosion may not occur if all parameters do not reach the explosible range [NFPA, 2007].

In this study, a conceptual framework for a dust explosion prediction model is proposed which considers a process plants operating conditions and provides a quick estimate of dust explosion occurrence. For the development of the model, six basic parameters are identified that are necessary to describe dust explosion phenomena in a conditional probabilistic way. These parameters are analysed thoroughly to understand their pattern. The parameters have a wide range of numerical values so their inherent distributions are identified. The distribution highlights the characteristics of the parameter and also imparts knowledge on the variety of the data. These distributions are used to develop the dust explosion prediction model. To assess the conditional probability, two parameters at a time have been considered to estimate the probability of explosion occurrence for a given scenario. Estimating the conditional probability for each parameter and integrating them over a range provides the total probability of dust explosion occurrence. The systematic approach provides a simple guideline which can be used in monitoring process facility conditions. A simplified "nomograph" is introduced to make the model easier and more user-friendly. A nomograph is a very useful tool for understanding the operating conditions of a process plant in terms of the probability of a dust explosion.

In this paper, an overview of the methodology and a brief description of the proposed model are provided in sections 4.2 and 4.3. The application of the proposed model in the industry is described in section 3.4. Section 3.5 is devoted to discussion and section 3.6 gives the conclusions, which include recommendations for future work.

### 3.1.2 Mechanism and causes

A dust explosion is a rapid and simultaneous combustion of flammable suspended particles [Abbasi and Abbasi, 2007]. Its strength is dependent on flame speed and the degree of confinement of the particles [Eckhoff, 2003]. As mentioned earlier, five basic parameters are responsible for dust explosion occurrence. The outcome of the dust explosion is measured in terms of severity. In the study, the maximum explosion pressure is the indicator of the severity, as it is the most widely used indicator of the explosion scenario for a particular dust. A brief description of these six parameters is given below:

- Particle Diameter (PD): Dust particles have different shapes and sizes.In this study, the particle median diameter is chosen as PD and only micron-sized dusts are considered. Median diameter may be different if it is on a mass basis or a volume basis. However, for most dusts particles of interest, it is assumed that density remains constant throughout the entire particle size distribution. Thus mass basis analysis can be treated similar as volume basis. The unit of the PD is $\mu$m.

- Minimum Explosible Concentration (MEC): If the dust particles are accumulated in a certain volume then the concentration is a major factor in an explosion. A dust cloud must maintain a minimum concentration below which it will not be able to explode. MEC is measured in g/m$^3$.
- Minimum Ignition Energy (MIE): If the minimum ignition energy requirement is not met the explosion will not take place. The unit of MIE is mJ.
- Minimum Ignition Temperature (MIT): The minimum temperature which is required to initiate the ignition process is called the minimum ignition temperature, MIT. The unit used to measure MIT is °C.
- Limiting Oxygen Concentration (LOC): Limiting oxygen concentration is the availability of the oxidant. The LOC is measured by volume % of $O_2$ above which a deflagration can take place [NFPA, 2008].
- Maximum Explosion Pressure ($P_{max}$): When an explosion takes place the parameter which measures the severity of the explosion is pressure. The unit of measurement for maximum explosion pressure is bar(g).

For a given dust material, $P_{max}$ increases with a decrease in PD. Usually, MIE decreases with a decrease of PD and a decrease of PD can also lower MEC and MIT [Eckhoff, 2003]. Dust particles vary considerably from industry to industry, based on their chemical composition, which includes food, wood, coal, pharmaceuticals, plastic, metal and paper. However, in this study, the chemical composition is not considered. Therefore, the developed model to assess the probability of dust explosion is a generic model irrespective of dust type. All dusts are not likely to be explosible. The finer the particle size the lesser the requirement for MIE, which allows the dust particles to burn easily. Once they are in contact with air and fuel in a confined space, this can produce an explosion. Sometimes partial confinement can cause an explosion which is similar to a flammable gas [Proust, 2006]. Industrial process plants are dependent mostly on 'scaling up' to enhance their production and most of them are huge, complex facilities which are also associated with greater risk of human injury, environmental damage and economic loss [Khan and Amyotte, 2004, Khan et al., 2002].

A dust explosion may follow a domino effect: a primary explosion followed by a secondary one. Most of the safety hazard mitigation processes try to eliminate the possibility of an explosion by imposing a layer of protection to prevent the simultaneous deterioration of the safety barrier. Once the secondary explosion begins it might take on a more violent form causing a great amount of loss [Pickup, 2001].

### 3.1.3 Current status of dust explosion research

Dust explosion hazards are a continuous threat to process facilities that deal with powders or combustible materials. Research on safer plant design, safer work places and several standard safety codes is available in contemporary literature and books [Amyotte et al., 2009, Amyotte et al., 2003, Khan and Amyotte, 2003, Eckhoff, 2003, Eckhoff, 2005].

Amyotte et al. [Amyotte et al., 2003] proposed inherent safety as a proactive approach for hazard and risk mitigation during the design and operation phase. The proposed methodology discusses safer process implementation, considering inherent safety in the reduction of hazards at the very first instance in the workplace. Their conceptual framework mainly discusses minimizing, substituting, moderating and simplifying the process plant to eradicate the possibilities of hazards to improve safety and protection [Khan and Amyotte, 2003].

The framework proposed by Amyotte et al. [Amyotte and Khan, 2002] incorporates the principle of inherent safety, which is actually aimed at first reducing or completely removing the hazard, followed by addressing the frequency of occurrence and the subsequent severity component of risk.

Eckhoff [Eckhoff, 2005] analysed a comprehensive compendium of the current status and expected future of dust explosion research. He discussed various existing safety precautionary measures used or under consideration. Flame propagation reduction, preventing explosive dust clouds and ignition sources were elaborately analysed. Moreover, explosion isolation, automatic explosion suppression and explosion venting were discussed throughout his study.

A number of safety codes are available that help to protect the industry from dust explosions. The National Fire Protection Association (NFPA) provides a number of codes (e.g. NFPA 68, 69, 650, 654) to prevent and mitigate dust explosions [Abbasi and Abbasi, 2007].

### 3.1.4 Probabilistic measure for dust explosion

The aforementioned safety standards are widely followed by industry. Different safety methods have been proposed and analysed with case studies to make process plants safer. Still, dust explosion is an alarming issue for industries which are dealing continuously with dust materials.

Research has been done and is still ongoing on the prevention system, inherently safer design and protective or mitigatory measures. To maintain a high level of safety, process industries are trying to provide more safety training and education. Hence, it is very important to analyse the process parameters and to understand the probability of dust explosion occurrence in a specific scenario. Dust explosion researchers have contributed significantly to dust explosion parameters and their characteristics. This existing knowledge can be effectively utilized in probabilistic approaches to get a predictive model. A vast amount of data has never been analysed to understand the distribution of the dust explosion parameters. These distributions are used in the probabilistic model to adopt a better and safer process facility.

The risk assessment involves two quantitative terms: the probability of an occurrence and the consequence. Significant research has been done on the latter part. While considering risk assessment the probability of the explosion is either chosen or derived from the frequencies of dust explosion [Voort et al., 2007]. In this paper, a newly developed model is introduced to estimate the probability of a dust explosion.

The model considers six parameters. These parameters are divided into two major divisions: the influencing parameter and the severity parameter. Five influencing parameters are mentioned earlier and one parameter is taken as a severity parameter to determine the conditional probability of a dust explosion. Five conditional probabilities are combined to estimate the total probability of dust explosion occurrence. A probabilistic model for assessing and quantifying the probability of a dust explosion occurrence is the novelty of this paper. A conditional probabilistic way to determine the probability, and developing the nomograph is the main focus of this paper.

## 3.2 Methodology for dust explosion probability assessment

The proposed methodology to assess dust explosion likelihood is comprised of five steps. These steps are subdivided into several sub-steps. Figure 4.1 represents the framework of the proposed methodology. Details are given below:

1. Hazard identification,
2. Data collection,
3. Data analysis,
4. Probabilistic modelling and
5. Nomograph development

### 3.2.1 Step 1 : Hazard identification

Hazard identification is the first step of the methodology. The possible hazards for a dust explosion are identified in this step. The list of possible hazards is considered and the elements with the most potential for contributing to the hazards are determined. For example, a dust explosion occurs when the process parameters are not in the safe operating region. Dust explosion parameters are monitored and compared with the limiting state (regulatory standard or operating limit). If the parameter exceeds the limiting state, it is considered as a potential hazard for the process facility. All the potential hazards are identified and listed in this step.

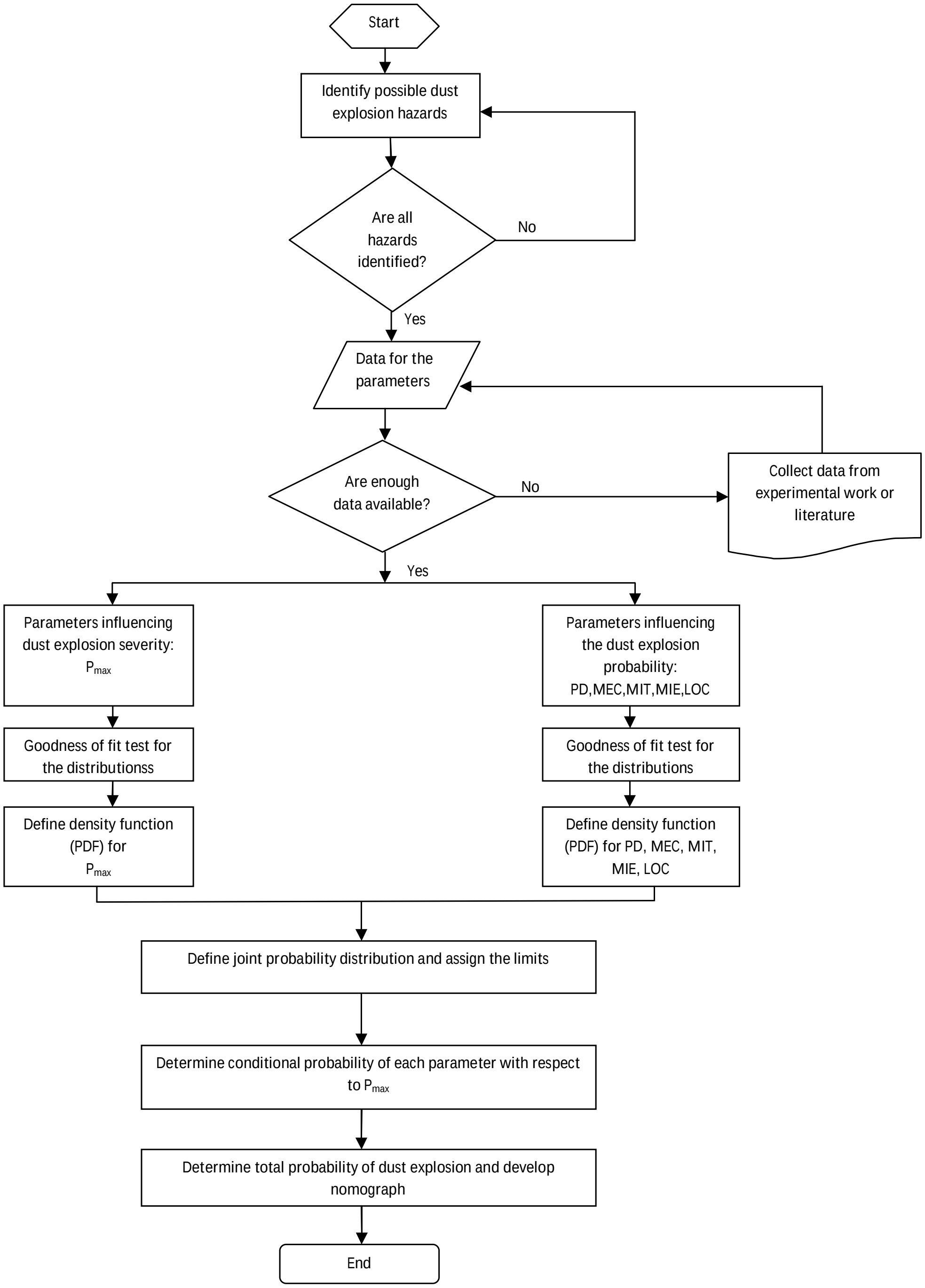


Figure 3.1: A framework for assessing dust explosion occurrence

### 3.2.2 Step 2 : Data collection

Collecting available data is the focus of this step. After identifying possible hazards, relevant parameters are searched individually for the available data. These data may be collected either from experimental work, standard literature or pertinent databases. If sufficient data are available, the process proceeds to the next step. Otherwise, an engineering judgement is made with regard to the missing data. In this study, Rolf Echkoff's book (Appendix: Table: A1 in reference [Eckhoff, 2003] and NFPA 69 standard (Table C.1(b) in reference [NFPA, 2008] are used for collecting data. To obtain a generic model the considered data contains dust particle of food feed; metal alloys; plastic, resin and rubber; coal products and pharmaceuticals.

### 3.2.3 Step 3 : Data analysis

In this step, the underlying distribution for six parameters is determined from the collected data and the probability density functions (PDFs) are also defined. This step involves three sub-steps which are discussed below:

#### 3.2.3.1 Parameter classification

The potential hazard and associated parameters identified in step 1 are classified in two different groups: dust explosion influencing parameters and severity parameters. Particle Diameter (PD), Minimum Explosible Concentration (MEC), Minimum Ignition Temperature (MIT), Minimum Ignition Energy (MIE) and Limiting Oxygen Concentration (LOC) are considered as dust explosion influencing parameters. The Maximum Explosion Pressure, $P_{max}$ is considered as the dust explosion severity parameter.

#### 3.2.3.2 Statistical analysis

In this sub-step, the obtained data is analysed statistically to determine distribution. For each parameter, the collected data is analysed through different statistical tests such as non-parametric goodness of fit tests; e.g. the Anderson Darling (AD) and Kolmogorov Smirnov (KS) test. The analysis helps to determine the best fitted distribution for each parameter.

#### 3.2.3.3 PDFs determination

In this sub-step, the mathematical functions for good-fit-distributions for each parameter are determined using the supportive statistical tools of Minitab and Matlab.

### 3.2.4 Step 4 : Probabilistic modelling

The results from step 2 and the obtained distributions and mathematical functions from step 3 are successively used in modelling the dust explosion likelihood for a given condition. Step 4 is comprised of three sub-steps as discussed below:

#### 3.2.4.1 Joint probability distribution determination and integral limit specification

For the conditional probability estimation, the joint probability distribution must be determined. Once the distributions are defined the next step is to form a joint probability distribution. To determine a joint probability distribution, correlation between the distributions needs to be defined. To determine the joint probability equation, a single parameter is always considered from influencing parameters along with the severity parameter, and the remaining parameters are kept constant.

One of the most challenging parts of the methodology is to correlate two distributions with a single parameter. To solve this problem, the correlation between the parameters is defined by using a copula function. Integral limits are developed by analysing the available data. The upper and lower bounds of the integrals of the joint probability equations are replaced accordingly, with the lower and higher values of the data. The same procedure is repeated for the other influencing parameters. The final outcome of this section is the joint probability distribution equation for all potential parameters, correlating the severity parameter and influencing parameters.

#### 3.2.4.2 Conditional probability assessment

This sub-step's aim is to quantify the conditional probability of the dust explosion. The joint probability equations are solved to obtain the quantitative estimate of the conditional probability. A software, Maple is used to solve the complex integrals of joint probability functions. The conditional probability evaluates the likelihood of the dust explosion for a given parameter with a specific range. Again, the solution of the complex integral of joint probability function is obtained by considering one parameter at a time. The adoption of the discussed procedure enables the quantification of the likelihood of dust explosion for a given range of any parameter which has been earlier identified and analysed in steps 1, 2 and 3.

#### 3.2.4.3 Total probability estimation

The final sub-step of the probabilistic modelling [3.2.4] is to determine the total probability of a dust explosion and to develop the nomograph. The results obtained from the sub-steps [3.2.4.2] for different parameters are combined to assess the total probability. This helps to estimate the total probability of a dust explosion for a given condition of operating parameters.

### 3.2.5 Step 5 : Nomograph development

The final step of the methodology is to develop a nomograph. A nomograph is developed to provide a quick estimation and a visual representation of the dust explosion probability. A dust explosion pentagon is used for depicting the vulnerable region and visualizing the area under the pentagon to represent the total probability of dust explosion. The nomograph is a simpler way to study the impact of the operating conditions in terms of probability of exceedance.

## 3.3 Model for dust explosion prediction

The proposed methodology employs the rules of conditional probability to determine the total probability of a dust explosion. Conditional probability defines the probability of a specific event with given conditions. For instance, consider A and B as two dependent events. The conditional probability of an event B in relationship to event A is the probability that event B occurs given that event A has already occurred. The concept is identical if event B happens prior to event A.

General equation for conditional probability rules:

$$\begin{aligned}
P(A \cap B) &= P(A) * P(B/A) \\
&= P(B) * P(A/B) \\
or, P(B/A) &= \frac{P(A \cap B)}{P(A)} \\
&= \frac{\int_A \int_B (Joint\, function\, of\, A\, and\, B)\, dB\, dA}{\int_A (function\, of\, A)\, dA} \\
or, P(A/B) &= \frac{P(B \cap A)}{P(B)} \\
&= \frac{\int_A \int_B (Joint\, function\, of\, A\, and\, B)\, dB\, dA}{\int_B (function\, of\, B)\, dB}
\end{aligned} \tag{3.1}$$

The conditional probability rules can be applied for the dust explosion phenomenon considering its occurrence as a consequence of influencing parameters. For any influencing parameter there is a threshold value up to which the dust explosion will not be triggered. Therefore, the dust explosion is a conditioned event, depending on the transcendence of the limiting value of influencing parameters. To model dust explosion probability, one influencing parameter is considered at a time. To determine a conditional probability equation two dust explosion variables are used. One variable is considered from the dust explosion influencing parameters and the other one is P$_{max}$, as a severity parameter. The joint probability equation can be determined by using these two parameters.

The joint probability equation for particle diameter and dust explosion pressure is:

$$P(P_{max}/PD) = \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{PD_{critical_{min}}}^{PD_{critical_{max}}} P(P_{max} \cap PD)\, dPDdP_{max}}{\int_{PD_{min}}^{PD_{max}} PDdPD} \tag{3.2}$$

Joint probability equation for MEC and dust explosion pressure is:

$$P(P_{max}/MEC) = \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{MEC_{critical_{min}}}^{MEC_{critical_{max}}} P(P_{max} \cap MEC)\, dMECdP_{max}}{\int_{MEC_{min}}^{MEC_{max}} MEC\, dMEC} \tag{3.3}$$

Joint probability equation for MIT and dust explosion pressure is:

$$P(P_{max}/MIT) = \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{MIT_{critical_{min}}}^{MIT_{critical_{max}}} P(P_{max} \cap MIT)\, dMITdP_{max}}{\int_{MIT_{min}}^{MIT_{max}} MIT\, dMIT} \tag{3.4}$$

Joint probability equation for MIE and dust explosion pressure is:

$$P(P_{max}/MIE) = \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{MIE_{critical_{min}}}^{MIE_{critical_{max}}} P(P_{max} \cap MIE)\, dMIEdP_{max}}{\int_{MIE_{min}}^{MIE_{max}} MIE\, dMIE} \tag{3.5}$$

Joint probability equation for LOC and dust explosion pressure is:

$$P(P_{max}/LOC) = \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{LOC_{critical_{min}}}^{LOC_{critical_{max}}} P(P_{max} \cap LOC)\, dLOC dP_{max}}{\int_{LOC_{min}}^{LOC_{max}} LOC\, dLOC} \tag{3.6}$$

Five influencing parameters in terms of severity parameters are expressed by the joint probability equation (from Equation 3.2 to Equation 3.6). In these equations, two different kinds of integral notation are used; e.g. PD has two different ranges. From the pool of extracted data from the source, the lower and upper limits are denoted by PD$_{min}$ and PD$_{max}$. From the extracted data, a 95% data range is considered as the critical limit. The lower and higher range of the critical limit is denoted by PD$_{critical_{min}}$ and PD$_{critical_{max}}$. The functional relationship between the influencing parameters and severity parameter is established by the joint probability equations.

While determining the conditional probability for each parameter with respect to P$_{max}$ as the severity parameter, two different sets of integral limits on the numerator and denominator part of the equation are considered. On the numerator part, the double integral of the joint function measures the most vulnerable region for both the influencing parameter and the severity parameter. On the denominator part, the integral of the parameter evaluates the probability of obtaining the parameter in a vulnerable region. To solve the joint probability equation the specific distribution for each of the parameters is required.

Four distributions : normal, lognormal, weibull and gamma were chosen for analysing the goodness-of-fit test for the particle diameter (PD). The probability plot for the particle diameter shows four different distributions as part of the analysis. In the study, the level of significance, $\alpha$=0.05 is used. It provides a 95% confidence level. The probability plot (Figure 3.2) shows that the lognormal distribution provides the best fit for PD. Depending on the statistical analysis, given earlier in section 3.2.3, it can be deduced that the best distribution for particle diameter is lognormal distribution. The distribution parameters are determined through detailed statistical analysis.

A similar goodness-of-fit test approach has been implemented for MEC, MIE, MIT and LOC to determine the best fit distributions and to identify the distribution parameters. The details of each distribution are depicted in Table 4.1.

Table 3.1: Dust explosion parameter distribution identification

| Dust explosion parameters | Best fitted distribution | Estimated distribution parameter | 95% Data range |
|---|---|---|---|
| PD | Lognormal | $\lambda_{PD}$=4.02, $\zeta_{PD}$=0.95513 | 25-400 $\mu$m |
| MEC | Normal | $\mu_{MEC}$=80, $\sigma_{MEC}$=45 | 15-215 g/m$^3$ |
| MIT | Normal | $\mu_{MIT}$=504, $\sigma_{MIT}$=65 | 400-700 °C |
| MIE | Lognormal | $\lambda_{MIE}$=4.71518, $\zeta_{MIE}$=1.50173 | 10-700 mJ |
| LOC | Normal | $\mu_{LOC}$=10.97, $\sigma_{LOC}$=2.12468 | 8.75-12 % $O_2$ |
| $P_{max}$ | Weibull | $\beta_{P_{max}}$=8.89, $\theta_{P_{max}}$=10.7 | 8-10.5 bar(g) |

The estimated parameters of the identified distributions can be used in the mathemat-

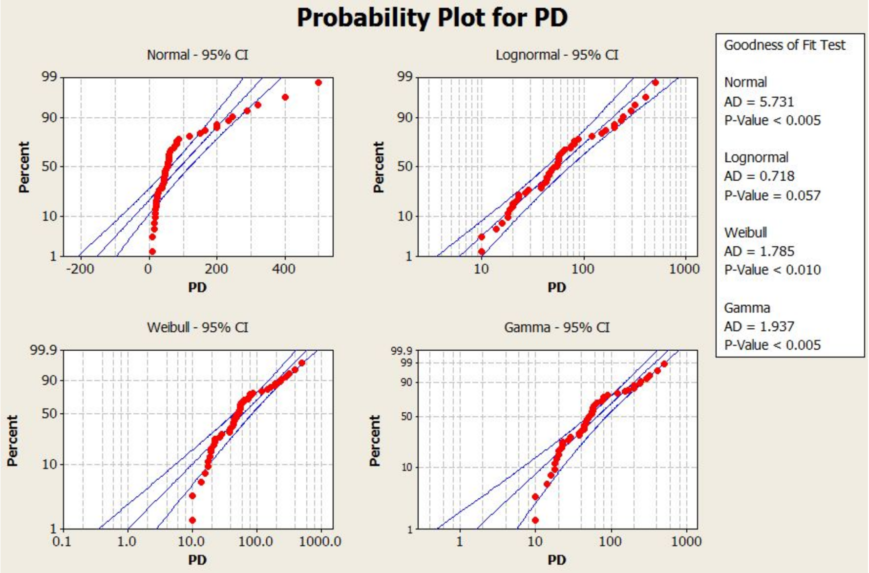


Figure 3.2: The probability plot for particle diameter analysis

ical formulation of the probability distribution function. Equations with parameters to assist the analysis to determine the likelihood of the dust explosion phenomenon are given as:

For PD:

$$f_{PD}(PD;\lambda_{PD},\zeta_{PD}) = \frac{1}{PD\zeta_{PD}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{\ln(PD)-\lambda_{PD}}{\zeta_{PD}})^2} \tag{3.7}$$

For MEC:

$$f_{MEC}(MEC;\mu_{MEC},\sigma_{MEC}) = \frac{1}{\sigma_{MEC}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{MEC-\mu_{MEC}}{\sigma_{MEC}})^2} \tag{3.8}$$

For MIT:

$$f_{MIT}(MIT;\mu_{MIT},\sigma_{MIT}) = \frac{1}{\sigma_{MIT}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{MIT-\mu_{MIT}}{\sigma_{MIT}})^2} \tag{3.9}$$

For MIE:

$$f_{MIE}(MIE;\lambda_{MIE},\zeta_{MIE}) = \frac{1}{MIE\zeta_{MIE}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{\ln(MIE)-\lambda_{MIE}}{\zeta_{MIE}})^2} \tag{3.10}$$

For LOC:

$$f_{LOC}(LOC;\mu_{LOC},\sigma_{LOC}) = \frac{1}{\sigma_{LOC}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{LOC-\mu_{LOC}}{\sigma_{LOC}})^2} \tag{3.11}$$

For P$_{max}$:

$$f_{P_{max}}(P_{max};\beta_{P_{max}},\theta_{P_{max}}) = \frac{\beta_{P_{max}}}{\theta_{P_{max}}}(\frac{P_{max}}{\theta_{P_{max}}})^{\beta_{P_{max}}-1}e^{-(\frac{P_{max}}{\theta_{P_{max}}})^{\beta}_{P_{max}}} \tag{3.12}$$

Equations (3.2 to 3.6) correlate the dust explosion severity as a function of the influencing parameters. For example, consider the parameter PD for the explanation. Data analysis for PD confirms the range of 25 $\mu$m to 400 $\mu$m covers the 95% of the data which is the addressed critical zone at this analysis. The limits for the integral reflect the vulnerable region where a dust explosion is likely. The vulnerable region is determined by assessing the data frequency in the specific range. The data used for the analysis are arranged and analysed to understand the range. Data analysis for the severity parameter $P_{max}$ confirms that most dust explosion pressure data are likely to be within 8 to 10.4 bar(g) [Eckhoff, 2003]. For the calculation, the upper bound is rounded up to 10.5 bar(g). Analysing the dust explosion phenomenon in terms of $P_{max}$ and PD alone, the probability of having a dust explosion due to the PD range susceptible to explosion may be written as Equation 4.7:

$$\begin{aligned} P(P_{max}/PD) &= \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{PD_{critical_{min}}}^{PD_{critical_{max}}} P(P_{max} \cap PD)\, dPDdP_{max}}{\int_{PD_{min}}^{PD_{max}} PDdPD} \\ &= \frac{\int_{25}^{400} \int_{8}^{10.5} P(P_{max} \cap PD)\, dPDdP_{max}}{\int_{1}^{420} PDdPD} \\ &= \frac{\int_{25}^{400} \int_{8}^{10.5} C(f_{PD}, f_{p_{max}}) * f_{PD}(PD; \lambda_{PD}, \zeta_{PD}) * f_{P_{max}}(P_{max}; \beta_{P_{max}}, \theta_{P_{max}})\, dPDdP_{max}}{\int_{1}^{420} f_{PD}(PD; \lambda_{PD}, \zeta_{PD}) dPD} \end{aligned} \tag{3.13}$$

All the parameters and their values are already known and the function for the PD and $P_{max}$ are also determined from the distribution characteristic.

Copula function is used to quantify the dependence among variables. Copula can be used for parametric, semi-parametric and non-parametric functions [Joe, 1997]. It can model the non-linear dependencies between the parameters [Chen and Huang, 2007, Genest and Favre, 2007]. In our analysis, the copula function is introduced and kept as unity, $C(f_{PD}, f_{P_{max}})=1$. Two distributions are multiplied along with the copula function to represent the joint probability function. Further study is required to establish the copula function for a specifically defined parameter relation. Interest in copulas arises from several perspectives. The copula function is a very helpful method for deriving joint distributions. Second, copulas can be used to define non-parametric measures of dependence for pairs of random variables when a bivariate context is considered.

When the modes of dependence go beyond correlation or linear association, copula function plays a significant role in establishing the relationship. Finally, copulas are useful extensions and generalizations of approaches for modelling joint distributions and dependence that have appeared in the literature [Trivedi and Zimmer, 2007].

For instance, PD and P$_{max}$ distributions are multiplied with the integral limit as their coexistence is responsible for the explosion occurrence. Once Equation 4.7 is solved for a particular PD limit within operational range it will show the estimated probability of the dust explosion for the specific PD range. The value for the upper and lower limits can be varied as users define bounds within the operational range. This provides the model with a suitable degree of flexibility to obtain a posterior probability of dust explosion. The above equation (Equation 4.7) is solved for the entire range of the vulnerability. The vulnerable region here is defined as the region of the data most likely to cause an explosion. The range is chosen by screening the data collected from Echkoff's book (Appendix: Table: A1 in reference [Eckhoff, 2003]) for all the parameters except LOC. LOC data were excerpted from the NFPA 69 (Table C.1(b) in reference [NFPA, 2008]).

Once the complex integral is solved it quantifies the posterior probability of dust explosion for the given integral limit. The complete range of probability with respect to the PD variation is plotted as probability density function. This provides an excellent opportunity to determine the probability of explosion for a specific range of PD.

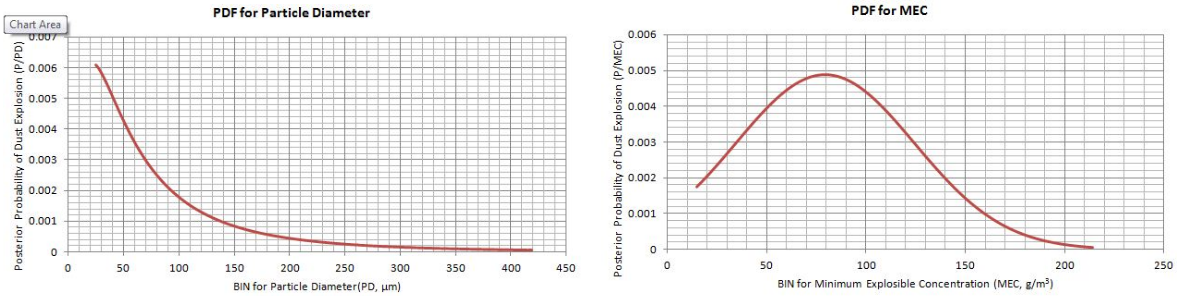
The above process is repeated for the other parameters (MEC, MIT, MIE and LOC) with respect to the severity parameter, Pmax. The posterior probability density function is eventually transformed into the CDF to read the posterior conditional probability, according to the specific range. For a given scenario, if the limits of operational condition are known for PD, the conditional probability can be read from Figure 3.4(a). For instance, if a process plant handles dust particle ranges between 36 $\mu$m to 410 $\mu$m, the conditional probability can be read from Figure 3.4(a) which gives a probability value of 0.336 (From Figure 3.4(a), for 410 $\mu$m the conditional probability value read is 0.4 and for 36 $\mu$m the conditional probability value is 0.064. subtracting these two gives 0.336 as the conditional probability value for PD. Statistically, the value is the area under the curve in Figure 3.3(a) for the PD ranges between 36 $\mu$m to 410 $\mu$m). This helps to identify the critical upper limit zone of operation.

The above process is repeated for the other parameters (MEC, MIT, MIE and LOC) with respect to the severity parameter, $P_{max}$. The posterior probability density function is eventually transformed into the CDF to read the posterior conditional probability, according to the specific range. This helps to identify the critical upper limit zone of operation.

Figure 3.3 shows the probability density plot of dust explosion for specific conditions. It depicts the change of probability value with respect to the parameter value. Figure 4.2 is a cumulative density function graph which shows the entire probability covered for the given parameter range. It is used in determining the posterior probability of explosion up to a certain range.

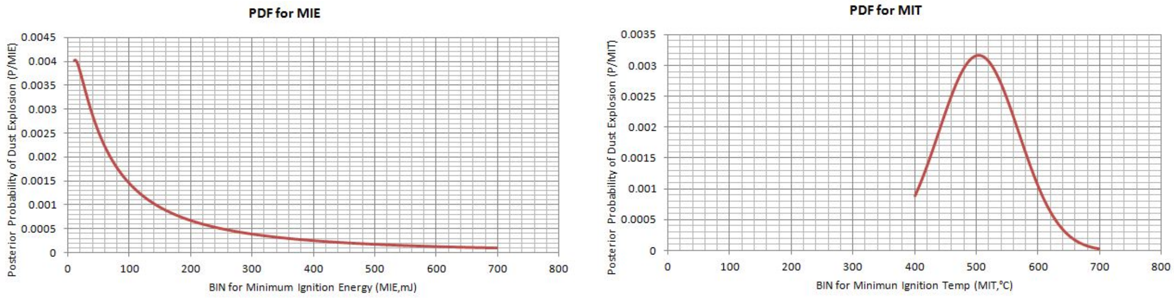
The PDF plot (Figure 3.3) for PD shows the trend of probability value change with respect to the change of particle diameter. As the particle diameter increases, the posterior probability of dust explosion decreases. The probability of explosion is higher in the PD zone of 25-100 $\mu$m than the zone above 100 $\mu$m (Figure 3.3(a)). Figure 3.3(a) shows that the chance of having an explosion is less than 0.001 if the PD is more than 150 $\mu$m. This suggests that bigger PD poses less chance of explosion. It also provides significant insight regarding the operating limit of the particle diameter.

The PDF plot for MEC, Figure 3.3(b) shows the trend of increasing MEC value and



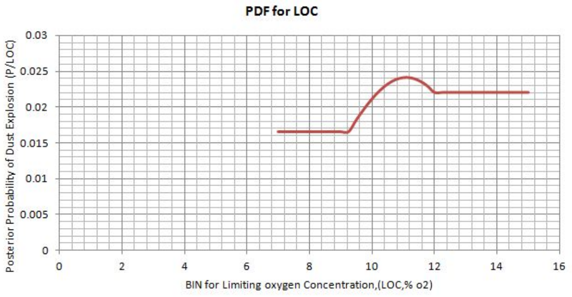
(a) Probability density plot for PD

(b) Probability density plot for MEC



(c) Probability density plot for MIE

(d) Probability density plot for MIT

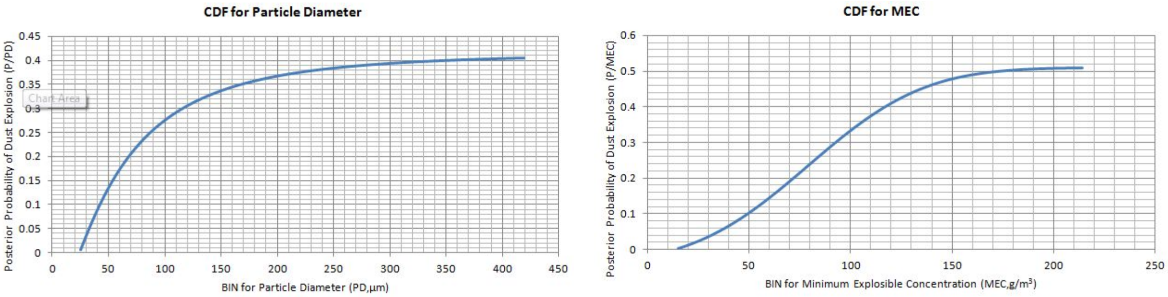


(e) Probability density plot for LOC

Figure 3.3: Probability density plot at a given condition for all the parameters.

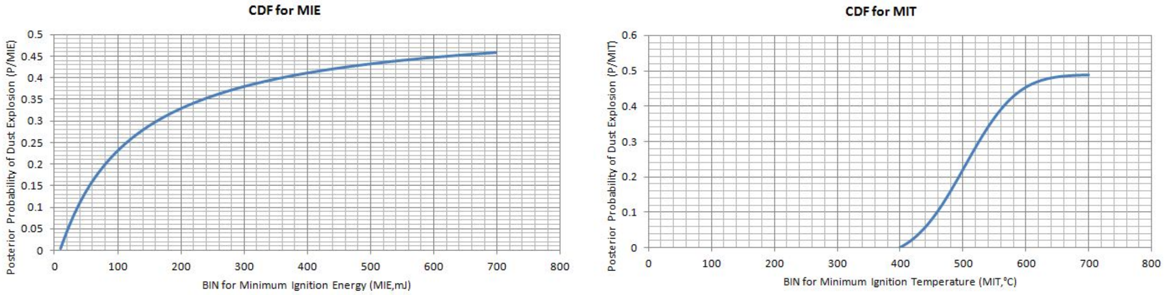
its effect on the probability of a dust explosion. The probability of an explosion increases from 15-80 g/m$^3$ and then it descends. The probability of a dust explosion reduces to below 0.1% after 160 g/m$^3$.

The PDF plot for MIE, Figure 3.3(c) shows that the probability of dust explosion decreases when the MIE value increases. This plot shows that the zone of 20-100 mJ



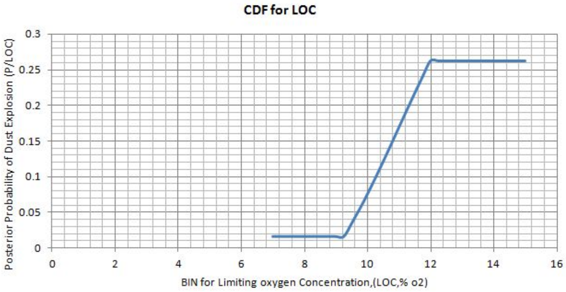
(a) Posterior probability for PD

(b) Posterior probability for MEC



(c) Posterior probability for MIE

(d) Posterior probability for MIT



(e) Posterior probability for LOC

Figure 3.4: Posterior probability plot at a given condition for all the parameters.

poses much higher dust explosion probability than the following zone. The probability of a dust explosion becomes less (less than 0.05%) when the upper range exceeds 240 mJ.

The PDF plot for MIT, Figure 3.3(d) shows the variation of dust explosion probability with the increase of MIT value. It shows the probability of dust explosion increases with the increase of MIT value and this trend is valid up to 500 °C. Above 500 °C, the dust explosion probability reduces and drops to 0.05% when the MIT values are above 620 °C.

The PDF plot for LOC, Figure 3.3(e) shows the change of dust explosion probability with respect to the change of oxygen concentration. NFPA 69 regulation states that : LOC value usually varies from 7(% of $O_2$) to 15(% of $O_2$) in different process facilities [NFPA, 2008]. Figure 3.3(e) depicts a significant rise of dust explosion probability for the LOC value of 8.75(% of $O_2$) to 10.75(% of $O_2$). After that, it decreases up to 12(% of $O_2$). The top probability is found to be 0.024 for the LOC of 10.75 (% of $O_2$). According to NFPA 69: The most vulnerable region which facilitates dust explosion is most often 9(% of $O_2$) to 12(% of $O_2$). Therefore, in this study the range is considered constant from 7-8.75 (% of $O_2$) and 12-15 (% of $O_2$).

## 3.4 Applicability of the developed probabilistic model

The model discussed earlier is a systematic approach to determine the probability of a dust explosion for a given range of operating parameters in the process facility. This is a generic model which considers dust particles regardless of their chemical composition and is a handy tool to monitor the plant condition with respect to the likelihood of dust explosion. To avoid the complexity of the mathematical procedure, a simplified nomograph is developed. The process parameters are monitored and the data are used in calculating the dust explosion probability.

The model enables using the upper and lower limits of the observed parameter as the range of operation. It can also calculate the probability of dust explosion if only the upper bound of the process parameter is provided. These features make the model very flexible and user friendly. For instance, consider the following monitored data at a specific time in a process facility. The following process condition is chosen to demonstrate the applicability of the model.

- PD varies from 36 $\mu$m to 410 $\mu$m
- MEC varies within 26 g/m$^3$ to 202 g/m$^3$
- Upper limit for MIT is 600 °C
- Upper limit of MIE is 550 mJ
- Upper limit for LOC is 10.75 (% of $O_2$)

The observed data or data range is used to calculate the dust explosion probability. The conditional probabilities for five different parameters are calculated in the first step. The total probability is then calculated considering five conditional probabilities. All the information is depicted in the nomograph, which represents the conditional probability and total probability of dust explosion, and makes the model easier to interpret.

The nomograph in Figure 3.5 describes the conditional probability in five vertices and the total probability is a combination of these conditional probabilities. In Table 2,

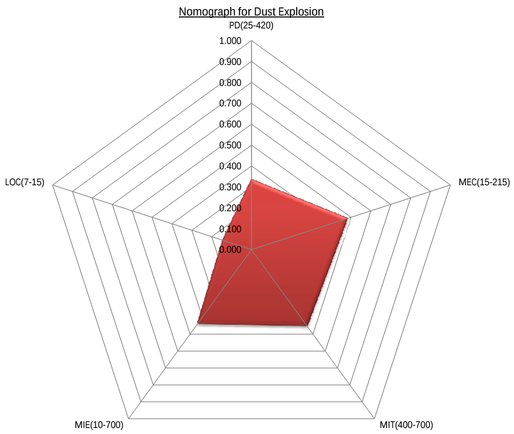


Figure 3.5: Nomograph for dust explosion

the far left column indicates the parameters and their operational range. Two middle columns show the upper and lower bounds of the observed process parameters. The far right column provides the calculated conditional probability for each parameter and the total probability as well.

Table 3.2: Nomograph calculation interface

| Influencing Parameters | Lower bound | Upper bound | Conditional probability |
|---|---|---|---|
| PD (25-400) | 36 | 410 | 0.336 ($P_{PD}$) |
| MEC (15-215) | 26 | 202 | 0.483 ($P_{MEC}$) |
| MIT (400-700) | 400 | 600 | 0.453 ($P_{MIT}$) |
| MIE (10-700) | 10 | 550 | 0.429 ($P_{MIE}$) |
| LOC (7-15) | 7 | 10.75 | 0.128 ($P_{LOC}$) |
| Total probability of dust explosion | | | 0.135 ($P_{Total}$) |

The development mechanism of the nomograph includes three important steps. The first step is gathering the data for each parameter. The upper and lower bounds of each parameter are provided in this step. In the absence of a lower bound, the upper bound can be used in this model. The second step is calculating the conditional probability by using the method described earlier. The final step of the nomograph development is calculating the total probability of explosion. This is the most intricate step, and it involves a governing equation:

$$
\begin{aligned}
P_{Total} \;=\; & \tfrac{1}{2} * [(P_{PD} * P_{MEC}) + (P_{MEC} * P_{MIT}) + (P_{MIT} * P_{MIE}) + \\
& (P_{MIE} * P_{LOC}) + (P_{LOC} * P_{PD})] * \sin 72 * S_f * N_f
\end{aligned}
\tag{3.14}
$$

For the given scenario, the total probability can be assessed by using the Equation 3.14. A scaling factor, $S_f$=0.684 and normalizing factor, $N_f=\frac{1}{1.04976}$ are multiplied with the Equation 3.14. These factors are included to fix the impact of tailoring the decimal point of probability values. Table 4.2 provides the conditional probability values which have already been calculated. In the above condition the $P_{Total}$ is calculated as :

$$
\begin{aligned}
P_{Total} \;=\; & \tfrac{1}{2} * [(0.336 * 0.483) + (0.483 * 0.453) + (0.453 * 0.429) + \\
& (0.429 * 0.128) + (0.128 * 0.336)] * \sin 72 * S_f * N_f \\
=\; & \tfrac{1}{2} * [(0.336 * 0.483) + (0.483 * 0.453) + (0.453 * 0.429) + \\
& (0.429 * 0.128) + (0.128 * 0.336)] * 0.951 * 0.684 * \tfrac{1}{1.04976} \\
=\; & 0.135
\end{aligned}
\tag{3.15}
$$

The calculation depicted above indicates that the occurrence probability of dust explosion is 0.135 for the given conditions of the process facility. The nomograph indicates the probability of 0.135 inside the pentagon with the shaded portion (Figure 3.5).

A regular pentagon depicts total probability of dust explosion considering five parameters exceeding the threshold limit. Each parameter follows a probability distribution, so the exceedance of a particular value can be determined from the probability distribution. The same procedure is applied for the rest of the parameters, and while they are all present in a specific facility, at a specific time, the nomograph represents the total probability of a dust explosion. It includes a mechanism to aggregate all the conditional probabilities into the total probability of a dust explosion. It accounts for all the parameters responsible for dust explosion.

The nomograph (Figure 3.5) is an easy method for the pictorial depiction of dust explosion probability. The data handling and processing is made simple for the user so that it would take little effort to use the method. In addition, the nomograph is made easier to interpret. It is user-oriented and requires less effort and time to compute the complex calculation. Moreover, the model is very flexible and can be used for any dust handling facility.

## 3.5 Discussion

This paper discusses a newly proposed probabilistic model to estimate dust explosion probability and demonstrate its application to different processing facilities.

The paper consists of three important parts. The first part is data monitoring. In an industry, the potential dust explosion hazard causing parameters are: Particle Diameter (PD), Minimum Explosible Concentration (MEC), Minimum Ignition Temperature (MIT), Minimum Ignition Energy (MIE) and Limiting Oxygen Concentration (LOC). MIT and MIE are material parameters and these values are chosen for the specific material. Other parameters (e.g. PD, MEC and LOC) are monitored and the readings are used in the predictive model.

Once the data is obtained, the second part is the analysis and estimation of the probability of a dust explosion. For each parameter individual conditional probability is assessed and then the total probability of a dust explosion is calculated. The total probability takes all the conditional probabilities into consideration which reflects the plant operating conditions, in terms of probability of explosion.

The last part of the paper provides the nomograph for a quicker assessment of dust explosion occurrence. This is a simple pictorial representation of the plant operating condition in terms of probability of explosion. The nomograph shows the conditional probability for each parameter and also the total probability in a closed region. The area covered by the closed region inside the nomograph depicts the total probability of dust explosion.

The proposed model is very convenient and effective in the following ways:

- *Easier and faster implementation:* The model consists of systematic structured steps and requires very simple techniques to follow. Moreover, the software aided steps reduce the data processing and modelling time significantly.
- *Easy to interpret:* The outcome of the analysis is presented with a simple visual tool called a "nomograph". Conditional probability and total probability are depicted in such a way that facilitates easy interpretation of results.
- *Quick assessing of the facility condition:* The model renders a quick explosion probability assessment for the dust handling facility.

This study demonstrated the use of the conditional probabilistic approach and its application as a useful tool in dust explosion prediction. It can assess dust explosion probability based on the continuous monitoring of specific dust explosion parameters. The developed nomograph can be used as a handy tool to use in industry as a safety monitoring aid.

## 3.6 Conclusion

Three aspects of the proposed model could be further explored in the future. First, the chemical composition of the dust is not considered in the existing model development. Classification of dust on the basis of chemical composition can be incorporated into the model. This would lead to a specific dust explosion likelihood prediction model. The recommended classifications would be:

1. Food feed
2. Plastic, resins and rubbers
3. Pharmaceuticals, cosmetics, pesticides
4. Metal alloys
5. Coal and coal products
6. Cotton, wood and peat

Second, copula function needs to be further tested and developed for specifying dependency scenarios, such as the correlation between $P_{max}$ and PD, $P_{max}$ and MIT etc.

Third, in the study, one parameter at a time was considered for conditional probability estimation. To achieve better accuracy five parameters could be considered together. This would require solving more complex mathematical functions.

## Acknowledgement

The authors gratefully acknowledge the financial support provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada in the form of a strategic grant.

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# Chapter 4

# An Industry Specific Dust Explosion Assessment Model with Case Studies

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## Preface

A version of this manuscript is accepted in the *Journal of Chemical Health and Safety, November 2013 (Reference No: JCHAS-D-13-00026).* The co-authors, Dr. Khan, Amyotte and Refaul supervised the principle author, Junaid, to develop the research on the entitled topic and helped him to conceptualize the techniques and theories available for this topic. Junaid conducted the dust explosion prediction modelling and associated statistical tests and necessary analysis while Dr. Khan, Amyotte and Refaul reviewed the manuscript and provided necessary suggestions.

## Abstract

Dust explosion is a potential threat to the process facilities handling dusts. Dust explosion occurrences are frequently reported in these industries. Industrial professionals and researchers have been trying to develop effective measures to assess and mitigate and/or prevent dust explosion. To develop effective prevention and mitigation strategies, it is important to understand the interaction of dust explosion controlling parameters and also to assess likelihood of occurrence in given conditions. A conceptual framework has earlier been developed by the authors to model dust explosion likelihood. In this paper, a detailed implementation of the conceptual model is presented. Three different dust classes ( i.e. food feed; plastic, resin and rubber; and metal alloys) are considered for model development. The proposed model considers six key parameters of dust explosion: dust particles diameter, minimum ignition energy, minimum explosible concentration, minimum ignition temperature, limiting oxygen concentration and explosion pressure. These parameters are conditional to the type of dust and chemical composition. A conditional probabilistic approach is used to determine the total probability of dust explosion in a given process facility. Use of this model will help to assess the likelihood of dust explosion in given operating conditions. Moreover, it will help to develop prevention strategies focusing on the parameters that are responsible for dust explosion. Three case studies are presented here to demonstrate the application of the model in real life.

Keywords: Probabilistic assessment, Probability distribution, Dust explosion, Dust explosion parameter, Nomograph

**Acronyms and Symbols:**

PD : Particle Diameter, micron ($\mu$m)

MEC: Minimum Explosible Concentration, g/m$^3$

MIT: Minimum Ignition Temperature, °C

MIE: Minimum Ignition Energy, mJ

LOC: Limiting Oxygen Concentration, %

P$_{max}$ : Maximum Pressure Rise, bar(g)

PDF: Probability Density Function

CDF: Cumulative Density Function

$\mu$: Mean for normal distribution

$\sigma$ : Standard Deviation for normal distribution

$\zeta$: Standard deviations for lognormal distribution

$\lambda$ : Mean of lognormal distributions

$\beta$: Shape parameter for weibull distribution

$\theta$: Scale parameter for weibull distribution

P$_x$ = P/X =: Probability of dust explosion given that a particular parameter satisfies necessary condition (where X = PD or MEC or MIT or MIE or LOC)

P$_{Total}$ : Total probability of dust explosion for a given scenario considering all parameters

## 4.1 Introduction

A dust explosion can take place when the suspended solid particles accumulated in the air receive sufficient energy from the source. The consequence is akin to a typical gas explosion in terms of the impact on the surrounding environment, industrial assets and monetary value. Unfortunately, the dust explosion's causation and severity are less familiar compared to the gas explosion among industrial practitioners [Amyotte and Eckhoff, 2010]. For gas explosion, fuel, oxidant and ignition sources are necessary, while dust explosion requires two more vital criteria: appropriate mixing and confinement. These five elements are denoted with the dust explosion pentagon. The phase of the fuel during gas and dust explosion is different. Gas particles are in a gaseous phase, whereas dust particles are in a solid phase. Therefore, particle size of the dust is a very important fact on which to focus. According to the National Fire Protection Association (NFPA), any finely divided solid, 420 $\mu$m (micron) or 0.017 in. or less in diameter (i.e., material capable of passing through a U.S. No. 40 Standard sieve) is defined as dust [NFPA, 2008]. The prime concern is combustible dust. Any dust capable of creating a violent explosion when it is suspended in air in ignitable concentrations, regardless of size, shape or chemical composition is called combustible dust [Amyotte and Eckhoff, 2010]. The range of explosible particle size may be larger than the defined range for a specific material. Particle sizes distributions are often considered as a measure of the particle diameter in addition to the mean or median diameter [Amyotte and Eckhoff, 2010]. In this paper, the median particle diameter is considered throughout the study.

A number of recent dust explosion phenomena caused severe loss to human lives and associated industries. On January 29, 2003, a massive dust explosion at the West Pharmaceutical Services facility in Kinston, North Carolina, killed six workers and destroyed the facility [CSB, 2004]. On February 20, 2003, a series of dust explosions at the CTA Acoustics facility in Corbin, Kentucky, killed seven workers, injured 37, and destroyed the facility [CSB, 2004]. On October 29, 2003, an aluminum dust fueled explosion killed one worker and injured several others at Hayes Lemmerz International in Huntington, Indiana [CSB, 2005]. On January 9, 2001, at the wool factory "Pettinatura Italiana" in Vigliano Biellese (BI), a massive explosion caused the death of three people, five severely injured personnel and considerable damage to part of the factory [Piccinini, 2008]. On February 7, 2008, a series of sugar dust explosions at the Imperial sugar manufacturing facility in Port Wentworth, Georgia, resulted in 14 worker fatalities [CSB, 2009].

With the increasing number of dust explosions in process facilities, the risk has become more alarming. However, substantial progress has been made through extensive research and development for better understanding of dust explosion dynamics. Preventing an ignition source and explosive dust clouds, explosion venting, automatic explosion suppression and good housekeeping are elaborately reported in existing literatures as the means of protective measures of dust explosions [Eckhoff, 2005].

Industry professionals and researchers are striving for more pragmatic and easily implementable solutions to prevent dust explosion phenomena. However, in the context of quantitative assessment, a predictive tool to assess the explosion probability in a particular industry is absent. In this paper, an effort has been made to establish a probabilistic model to assess dust explosion occurrence. The model is applied for three dust classes: Food feed; plastic, resin and rubber; and metal alloys. Five parameters are identified as dust explosion influential parameters: particle diameter, minimum explosible concentration, minimum ignition energy, minimum ignition temperature and limiting oxygen concentration, whereas the maximum explosion pressure represents the severity of a dust explosion. Five essential elements ( e.g. fuel, oxidant, ignition source, mixing and confinement) form a dust explosion pentagon [Kauffman, 1982]. These five elements are represented by five influencing parameters of dust explosion. When these parameters reach the explosible range, dust explosion occurs [Abbasi and Abbasi, 2007]. Explosion may not occur if all parameters do not reach the explosible range [NFPA, 2007]. A conceptual framework has earlier been developed by the authors which describes the method of assessing the dust explosion probability [Hassan et al., 2013]. In this paper, the implementation of the earlier model is discussed elaborately for different dust classes. Three case studies have been studied to demonstrate the applicability of the model. This paper attempts to use the existing information (experimental data) for a particular industry to develop the dust explosion assessment model. To assess the conditional probability, two parameters at a time have been considered to estimate the probability of explosion occurrence for a given industry. Estimating the conditional probability for each parameter and integrating them over a range provides the total probability of dust explosion occurrence. The model renders a nomograph as a quick assessment tool. For a particular industry, the model can assess the probability of explosion in the base condition (normal operating condition). Based on the assessment, the processing facility can implement safety measures ( e.g. inherent safety, procedural safety, safety management system etc.) and can develop effective prevention and mitigation strategies in the working environment.

## 4.2 Methodology for dust explosion assessment and mathematical modelling

The proposed methodology to assess dust explosion likelihood is comprised of five steps as outlined in the conceptual model [Hassan et al., 2013]. These steps are subdivided into several sub-steps. Figure 4.1 represents the framework of the proposed methodology. The main steps are given below; for details see the work on dust explosion likelihood assessment [Hassan et al., 2013].

1. Hazard identification,
2. Data collection,
3. Data analysis,
4. Probabilistic modelling,
5. Nomograph Development

## 4.3 Mathematical modelling of dust explosion assessment

The proposed methodology employs the rules of conditional probability and an elaborate description is given in the recent work on dust explosion likelihood assessment by Junaid et al [Hassan et al., 2013].

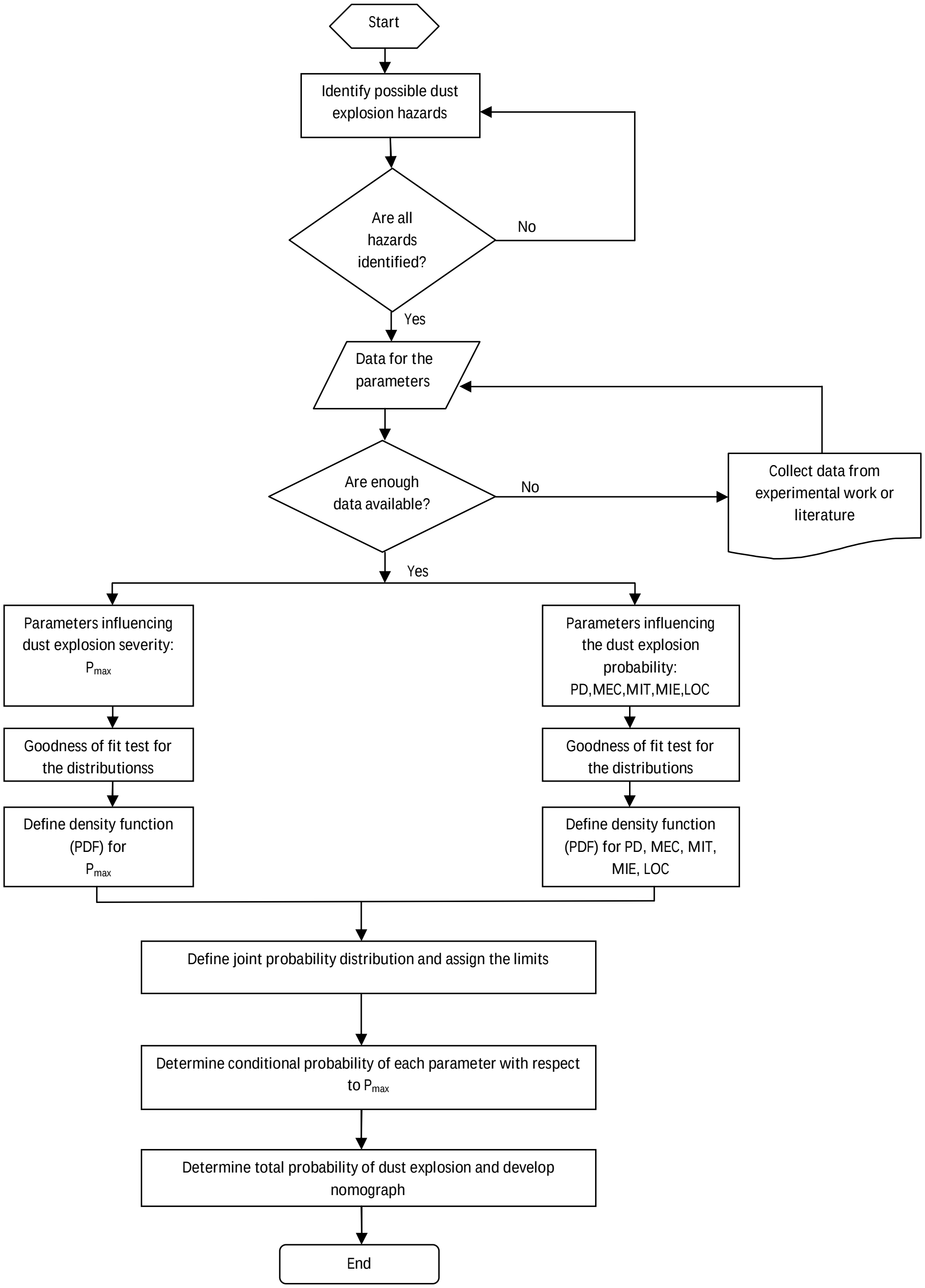


Figure 4.1: A framework for assessing dust explosion occurrence [Hassan et al., 2013]

## 4.4 Model testing

To use the model, probability distributions of the dust explosion parameters need to be determined for each dust class. The PDFs can be determined from the known distribution. These PDFs are used to formulate the joint probability distribution functions and are integrated over a range to get the CDFs. The integral range is identified according to the available data. Hence, the conditional probability values can be assessed for the particular dust classes. The total probability of dust explosion can be determined from the model and the nomograph is generated as a part of the model. The testing of the model is described in four steps with an example:

### 4.4.1 Data collection

In this step, data for dust explosions parameters are collected. Six parameters are already identified in section 4.2. The data for analysis are collected from Echkoff's book (Appendix: Table: A1 in reference [Eckhoff, 2003]) for all the parameters except LOC. LOC data are excerpted from the NFPA 69 (Table C.1(b) in reference [NFPA, 2008]).

### 4.4.2 Data analysis and PDFs determination

In this step, the collected data are analysed to determine the underlying distributions of each identified parameter. This step provides the significant details of the distribution parameters. This information is used to determine the PDFs for each parameter.

For example, consider a case where the statistical analysis for the hazard causing parameters is listed in Table 4.1 for a particular process facility.

The estimated parameters of the identified distributions (from Table 4.1) can be used

Table 4.1: Dust explosion parameter distribution identification

| Dust explosion parameters | Best fitted distribution | Estimated distribution parameter | 95% Data range |
|---|---|---|---|
| PD | Lognormal | $\lambda_{PD}$=4.02, $\zeta_{PD}$=0.95513 | 25-400 $\mu$m |
| MEC | Normal | $\mu_{MEC}$=80, $\sigma_{MEC}$=45 | 15-215 g/m$^3$ |
| MIT | Normal | $\mu_{MIT}$=504, $\sigma_{MIT}$=65 | 400-700 °C |
| MIE | Lognormal | $\lambda_{MIE}$=4.71518, $\zeta_{MIE}$=1.50173 | 10-700 mJ |
| LOC | Normal | $\mu_{LOC}$=10.97, $\sigma_{LOC}$=2.12468 | 8.75-12 % O$_2$ |
| P$_{max}$ | Weibull | $\beta_{P_{max}}$=8.89, $\theta_{P_{max}}$=10.7 | 8-10.5 bar(g) |

in the mathematical formulation of the probability distribution function. Based on the distribution types, formulated PDFs are given as:

For PD:

$$f_{PD}(PD;\lambda_{PD},\zeta_{PD}) = \frac{1}{PD\zeta_{PD}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{\ln(PD)-\lambda_{PD}}{\zeta_{PD}})^2} \tag{4.1}$$

For MEC:

$$f_{MEC}(MEC;\mu_{MEC},\sigma_{MEC}) = \frac{1}{\sigma_{MEC}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{MEC-\mu_{MEC}}{\sigma_{MEC}})^2} \tag{4.2}$$

For MIT:

$$f_{MIT}(MIT;\mu_{MIT},\sigma_{MIT}) = \frac{1}{\sigma_{MIT}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{MIT-\mu_{MIT}}{\sigma_{MIT}})^2} \tag{4.3}$$

For MIE:

$$f_{MIE}(MIE;\lambda_{MIE},\zeta_{MIE}) = \frac{1}{MIE\zeta_{MIE}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{\ln(MIE)-\lambda_{MIE}}{\zeta_{MIE}})^2} \tag{4.4}$$

For LOC:

$$f_{LOC}(LOC;\mu_{LOC},\sigma_{LOC}) = \frac{1}{\sigma_{LOC}\sqrt{2\pi}}e^{-\frac{1}{2}(\frac{LOC-\mu_{LOC}}{\sigma_{LOC}})^2} \tag{4.5}$$

For P$_{max}$:

$$f_{P_{max}}(P_{max};\beta_{P_{max}},\theta_{P_{max}}) = \frac{\beta_{P_{max}}}{\theta_{P_{max}}}(\frac{P_{max}}{\theta_{P_{max}}})^{\beta_{P_{max}}-1}e^{-(\frac{P_{max}}{\theta_{P_{max}}})^{\beta}_{P_{max}}} \tag{4.6}$$

### 4.4.3 Identification of integral limits and CDFs determination

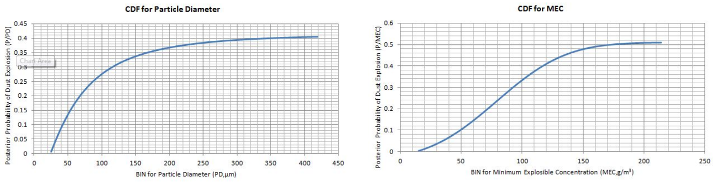
The above equations (4.1 to 4.6) are used in determining joint probability distribution functions and are integrated over a specific range to get the CDFs. The range of integral limits and CDFs are determined in this step.

For example, consider the parameter PD in the explanation. Data analysis for PD confirms that the range of 25 $\mu$m to 400 $\mu$m covers 95% of the data (Table 4.1) which is the addressed critical zone in this analysis. The limits for the integral reflect the vulnerable region where a dust explosion is likely. The vulnerable region is determined by assessing the data frequency in the specific range. The data used for the analysis are arranged and analysed to understand the range. Data analysis for the severity parameter P$_{max}$ confirms that most dust explosion pressure data are likely to be within 8 to 10.4 bar(g) [Eckhoff, 2003]. For the calculation, the upper bound is rounded up to 10.5 bar(g). Analysing the dust explosion phenomenon in terms of P$_{max}$ and PD alone, the probability of having a dust explosion due to the PD range susceptible to explosion may be written as Equation 4.7:

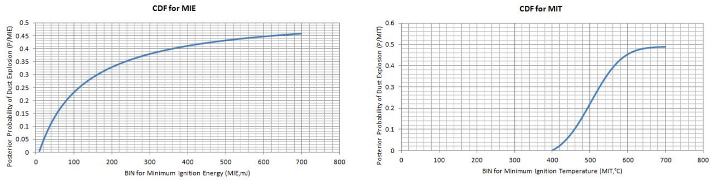
$$\begin{aligned} P(P_{max}/PD) &= \frac{\int_{P_{max_{critical_{min}}}}^{P_{max_{critical_{max}}}} \int_{PD_{critical_{min}}}^{PD_{critical_{max}}} P(P_{max} \cap PD)\, dPDdP_{max}}{\int_{PD_{min}}^{PD_{max}} PDdPD} \\ &= \frac{\int_{25}^{400} \int_{8}^{10.5} P(P_{max} \cap PD)\, dPDdP_{max}}{\int_{1}^{420} PDdPD} \\ &= \frac{\int_{25}^{400} \int_{8}^{10.5} C(f_{PD}, f_{p_{max}}) * f_{PD}(PD; \lambda_{PD}, \zeta_{PD}) * f_{P_{max}}(P_{max}; \beta_{P_{max}}, \theta_{P_{max}})\, dPDdP_{max}}{\int_{1}^{420} f_{PD}(PD; \lambda_{PD}, \zeta_{PD}) dPD} \end{aligned} \tag{4.7}$$

All the parameters and their values are already known and the functions for the PD and P$_{max}$ are also determined from the distribution characteristics. Solving Equation

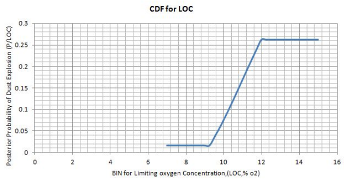
4.7 provides the conditional probability of dust explosion due to the PD. The above process is repeated for the rest of the parameters (MEC, MIT, MIE and LOC) with respect to the severity parameter, P$_{max}$. The posterior probability density function is eventually transformed into the CDF to read the posterior conditional probability, according to the specific range as provided in Figure 4.2 for the above analysis.



(a) Posterior probability for PD (b) Posterior probability for MEC



(c) Posterior probability for MIE (d) Posterior probability for MIT



(e) Posterior probability for LOC

Figure 4.2: Posterior probability plot at a given condition for all the parameters.

### 4.4.4 Dust explosion assessment in a given operating condition

The steps described in sections [4.4.1], [4.4.2] and [4.4.3] develop the predictive model which can be used for a specific case in the considered process facility. To use the model, the operating conditions of the process facility are required. For instance, consider the following monitored data in the considered process facility. The following process operating condition is chosen to demonstrate the applicability of the model.

- PD varies from 40 $\mu$m to 350 $\mu$m
- MEC varies within 30 g/m$^3$ to 200 g/m$^3$
- Upper limit for MIT is 650°C
- Upper limit of MIE is 600 mJ
- Upper limit for LOC is 11.75(% of $O_2$)

For the given process parameters the predictive model analyses the data and provides the following result listed in Table 4.2. The predictive model also provides a nomograph as an easy way to interpret the result in a graphical form which is given in Figure 4.3:

Table 4.2: Nomograph calculation interface

| Influencing Parameters | Lower bound | Upper bound | Conditional probability |
|---|---|---|---|
| PD (25-400) | 40 | 350 | 0.311 ($P_{PD}$) |
| MEC (15-215) | 30 | 200 | 0.473 ($P_{MEC}$) |
| MIT (400-700) | 400 | 650 | 0.482 ($P_{MIT}$) |
| MIE (10-700) | 10 | 600 | 0.444 ($P_{MIE}$) |
| LOC (7-15) | 7 | 11.75 | 0.223 ($P_{LOC}$) |
| Total probability of dust explosion | | | 0.151 ($P_{Total}$) |

The calculation depicted above indicates that the occurrence probability of dust explosion is 0.151 for the given conditions of the process facility. The nomograph indicates the probability of 0.151 inside the pentagon with the shaded portion (Figure 4.3). It shows that 1 out of 6 operations is susceptible to an explosion at the normal operating condition. The nomograph is a simple way to interpret the result of the complex

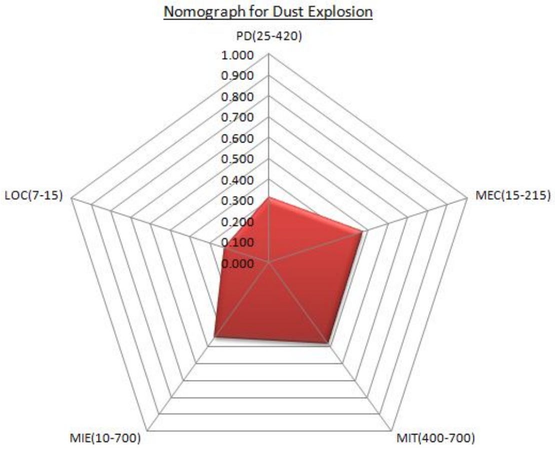


Figure 4.3: Nomograph for dust explosion

mathematical equation in a graphic way. The process facility can formulate necessary prevention and mitigation strategies based on the assessment.

## 4.5 Identified dust classes and case studies

Three dust classes are identified to use the model in three specific industries. These classes are food feed; plastic, resin and rubber; and metal alloys. The industries dealing with the aforementioned dust classes can utilize the proposed model to assess the probability of dust explosion for a normal operating condition. The dust explosion assessment in a process facility may lead to significant modification of safety measures. It can be very helpful to formulate effective mitigation or prevention strategies. The proposed model includes three specific industries and they are discussed in the case studies below:

### 4.5.1 Dust class 1: Food feed

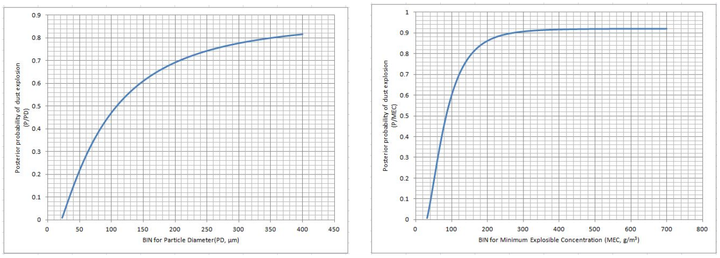
Dust produced or handled in the food processing industries is susceptible to explosion if necessary conditions are met. The food processing industries deal with dust such as: dextrose, fructose, coffee, milk powder, wheat flour, sugar etc. Based on the statistical analysis on the available data of food feed, the dust explosion parameters and the distributions are provided in Table 4.3.

Table 4.3: Food feed: Dust explosion parameter distribution identification

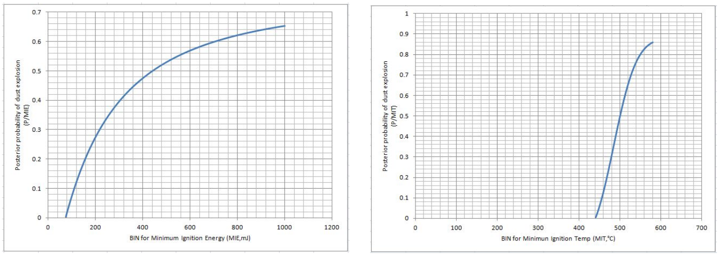
| Dust explosion parameters | Best fitted distribution | Estimated distribution parameter | 95% Data range |
|---|---|---|---|
| PD | Lognormal | $\lambda_{PD}$=4.38, $\zeta_{PD}$=1.03 | 23-400 $\mu$m |
| MEC | Lognormal | $\lambda_{MEC}$=4.31, $\zeta_{MEC}$=0.63 | 31-700 g/m$^3$ |
| MIT | Lognormal | $\lambda_{MIT}$=6.19, $\zeta_{MIT}$=0.085 | 441-580 °C |
| MIE | Lognormal | $\lambda_{MIE}$=5.29, $\zeta_{MIE}$=1.21 | 76-1000 mJ |
| LOC | Normal | $\mu_{LOC}$=10.97, $\sigma_{LOC}$=2.12468 | 8.75-12 % O$_2$ |
| P$_{max}$ | Normal | $\mu_{P_{max}}$=7.93, $\sigma_{P_{max}}$=1.43 | 5.1-10.2 bar(g) |

Taking the distribution parameter into account, the conditional PDFs are formulated. The analysis (in Table 4.3) also provides the integral range with which the conditional PDFs are integrated to obtain the CDFs. The CDFs are represented in Figure 4.4 as the CDF plot. The CDF plot represents the probability of dust explosion for different operating ranges. It facilitates the reading of the conditional probability of dust explosion for a given operating range of a single parameter.

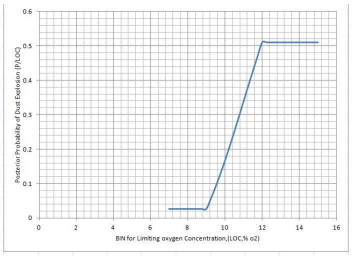
The total probability of dust explosion is assessed using the conditional probability of dust explosion for each parameter. The process of assessing the total probability of dust explosion based on the plant operating condition is described in section 4.5.1.1 with a case study.



(a) Posterior probability for PD (b) Posterior probability for MEC



(c) Posterior probability for MIE (d) Posterior probability for MIT



(e) Posterior probability for LOC

Figure 4.4: Posterior probability plot for the parameters (dust class: food feed).

#### 4.5.1.1 Case study: Sugar dust explosion and fire

On February 7, 2008, at about 7:15 p.m., a series of sugar dust explosions took place at the Imperial Sugar manufacturing facility in Port Wentworth, Georgia. It resulted in fourteen worker fatalities, and among them eight workers died at the work place and six were extremely injured and eventually died at the Joseph M. Still Burn Center in Augusta, Georgia. Thirty six workers were severely injured and burned which eventually caused permanent damage to them [CSB, 2009].

At about 7:15 p.m. on February 7, 2008, a sugar dust explosion occurred in the enclosed steel conveyor belt under the granulated sugar storage silos in the above facility. After a while, a massive secondary dust explosion propagated throughout the entire granulated and powdered sugar packing buildings, bulk sugar loading buildings, and parts of the raw sugar refinery [CSB, 2009].

The proposed model for food feed considers granulated and powdered sugar, and an effort to assess the dust explosion probability at the Imperial sugar manufacturing facility has been made in this section. To assess the probability of dust explosion, understanding the operating conditions of the facility is required. This information is collected from relevant reports available on the facility and its operation. Any missing information regarding operational and material parameters is replaced with the proper engineering judgement. According to US CSB, the dust explosion parameters at the facility are reported as [CSB, 2009]:

- PD varies from 23 $\mu$m to 286 $\mu$m
- MEC range is 115 g/m$^3$
- Upper limit for MIT is 450°C to 500°C
- Upper limit of MIE is 1000 mJ
- Upper limit for LOC is 10.5(% of $O_2$)

The LOC and MIT values are chosen for the assessment. From the above plant condition the predictive model assesses the facility condition. The gist of the assessment is given in Table 4.4 and the model provides a nomograph (Figure 4.5) to understand the plant condition easily.

Table 4.4: Nomograph (food feed) calculation interface

| Influencing parameters | Lower bound | Upper bound | Conditional probability |
|---|---|---|---|
| PD (23-400) | 23 | 286 | 0.76 ($P_{PD}$) |
| MEC (31-700) | 31 | 115 | 0.68 ($P_{MEC}$) |
| MIT (441-580) | 450 | 500 | 0.44 ($P_{MIT}$) |
| MIE (76-1000) | 76 | 1000 | 0.65 ($P_{MIE}$) |
| LOC (7.25-15) | 7.25 | 10.50 | 0.19 ($P_{LOC}$) |
| Total probability of dust explosion | | | 0.27 ($P_{Total}$) |

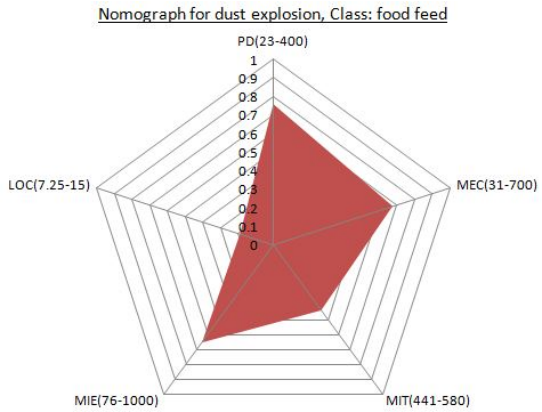


Figure 4.5: Nomograph (food feed) for dust explosion

According to the proposed model, the total probability of dust explosion at the Imperial sugar manufacturing company is 27% when the base operating condition is considered. A dust explosion took place which indicates the probability reaches 100%, denoting the accident occurred. The accident means that something must have happened to trigger the base condition into becoming a catastrophic explosion. 27% probability of dust explosion is a high probability. It means one out of three facilities under normal operating condition are explosion prone. A target value of 0.001 or one in a thousand would be a reasonable value to choose. If the probability of dust explosion can be reduced in the normal operating condition, it will reduce the chance of explosion during process upset conditions as well. The model also interprets that the PD, MEC and MIE make significant contributions in the conditional probability (from Table 4.4). At the facility, the primary explosion took place at the enclosed steel belt conveyor where the dust concentration accumulated to the explosive range and an ignition source provided the necessary energy source to begin the explosion [CSB, 2009], which validates the assessment of the model. To improve the safety of the facility, necessary design modification is needed to the steel belt conveyor and adequate housekeeping is required. These provide a better and safer condition for working. The model provides a quick estimate of the plant condition. Based on the assessment administrative controls, engineering design and operational modification can be done to reduce the total probability of dust explosion.

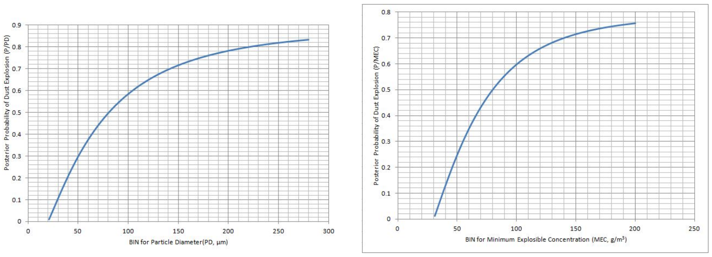
### 4.5.2 Dust class 2: Plastic, resin and rubber

Industries dealing with the following dust: rubber, melamine resin, polyester, polyvinyl-alcohol etc. are considered in this class. Based on the statistical analysis on the available data for aforementioned dust classes, the probability distribution type and details of the dust explosion parameters are listed in Table 4.5

Table 4.5: Plastic, resin and rubber: Dust explosion parameter distribution identification

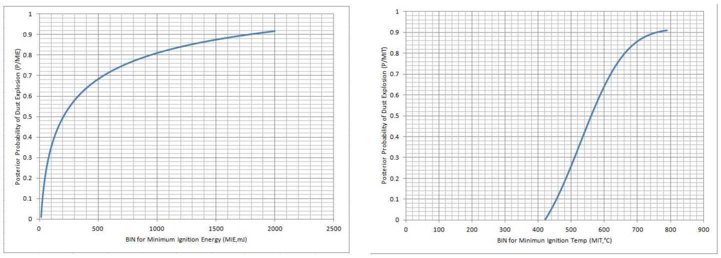
| Dust explosion parameters | Best fitted distribution | Estimated distribution parameter | 95% Data range |
|---|---|---|---|
| PD | Lognormal | $\lambda_{PD}$=4.11, $\zeta_{PD}$=0.9296 | 21-280 $\mu$m |
| MEC | Lognormal | $\lambda_{MEC}$=3.993, $\zeta_{MEC}$=0.706 | 31-200 g/m$^3$ |
| MIT | Normal | $\mu_{MIT}$=528, $\sigma_{MIT}$=108.54 | 421-790 °C |
| MIE | Lognormal | $\lambda_{MIE}$=5.177, $\zeta_{MIE}$=2.64 | 14-2000 mJ |
| LOC | Normal | $\mu_{LOC}$=10.97, $\sigma_{LOC}$=2.12468 | 8.75-12 % O$_2$ |
| P$_{max}$ | Normal | $\mu_{P_{max}}$=8.432, $\sigma_{P_{max}}$=1.04 | 6.2-10.2 bar(g) |

The model analyses the data and provides the conditional probability with respect to each parameter. The analysis is depicted with a CDF plot and represented by Figure 4.6. For a single parameter at any condition within operational range the plot can provide the conditional probability of dust explosion. The assessment of the total probability of dust explosion from the conditional probabilities is discussed in section 4.5.2.1.



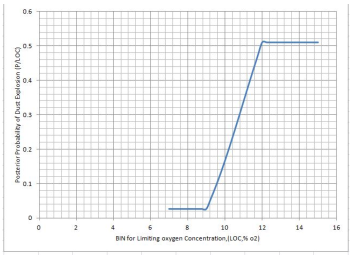
(a) Posterior probability for PD

(b) Posterior probability for MEC



(c) Posterior probability for MIE

(d) Posterior probability for MIT



(e) Posterior probability for LOC

Figure 4.6: Posterior probability plot for the parameters (dust class: plastic, resin and rubber).

#### 4.5.2.1 Case study: Dust explosion in wool factory

On 9 January, 2001, at the wool factory "Pettinatura Italiana" in Vigliano Biellese (BI), at 5:50 p.m. a massive explosion caused the death of three people, the injury of another five, and severe facility damage [Piccinini, 2008]. For over a century, the factory has been devoted to washing, carding, and combing wool. The production cycle which is described includes the extraction from the wool of several types of industrial rejects (e.g., burr) and waste (e.g., noils). A large amount of dust accumulated which was a by-product of the removal of burr from wool during the carding phase. A primary deflagration initiated by some electrical equipment of the lighting system caused a spark or source of heat. The flame front of the primary deflagration propagated quickly and ignited large quantities of dust.

An unusual explosive material was reported as a mixture of vegetable dust, wool fibers, and inorganic substances [Piccinini, 2008]. According to the estimation the deflagration involved at least 400−500 kg of flammable vegetal and wool fibres, without counting moisture and inert particles [Piccinini, 2008]. According to the technical reports [NFPA, 2008, Piccinini, 2008, Eckhoff, 2003] and standard material properties, the following plant conditions are determined for the study:

- PD varies from 25 $\mu$m to 150 $\mu$m
- MEC range is 125 g/$m^3$
- Upper limit for MIT is 450°C to 500°C
- Upper limit of MIE is 200 mJ
- Upper limit for LOC is 10.5(% of $O_2$)

Based on the normal operating condition the dust explosion assessment model provides conditional probability and eventually is aggregated to the total probability of explosion. The conditional probabilities, total probability and the generated nomograph are provided in Table 4.6 and Figure 4.7 subsequently.

Table 4.6: Nomograph (plastic, resin and rubber) calculation interface

| Influencing parameters | Lower bound | Upper bound | Conditional probability |
|---|---|---|---|
| PD (21-280) | 25 | 150 | 0.66 ($P_{PD}$) |
| MEC (31-200) | 31 | 125 | 0.66 ($P_{MEC}$) |
| MIT (421-790) | 450 | 500 | 0.17 ($P_{MIT}$) |
| MIE (14-2000) | 14 | 200 | 0.49 ($P_{MIE}$) |
| LOC (7.25-15) | 7.25 | 10.50 | 0.25 ($P_{LOC}$) |
| Total probability of dust explosion | | | 0.44 ($P_{Total}$) |

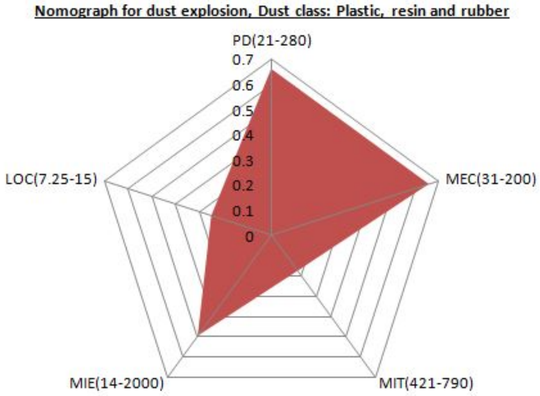


Figure 4.7: Nomograph (plastic, resin and rubber) for dust explosion

During the normal operational condition the total probability of dust explosion in the above industry is 44%. This means that, one out of two operations are susceptible to explosion, which is a high probability for a process facility. The nomograph provides a quick summary of the conditional probabilities and total probability of dust explosion. The occurrence of dust explosion indicates a process upset or standard work procedure breach. Table 4.6 shows that PD, MEC and MIE make significant contributions to the total probability of dust explosion. The investigation of this accident also notes the ignition source (electrical system of the lighting system) and explosible concentration which caused the initiation of the primary explosion [Piccinini, 2008]. Based on the quantitative analysis, an industry practitioner, design engineer or administrative personnel can modify the safety measures, work procedures or managerial control to reduce the probability of explosion in normal operating condition. The proposed model provides a simple assessment of dust explosion probability in the normal operating conditions for industries handling dust plastic, resin and rubber.

### 4.5.3 Dust class 3: Metal alloys

In this class the considered dusts are: aluminum powder, bronze powder, manganese, silicon, ferrochromium etc. Industries dealing with such dusts are considered in this class and the result of the statistical analysis for dust explosion parameters of such dust class is listed below:

Table 4.7: Metal alloys: Dust explosion parameter distribution identification

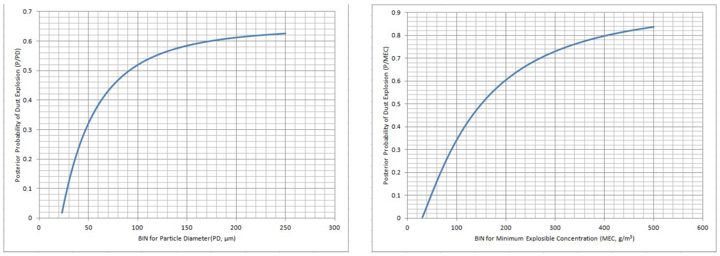
| Dust explosion parameters | Best fitted distribution | Estimated distribution parameter | 95% Data range |
|---|---|---|---|
| PD | Lognormal | $\lambda_{PD}$=3.397, $\zeta_{PD}$=1.034 | 23-250 $\mu$m |
| MEC | Lognormal | $\lambda_{MEC}$=4.8, $\zeta_{MEC}$=1.034 | 31-500 g/m$^3$ |
| MIT | Normal | $\mu_{MIT}$=700.28, $\sigma_{MIT}$=156.98 | 381-800 °C |
| MIE | Lognormal | $\lambda_{MIE}$=5.14, $\zeta_{MIE}$=1.39 | 41-250 mJ |
| LOC | Normal | $\mu_{LOC}$=10.97, $\sigma_{LOC}$=2.12468 | 8.75-12 % O$_2$ |
| P$_{max}$ | Normal | $\mu_{P_{max}}$=8.64, $\sigma_{P_{max}}$=2.29 | 5.2-12.4 bar(g) |

Analysing the dust explosion parameters and their distribution, the PDFs are determined. These PDFs are integrated over a specific operational range to get the CDFs. The range is determined from the analysis presented in Table 4.7. The CDFs are plotted in Figure 4.8. This enables the determination of the conditional probability of dust explosion for a single parameter in metal handling facilities.

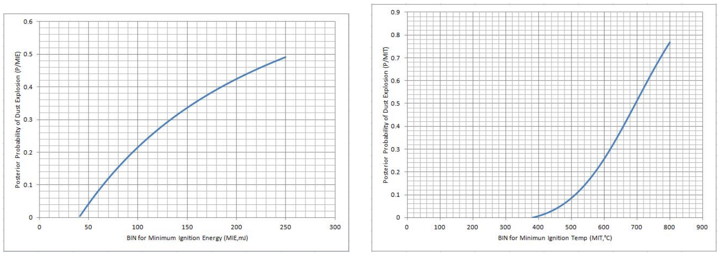
#### 4.5.3.1 Case study: Aluminum dust explosion

At about 8:30 p.m. on Wednesday, October 29, 2003, an aluminum dust explosion and fire occurred at the Hayes Lemmerz International Huntington Inc. (Hayes) facility in Huntington, Indiana.

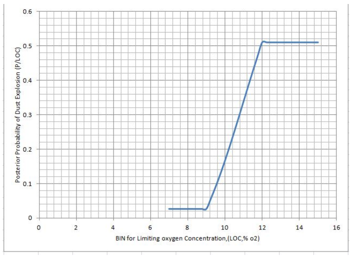
One employee was engulfed in fire and eventually died and two employees were severely burned. Three employees had minor injuries. The explosion took place in the scrap



(a) Posterior probability for PD (b) Posterior probability for MEC



(c) Posterior probability for MIE (d) Posterior probability for MIT



(e) Posterior probability for LOC

Figure 4.8: Posterior probability plot for the parameters (dust class: metal alloy).

reprocessing area, near the furnaces in the aluminum casting plant. The explosion completely destroyed dust collection equipment which was placed outside the building [CSB, 2005]. Equipment inside the building received minor damage. The explosion also lifted a portion of the building roof above one furnace and ignited a fire; insulation and other combustible materials burned for several hours [CSB, 2005].

Based on the technical reports [NFPA, 2008, CSB, 2005, Eckhoff, 2003] and standard material properties the following plant conditions are determined for the study:

- PD varies from 25 $\mu$m to 85 $\mu$m
- MEC range is 50 g/m$^3$
- Upper limit for MIT is 450°C to 500°C
- Upper limit of MIE is 240 mJ
- Upper limit for LOC is 10.5(% of $O_2$)

For the above operational condition, the model assesses the conditional probabilities, and using the information, the total probability of dust explosion is calculated. The conditional probabilities and total probability of dust explosion are listed in Table 4.8. The predictive model also provides a nomograph to represent the plant condition in terms of probability of explosion and is depicted in Figure 4.9.

Under normal operational conditions the probability of dust explosion at Hays Lemmerz International was 11%. This means that one out of eight operations is prone to explosion, which is a high probability. Table 4.8 shows that PD, MEC and MIE make higher contribution to dust explosion occurrence. From the technical report it is also evident that, the dust collector system was not designed properly and the chip system was releasing excess dust, which was unreported before the explosion took

Table 4.8: Nomograph (metal alloy) calculation interface

| Influencing parameters | Lower bound | Upper bound | Conditional probability |
|---|---|---|---|
| PD (23-250) | 25 | 85 | 0.45 ($P_{PD}$) |
| MEC (31-500) | 31 | 50 | 0.11 ($P_{MEC}$) |
| MIT (381-800) | 450 | 500 | 0.04 ($P_{MIT}$) |
| MIE (41-250) | 41 | 240 | 0.48 ($P_{MIE}$) |
| LOC (7.25-15) | 7.25 | 10.50 | 0.23 ($P_{LOC}$) |
| Total probability of dust explosion | | | 0.11 ($P_{Total}$) |

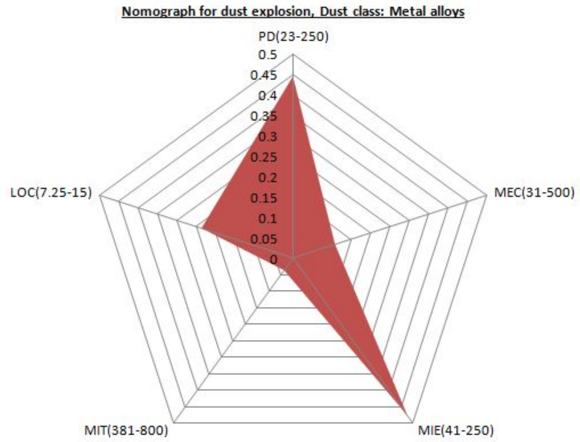


Figure 4.9: Nomograph (metal alloys) for dust explosion

place [CSB, 2005]. To reduce the explosion probability in normal operating conditions industries should focus on applicability of fire prevention standards, dust generation and hazard awareness, engineering project management, safety reviews for new and modified systems, and operating and maintenance practices. Adopting such modifications will minimize the probability of explosion in standard operating conditions which will reduce the probability of process upset conditions as well.

## 4.6 Discussion

This paper illustrates a novel approach of estimating dust explosion probability in specific operating conditions. The proposed model assesses dust explosion probability based on the operating conditions. The model is studied with three case studies considering three dust classes: food feed; plastic, resin and rubber; and metal alloys.

The model described in the paper consists of three parts. The first part is monitoring the data. In a specific industry the hazard causing parameters are: PD, MEC, MIE, MIT and LOC. PD, MEC and LOC are monitored and the obtained data are used in the predictive model for dust explosion likelihood assessment. MIT and MIE are material parameters and the specific range depends on the dust material. These values are chosen for the specific dust materials.

After obtaining the necessary data, the second step is the mathematical analysis of data and probability estimation. The model analyses the conditional probability for each parameter and estimates the total probability of dust explosion.

The final step of the model provides a nomograph as a quick estimate of the probability of dust explosion at a given facility. The nomograph is a simplified visual representation of the rigorous analysis process and makes the model easier to interpret. The nomograph provides the assessment of explosion probability in the facility in the base operational condition. Based on the assessment, the designers, engineers and workers can modify their safety measures ( e.g. inherent safety, procedural safety, safety management system etc.) and can formulate effective preventive and mitigatory measures to reduce the probability of explosion to provide a safe working environment.

The proposed model is very convenient and effective in the following ways:

- *Easier implementation:* The model consists of systematic structured steps and requires very simple techniques to follow. Moreover, the simplified mathematical steps reduce the data processing and modelling time significantly.

- *Easy to interpret:* The outcome of the analysis is presented with a simple visual tool called a "nomograph". Conditional probability and total probability are depicted this way to facilitate easy interpretation of results.
- *Quick assessing of the plant's base condition:* The model renders a quick assessment of explosion probability in operating conditions for specific dust handling facilities.
- *A condition based approach:* This condition based probabilistic model that will help to assess dust explosion likelihood for a given facility condition.

## 4.7 Conclusion

The objective of this paper is to discuss a recently proposed model for dust explosion likelihood assessment and to demonstrate its application to real life. Three dust classes are taken into consideration with case studies. Using a conditional probabilistic method enables the model to assess the likelihood of dust explosion for a given operating condition. The model can assess the total probability of explosion in the normal operating condition for a particular process facility. Based on the assessment, the process facility can implement safety measures ( e.g. inherent safety, procedural safety, safety management system etc.) and can develop effective prevention and mitigation strategies to achieve a safer working environment.

Two aspects of the model could be further explored in the future. First, the model can be applied to other dust classes based on chemical compositions that are not covered in this study. A few recommended classifications are:

- Pharmaceuticals, cosmetics and pesticides
- Coal and coal products
- Cotton, wood and peat

Second, copula function requires further testing to develop better dependency scenarios, such as the correlation between P$_{max}$ and PD, P$_{max}$ and LOC etc.

## Acknowledgement

The authors gratefully acknowledge the financial support provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada in the form of a strategic grant.

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# Chapter 5

# Summary, Conclusions and Recommendation

## 5.1 summary

A review of existing prevention and mitigation measures provides insight into limitations of the process system safety. It is evident that the majority of existing safety measures focus on dust explosion prevention and mitigation without considering any quantitative assessment of explosions occurrence in normal operating conditions. Moreover, these existing measures do not provide any assessment on dust explosion occurrence for an specific dust class. As a result, the existing safety system has no ability to determine the likelihood of the dust explosion occurrence. A predictive model to determine dust explosion probability at a given operating condition is absent in the contemporary literature.

The present study used probabilistic approaches in dust explosion assessment in processing facilities. It has focused on the estimation of dust explosion occurrence probability in the facility for a given operating condition.

A conceptual model is proposed to assess the dust explosion probability at process facility in chapter 3. A conditional probabilistic approach is used to developed the model. The model was further implemented in real life scenario and discussed elaborately in chapter 4. Three different dust classes: food feed; plastic, resin and rubber and metal alloys are incorporated in the model to assess the dust explosion probability in the industries associated with these dust particles. For each cases, the developed model is tested with case studies.

## 5.2 Conclusions

The proposed model in this study is capable of assessing the dust explosion probability based on the operational condition of the facility. A generic model is proposed to understand the underlying concept behind and further elaborated for specific cases to demonstrate the applicability in industrial aspect. For each cases, real time events are considered as case studies and the feasibility of the proposed model is assessed. Based on the assessment, the designers, engineers and workers can modify their safety measure ( e.g. Inherent safety, procedural safety, safety management system etc.) and can formulate effective preventive and mitigatory measures to reduce the probability of explosion to provide safe working environment.

## 5.3 Recommendations

The present work attempts to introduce new concepts and also overcome the limitation of existing safety measures of the process industries. This study, however, can be extended further in following ways:

First, the model can be applied for other dust classes based on the chemical composition that are not covered in this study. Some recommended classifications are:

1. Pharmaceuticals, cosmetics, pesticides
2. Coal and coal products
3. Cotton, wood and peat

Second, copula function needs to be further tested and developed for specifying dependency scenarios, such as the correlation between $P_{max}$ and PD, $P_{max}$ and MIT etc.

Third, in the study, one parameter at a time was considered for conditional probability estimation. To achieve better accuracy five parameters could be considered together. This would require solving more complex mathematical functions.

Fourth, a real time monitoring system can be utilized to observe and analyze the process parameters. A predictive alarm based system can also be implemented to monitor and assess the system continuously. It will provide a real time assessment of dust explosion occurrence.

Fifth, an uncertainty analysis can be integrated in the model to develop confidence on the estimated probability.

Sixth, the developed model can be integrated with the consequence model to estimate risk. The estimated risk may be used in designing or developing prevention strategies.

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