RISK ASSESSMENT FOR A DENIM MANUFACTURING PLANT IN TURKEY

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ABSTRACT

RISK ASSESSMENT FOR A DENIM MANUFACTURING PLANT IN TURKEY

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A risk assessment study is conducted in a denim manufacturing plant in Turkey. The study is carried out within the framework of a project on adopting the Integrated Pollution Prevention and Control (IPPC) Directive of the European Union. The scope of the assessment is fire or explosion risk with regards to hazardous chemicals present in the plant. The receptor of the study is defined as "people"; which include the employees in the plant, employees of nearby plants and people in residential around the mill. A semi-quantitative risk assessment is carried out using checklist, a risk matrix and risk evaluation forms. The highest risks in the plant are identified as dust explosions, natural gas jet fires, natural gas explosions. Also, it is identified that due to several causes, in case of a fire or explosion the scale of an accident may enlarge instantaneously. The main warehouse is determined to carry the highest risk value in the plant. Mathematical modelling studies are conducted to calculate the hazard radius for dust explosions and natural gas fire and explosion. According to the results of mathematical modelling, the highest consequences could lead to destruction of buildings or severe injuries/fatalities of people within large hazard

radius up to 700 m. The risk present at the manufacturing mill is communicated to the facility management throughout the study. Several suggestions are proposed to the facility management and some of them are already implemented.

Keywords: Major Industrial Accidents, Fire and Explosion Risk, Semi-Quantitative Risk Assessment, Fire and Explosion Modelling

ÖZ

TÜRKİYE'DEKİ BİR TEKSTİL FABRİKASININ RİSK ANALİZİ

MUNGAN ARDA, Meral
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Türkiye'de kot kumaşı üreten bir tekstil fabrikasında risk analizi çalışması yapılmıştır. Çalışma Avrupa Birliği'nin Entegre Kirlilik Önleme ve Kontrol Direktifi kapsamında gerçekleştirilmiştir. Çalışmanın kapsamı fabrikada bulunan tehlikeli kimyasallardan ötürü oluşabilecek bir yangın ya da patlamanın riski olarak belirlenmiştir. Riskin etki grubu olarak insan seçilmiştir; etki grubunda olan insanlara, fabrikada çalışan işçiler, fabrikanın etrafındaki endüstrilerin çalışanları ve fabrika etrafında yaşayan sakinler dahildir. Yarı niceliksel risk analizi için denetim listesi, risk değerlendirme formları ve matriks methodu kullanılmıştır. Fabrikada belirlenen en yüksek riskler toz patlaması, doğal gaz yangın ve patlamasıdır. Ayrıca, çeşitli nedenlerle, oluşabilecek herhangi bir yangın ve patlamanın boyutlarının kısa sürede büyüyebileceği tespit edilmiştir. Fabrikanın kimyasal deposunun tesis içinde en yüksek risk değerini taşıdığı görülmüştür. Toz patlaması ve doğal gaz yangını ve doğal gaz patlaması etki analizini saptamak üzere matematiksel modelleme çalışması yapılmıştır. Matematiksel modelleme yapıldıktan sonra, en yüksek risklerin gerçekleşmesi halinde yarıçapı 700 metreye ulaşabilen bir alanda binaların tahrip olabileceği ve insanların yaralanabileceği/ölebileceği anlaşılmıştır. Çalışmanın her aşaması fabrika yönetimi ile paylaşılmıştır. Riski indirgemek için fabrika yönetimine bazı önerilerde bulunulmuş, bu önerilerin bir kısmı hemen hayata geçirilmiştir.

Anahtar Kelimeler: Büyük Endüstriyel Kazalar, Yangın ve Patlama Riski, Yarı-niceliksel Risk Analizi, Yangın ve Patlama Modellemesi

To my dearest family and beloved husband...

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ABBREVIATIONS

ACMH: Advisory Committee on Major Hazards

AIChE: American Institute of Chemical Engineers

ALOHA: Areal Locations of Hazardous Atmospheres

BAT: Best Available Techniques

BLEVE: Boiling Liquid Expanding Vapour Explosion

BREF: BAT Reference Documents

CCPS: Center for Chemical Process Safety

EC: European Commission

EU: European Union

FMEA: Failure Modes and Effects Analysis

HAZOP: Guide word Hazard and Operability

IPPC: Integrated Pollution Prevention and Control Directive

MSDS: Material Safety Data Sheets

OSHA: Occupational Safety and Health Administration

RH: Relative Humidity

SLRA: Screening Level Risk Analysis

STP: Standard Temperature and Pressure

TNT: Trinitrotoluene

UK: United Kingdom

USA: United States of America

USEPA: United States Environmental Protection Agency

VCE: Vapour Cloud Explosion

CHAPTER 1

INTRODUCTION

The industrial revolution brought in increased production efficiency and product variety. This evolution made it possible to produce much more durable commercial products. It changed many things since the beginning of 18th century; for instance, the way production is done, the style natural resources are depleted, the types of wastes, the manner of employees, etc., and the types of dangers resulting from production.

Since then, the effects of industrialization have been discussed in different platforms, in terms of globalization, economy, international relations, human rights and with regards to environment, perhaps in a more intricate way. Industrialization that made mass production possible also led to wider scale pollution. Instead of the old time ateliers generating small amounts of waste from distributed locations, large factories started to produce huge amounts of waste from point sources.

The nature which could assimilate the waste produced by mankind to a certain extent, started to be degraded as the amount of waste produced by enormous factories seemed to be far beyond the assimilation capacity. Therefore, environmental impacts of industrialization have been discussed nearly for a century. These numerous impacts range from water pollution to toxicity, from air pollution to climate change, from industrial accidents to their environmental effects.

Throughout the previous century, these impacts increasingly mattered. During the second and third quarters where the problem was nearly realized, the solution was being sought by industries, and perhaps by the countries where these industries were active. However, when the international dimension of these effects was comprehended, environmental effects of industrialization started to be discussed among countries in international arena.

The European Union (EU) could serve a good example of cooperation in environmental issues. Twenty seven members of the country have a common approach towards environment as they also have common approaches towards economy, agriculture, commerce, human rights, etc. [1]. The first environmental policy of the European Community was launched in 1972 [2]. Since then, the EU has addressed issues like acid rain, ozone layer depletion, air quality, safety of chemicals, waste and water pollution. Today, the EU acts as a whole body in the environmental negotiations in the international arena. For instance, at the United Nations Climate Change Conference in 2007, the EU proposed a 50% cut in greenhouse gases by 2050 [3]. The discipline behind acting as a whole body on environmental issues comes from the force resulting from 73 directives of the Union regarding environmental issues [4].

Among all the directives of the EU on environmental issues, the Integrated Pollution Prevention and Control Directive (IPPC Directive; 1996/61/EC, 2008/1/EC) is the most extensive regarding the environmental concerns related to industries. The regulatory system proposal by the directive places an integrated approach to control the environmental impacts of certain industrial activities. The Directive does not only consider one aspect of environmental effects of industries, but also covers the matter in all its bearings. It means that the permits of the Directive must handle all aspects of environmental performance of an industrial plant, considering emissions to air, water and land, generation of waste, use of raw materials, energy efficiency, noise, and restoration of the site upon closure and prevention of industrial accidents [5].

The IPPC of the EU handles legal issues and gives the right to the inspecting authorities to deliver permits for industrial processes and also to monitor the environmental performance of industries. Permits within the IPPC Directive are given under a single permitting process. Inspecting authorities in each member country executes the Directive whereas BREF Notes which are guidelines for implementation of the Directive are published by the EU. The review of BREFs is a continuing process which is a consequence of the dynamic concept of "BATs" [6]. "BAT" means 'the most effective and advanced stage in the development of activities and their methods of operation which indicates the practicable suitability of particular techniques for providing the basis for emission limit values designed to prevent, and where that is not practicable, generally to reduce the emissions and the impact on the environment as a whole' [7].

The IPPC Directive is closely related to major industrial accidents. A facility should conduct studies towards prevention of accidents so as to obtain the IPPC permit. The Directive does not only cover major industrial accidents, but also smaller accidents and abnormal operations [8].

A risk assessment is a helpful instrument to consider how these events could occur. According to the IPPC, accident management within the industry should contain three particular components [9]:

- Identification of the hazards posed by the installation/activity,
- Assessment of the risks (hazard consequence x probability) of accidents and their possible consequences,
- Implementation of measures to reduce the risks of accidents, and contingency plans for any accidents that do occur.

As it can also be seen above, the Directive draws upon the risk assessment principles for permitting process [10]. It is also stated in Textile BREF Document that "Correct evaluation of the control of risks arising from the use of chemicals can only be achieved by performing a risk assessment" [11]. The depth and type of assessment will depend on the characteristics of the installation and its location. The main factors to take into account are the nature and scale of the accident hazard, the risks to areas of receptors [8].

Turkey, as a country that is in the accession period to the EU, has declared to transpose the IPPC directive to its legal context within 2008 [12]. However, the Directive is not widely known in Turkey [13]. There is a necessity of capacity building on the IPPC Directive as it is about to be legally transposed soon and especially industries lack information about the IPPC Directive. Hence, a project named "Studies on Adopting the EU IPPC Directive in the Textile Sector: BAT Applications" was developed by the Environmental Engineering Department of the Middle East Technical University. The project covered a plant scale application of the IPPC Directive for environmental management of a pilot plant in Turkey. This application was vital in terms of providing the first implementation of the Directive in Turkey.

The pilot plant selection was made considering Annex 1 of the IPPC Directive. Among different industries listed in Annex 1, the textile industry was selected for a pilot application. The reason behind this was the fact that "Textiles and their end products constitute the world's second largest industry, ranking only below food products. At least 10% of the world's productive energies are devoted to this activity [14]". In addition, "the textile industry has long been one of the most important components of the Turkish economy, accounting for 16 percent of the country's total industrial production and 10 percent of employment [15]". As Turkey could be stated as a country which is the largest textile producer in Europe [16], the pilot project was implemented to an integrated denim manufacturing plant in Turkey.

The project, executed via a large team of environmental professionals, was composed of waste management of the facility, alternative wastewater treatment methodologies, application of Best Available Techniques (BATs) which are contained in the BAT Reference documents (BREF documents) of the Directive, cleaner production opportunities regarding the implementation of the IPPC Directive. The theme of the project was about increasing the environmental performance of the facility while carefully adopting it to the IPPC Directive through BATs and the necessities of the Regulatory System.

The studies within the scope of the project included cleaner production opportunities through good housekeeping methods and hence, minimizing water and energy consumption. As highly coloured large volumes of wastewater is one of the major problems encountered in the textile industry [17], detailed analysis on alternative wastewater treatment methods, like membrane filtration, oxidation, anaerobic treatment and chemical treatment were conducted. Reuse of water and caustic were also included in the studies for the project. After BAT applications, improvements in energy and water consumption performances of the textile mill were underlined.

The IPPC Directive contains another issue apart from minimizing natural resources used during production and emissions, decreasing energy consumption and increasing manufacturing efficiency, handling wastes emerging from the industry appropriately. This issue is about preventing industrial accidents. According to Article 3/e of the IPPC Directive [5], the necessary measures should be taken to prevent accidents and limit their consequences.

Many industrial accidents occurred since the beginning of the industrial era. Unfortunately many people who were unaware of industrial accidents lost their lives in these upsetting events and many more carry the traces of these accidents. The IPPC Directive aiming at sustainable and safe production highlights the risk of industrial accidents and enforces the industries which are listed in Annex 1 to comprehend the importance, assess the risk they carry and to implement mitigation measures so that accidents do not occur. Hence, the project would have had crucial gap without a risk analysis of industrial accidents.

1.1. Objective and Scope of the Study

The aim of this study is to assess the industrial accident risk associated with a textile manufacturing plant in Turkey within the scope of the “Studies on Adopting the EU IPPC Directive in Textile Sector: BAT Applications” Project. Industrial Risk Assessment studies are required as a necessity of the Directive. This study is prepared so as to eliminate the crucial gap of not including accident risk analysis in the IPPC implementation project. Therefore, this study is a part of the above-mentioned project.

For this purpose, the textile mill was analysed in terms of industrial accidents. To determine the scope of the study, the ongoing processes related to industrial risk analysis were investigated. The textile mill had already conducted significant studies in terms of small-scale accidents involving safety and health at work. Accidents involving workers and their health were (strictly) analysed and training towards minimizing them were continuously delivered to workers. Also, analysis towards the accidents including unintentional spills of chemicals into the environment was also firmly carried out by the textile mill management board.

However, risk analysis towards fire and explosion in this plant was lacking. There were more than 100 chemicals inside the plant and a significant fraction of the chemicals presents a risk of fire or explosion. Also, cotton fibres with its high cellulose content are likely to cause fire through external ignition [18]. The selected denim manufacturing plant resides in the middle of the city centre; with a residential area only 350 m away. Thus, it is very important to assess the risk of fire and explosion in the plant and to assess the possible results of such a fire or explosion so as to take precautions against such an accident.

Due to the above-mentioned reasons, the scope of this study is determined as evaluation of fire and explosion risk at the denim manufacturing plant. Presence of such a risk should be carefully investigated as the results may lead to a catastrophe, considering the fact that the facility lies in the middle of a residential area, an industrial zone besides another manufacturing mill. A potential fire or explosion with a large effect radius could trigger an explosion or fire in the industrial zone or in the adjacent denim manufacturing mill which is only 20 m away.

Consequently, fire and explosion risk at the denim manufacturing plant is investigated in this study so as to lay down the risks associated with the plant. After examination of the risk, the occurrence mechanisms, dimensions (via mathematical modelling) and results of probable accidents are also questioned. In this respect, this study covers a semi-quantitative risk assessment for the plant within the scope of the IPPC Directive.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

This chapter gives a brief discussion on the evolution of industrial safety concept. It also gives an overview on risk assessment and explains the tools of risk assessment. Lastly, types of industrial accidents which are in focus of this study are defined and mathematical models to be used in this study are explained elaborately.

2.1. History of Industrial Safety

In the beginning of the 19th century, major changes were observed in agriculture, manufacturing and transportation in Britain and these changes spread to the world. Steam-powered machines led to a switch from manual labour to automated production. Mechanisation of production affected each and every aspect of life. This was the ignition leading to industrialization.

Technological improvements made exportation and importation easier, nearly resulting in an infinite market. Meeting the demands of the market required intense production. Massive increase in the number of factories led to pollution, child labour utilization and numerous occupational accidents. There were few safety rules [19]. Safety rules and insurance programmes towards workers increased in time.

During the 1960s, complex machines with a high risk of occupational accidents, modified chemicals most of which are hazardous and which are mostly operated under severe pressure and temperature conditions started to be experienced. The energy stored in the process increased and represented a greater hazard. Plants grew in size, typically by a factor of about 10, and were often single stream. Therefore, the risks industries represent increased drastically [20]. However, safety of industrial plants became a hot topic for the public during the 3rd quarter of 1900s. Around 1970s, it became increasingly recognized that there was a worldwide trend for losses, due to incidents, to rise more rapidly than gross national product [20]. These losses were mainly due to several notable accidents involving hazardous chemicals [21]. Some examples of these unfortunate accidents are presented in Table 2.1.

Table 2.1: Several industrial accidents [21]

Location	**Year**	**Number of Fatalities**	**Reason of Explosion**
Flixborough	1974	28	Cyclohexane leak [22]
Beek	1975	14	Propylene release
Mexico City	1984	500	Leak in LPG storage facility[23]
Aberdeen	1988	170	Natural gas explosion [24]
Ufa	1989	575	LNG release [25]
Visakhapatnam	1997	60	LPG release
Carlsbad	2000	12	Natural gas release [26]
Bhopal	1984	3800	Methyl isocyanate [27]

Many events like the ones above have been experienced throughout the history. In all of these cases, either a fire, or an explosion, or a runaway chemical reaction caused the large scale accident. Ubiquitously, there was growing public awareness and concern regarding the threat to people and to the environment from industrial activities, particularly those in which the process industries are engaged [20]. International arena started to discuss industrial accidents, their mitigation measures and the necessity of legislative action towards large scale industrial accidents more and more upon witnessing them. This has triggered the development of various pieces of legislation in many countries around the World.

Bhopal accident is one of the accidents strongly promoting industrial safety legislations. Methyl isocyanate (MIC) gas leaked from a plant in Bhopal, India. According to the state government of Madhya Pradesh, approximately 3,800 people died and several thousand other individuals experienced permanent or partial disabilities [27] due to the toxic gas cloud. Certain references give higher fatality rates for that accident.

For instance, Seveso I and Seveso II Directives of the EU came into force in 1982, 6 years after the well-known Seveso Disaster. Seveso Disaster was an industrial accident occurred in Seveso, Italy in 1976, in a small chemical manufacturing plant. Due to the release of 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) into the atmosphere, 3,000 pets and farm animals died and, later, 70,000 animals were slaughtered to prevent dioxins from entering the food chain. Luckily, no public fatalities were observed [28]. The disaster led to the Seveso Directive, which was issued by the European Community and imposed much harsher industrial regulations. The objective of the Directive is to prevent major accidents involving dangerous substances and to decrease their consequences for people and the environment.

Also, the US OSHA Regulation named Process Safety Management of Highly Hazardous Chemicals - 29CFR1910.119 came into effect in 1992 [29]. In 1992, the Convention on the Transboundary Effects of Industrial Accidents was produced as a result of international cooperation, promoting active international cooperation between the contracting parties, before, during and after an industrial accident [30].

IPPC Directive of EU [31] is an integrated directive providing an integrated approach to establish pollution prevention from industrial plants. The Directive also dictates that measures are taken so as to prevent accidents and to limit their consequences. Some milestones in the development of loss prevention are provided in Table 2.2. In Turkey, legal transposition of the Seveso Directive and the IPPC Directive is about to be in force soon, as the country prepares to be a member of the EU.

Table 2.2: Some milestones in development of loss prevention concept [20]

1971	European Federation of Chemical Engineering symposium on Major Loss Prevention in the Process Industries
1972	UK - Report of Robens Committee on Safety and Health at Work
1981	Norwegian Guidelines for Safety Evaluation of Platform Conceptual Design
1982	EC Directive on Control of Industrial Major Accident Hazards
1984	Third Report of ACMH; Control of Industrial Accident Hazards Regulations 1984 in the UK
1985	AIChE establishes the CCPS
1986	USA, California - Risk Management and Prevention Program; USA, New Jersey -Toxic Catastrophe Prevention Act

Table 2.2: Some milestones in development of loss prevention concept [20] (cont'd)

1990	USA - January -API Recommended Practice 750 (Management of Process Code of Management Practices; November - Clean Air Act Amendments of 1990; Formation of the US Chemical Safety Board
1992	Offshore Safety Act 1992; Offshore Installations (Safety Cases) Regulations 1992
1995	USA - Risk Management Program regulation promulgated by USEPA; Texas A&M University established the Mary Kay O'Connor Process Safety Centre

In Turkey, legal transposition of the Seveso Directive and the IPPC Directive is about to be in force soon, as the country is preparing to be a member of the EU. As this study is a part of the work done for an IPPC adoption project, the relation between the Directive with industrial accidents will further be analysed.

2.2. Risk Assessment

Legislation towards major industrial accidents aims to prevent large scale industrial accidents and to sustain the wellbeing of the public. In order to avoid accidents, it is vital to understand how they might occur and thus to determine the risk of such an event. Risk Assessment studies would reveal the risk of accident in an industry and hence should be conducted so as to meet the objectives of these Directives, especially for IPPC as its importance emphasized in the Directive and its BREF documents. After comprehending the risk present in an industry, it would be easier to conclude its consequences and probable effects to public, to apply mitigation measures and to prepare contingency plans.

2.2.1. Risk Assessment Concept

Risk assessment is the determination of qualitative, semi-quantitative or quantitative value of risk related to an existing hazard. The starting point for risk assessment is the identification of the hazards and definition of the hazard scenarios to be considered. For each hazard scenario, frequency and consequence values should be estimated. Risk of the event is equal to frequency times the consequence [20].

$$\text{Risk} = \text{Consequence of undesirable event x Likelihood of that event} \quad [32]$$

The estimation of frequency may require historical data. The estimation of the consequences (e.g. number of fatalities) involves the study of a sequence of events. Usually this is an emission of hazardous material which gives rise to certain physical effects [20].

Negative effects arousing from the realization of the hazardous event at the risk source, influences the risk receptor. Before conducting the risk assessment, the receptors of interest should be identified to orient the whole study. Receptors could be employees of the facility, the public, the environment, plant units and equipment, property, reputation of the corporation, etc. Consequences of a hazardous event will vary according to different receptors [32].

A full risk assessment taking the public as the receptor should contain models that determine the population at risk. Knowledge of population and radius of effects help decision makers on planning factors such as shelter and escape [20]. Contingency plans should hence be prepared after a detailed risk assessment.

In order to carry out a Risk Assessment Study the following procedure should be applied:

- Define consequence and frequency categories of undesired events for use in the study
- Determine population groups of interest and their characteristics
- Determine event outcomes of interest
- Estimate consequences of event outcomes
- Estimate frequencies of event outcomes
- Determine impacts of event outcomes at locations of interest
- Estimate risk [33].

Individual Risk

Individual risk is the quantification of combined importance of individual consequences (fatality of a single person) and the likelihood of those consequences (possibility of a fatality as a result of the undesired event).

Individual risk of a given hazard scenario (event) is calculated by multiplying the individual consequence curve of that event with its frequency. The summation of individual risk of different events that can occur at a facility gives the total facility risk. This is illustrated in Figure 2.1.

The risk that the facility imposes on a receptor is equal to the sum of all event risks at a receptor point. Units of this risk measure can be expressed as "the annual chance of a person who is living near the facility to die as a result of potential accidents in that facility" [34].

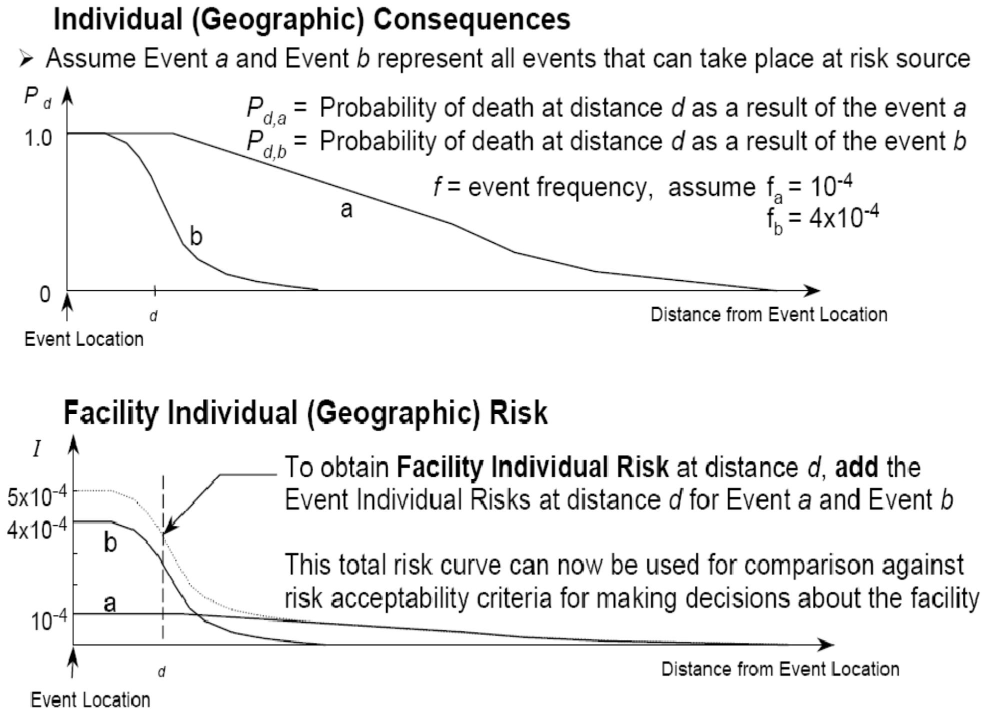

Figure 2.1: Calculation of facility individual risk via summation of event individual risks calculated by multiplying event frequency with the individual event consequences [34]

Societal (aggregate) Risk

Societal or aggregate risk is the quantification of combined importance of societal consequences (number of fatalities) and probability of those consequences occurring (likelihood of a number of people to die as a result of the undesired event) [32]. Individual risk is location dependent whereas societal risk is based on aggregate values.

2.2.2. Risk Assessment Procedure

Risk Assessment necessitates an initiation step to set the framework of the study. Then, hazards should be identified. The hazard identification step involves the "identification of hazards and potential hazardous events that may occur due to operation of the facility". In a risk assessment with a focus on hazardous materials, this step requires an intense knowledge on the manufacturing process, hazardous materials and their hazardous properties, such as flammability and toxicity data [34]. Hazards in a plant can be classified into five different types:

- **physical:** includes floors, stairs, work platforms, steps, falling objects, slippery surfaces, manual handling (lifting, pushing, pulling), excessively loud and prolonged noise, vibration, heat and cold, radiation, poor lighting, ventilation and air quality,
- **mechanical and/or electrical**: includes electricity, machinery, equipment, pressure vessels, dangerous goods, forklifts,
- **chemical:** includes chemical substances such as acids or poisons and those that could lead to fire, explosion or toxic gas cloud like flammable substances and dust,
- **biological:** includes bacteria, viruses, mould, mildew, insects, vermin, animals,
- **psycho-social environment:** includes workplace stressors arising from a variety of sources [35].

Consequently, what may go wrong at the plant is revealed as a result of hazard identification and the draft of the study is sketched. After identifying potential hazards inside the plant, frequency and consequence categories of the potential hazardous events should be determined. Consequences are handled in six different categories:

- consequences to the public
- consequences to the environment

- consequences to the employees
- consequences to the production loss
- consequence to the capital loss
- consequence to the reputation of company/market share [34]

In order to conduct the consequence and frequency analysis in an appropriate way, it is necessary to set the categories for consequences and frequencies which are specific to the studied plant. A practical principle in defining the different category ranges is that they should provide sufficient resolution to differentiate the risk levels all the different events that could occur at the facility. Table 2.3 and Table 2.4 present example values for frequency and consequence categories. These consequence values should be prepared specific to the facility and these values should also reconfirmed by the management board of the plant [34].

Table 2.3 Example frequency categories [34]

Category number	Category Description
1	Not likely to occur during the facility lifetime (<0.02/year)
2	Once during the facility lifetime (0.02 to 0.05/year)
3	Several times during the facility lifetime (0.05-1/year)
4	More than once in a year (>1/year)

Table 2.4: Example Consequence Categories [34]

Category number	Public Consequences - Category Description
1	No injury of health effects
2	Minor injury or health effects
3	Injury or moderate health effects
4	Death or severe health effects

Table 3.4: Example Consequence Categories (cont'd) [34]

Category number	Consequences on Employee Safety - Category Description
1	No injury of occupational safety impact
2	Minor injury or minor occupational illness
3	Injury or moderate occupational illness
4	Death or severe occupational illness
Category number	**Environmental Consequences - Category Description**
1	Less than \$ 1000
2	Between \$ 1000 and \$ 10000
3	Between \$ 10000 and \$ 100000
4	Above \$ 100000
Category number	**Consequences on Production Loss - Category Description**
1	Less than 8 hours
2	Between 8 hours and 24 hours
3	Between 24 hours and one week
4	More than one week
Category number	**Consequences on Capital - Category Description**
1	Less than \$ 10000
2	Between \$ 10000 and \$ 1000000
3	Between \$ 100000 and \$ 500000
4	Above \$ 500000
Category number	**Consequences on Market Share - Category Description**
1	Less than 1% of annual revenue
2	Between 1% and 10% of annual revenue
3	Between 10% and 25% of annual revenue
4	More than 25% of annual revenue

Consequence Analysis

Consequence Analysis is based on predicting effects of undesirable events via using historical experience and mathematical models [32]. After the hazardous events are identified, their consequences should be estimated. These consequences may be named as the magnitude of damage it causes on the receptors of interest. In order to conduct consequence analysis, statistical accident databases, logical judgement and mathematical models can be used. Consequence analysis with respect to hazardous substances aims to determine potential physical effects on the receptor which results from the release. Information necessary to conduct the analysis involved physical, chemical and toxicity data of hazardous substances utilized within the manufacturing plant. Also, the system (vessel, pressurized pipeline, reactor, etc.) in which the substance stored should be known. Consequence analysis should be carried out elaborately if it is used as a tool to prepare contingency plans [34].

Release scenarios, assumptions in mathematical models, the limits of the model used determine the quality of consequence analysis. The aim of elaborate consequence analysis with respect to hazardous chemicals is to determine flammable or toxic concentrations. These concentrations in the air will result in a fire, explosion or a toxic gas release. Consequence analysis has two steps: “Hazard Analysis” and “Vulnerability Analysis”. Hazard Analysis gives the level of thermal radiation at the receptor, overpressure, etc. Vulnerability Modelling, then relates the hazard level to the level of damage a given type of receptor would receive as a result of being exposed to that hazard level [34].

There might already be some mitigation measures against the risk. Consequence analysis should take into account the presence of mitigation measures to prevent the hazard occurrence. Risk levels may overestimate the hazard present for cases in which mitigation measures are already implemented in the facility (the judgement should be done accordingly).

Frequency Analysis

In order to understand the likelihood of the hazardous events, frequency analysis should be conducted. Frequency of the event is generally expressed as number of event occurrence per year. This value is estimated using frequency analysis methods which mainly rely on past experience as well as logic models that describe how a given system would behave in case of failures.

The methods of frequency analysis include:

- historical data analysis,
- fault tree analysis,
- event tree analysis,
- human reliability analysis, and
- external events analysis.

Historical data can be used to directly estimate the frequency of the hazardous event itself, called as top event or to estimate frequencies of events that cause the occurrence of the top event.

Fault Tree Analysis is used when failure data is not available for the top event. Then, a backward logic is followed. This logic begins with an undesired event like the release of a hazardous substance and analyzes the basic causes of such a release. Via top down trees illustrating the sequence of events, top event frequency is calculated with a de deductive approach.

Event Tree Analysis is applied with a forward looking method. In this method, the initiating event is taken into consideration and form a logic tree where each possible outcome following the initiating event is tracked. These tracks are shown as positive or negative branches. In this way, likelihood of undesirable outcomes, such as releases of hazardous materials can be estimated [34]

Quantitative Risk Analysis

The frequency and consequence information obtained from consequence and frequency analysis mentioned above are combined to reveal the quantitative risk. For instance, if two events are identified as credible (i.e. to contribute to overall risk); the risk can be calculated as presented in Table 2.5.

Table 2.5: Calculation of risk from frequency and consequence values [34]

	Frequency	**Consequence**	**Risk**
Event 1	f1	s1	f1 x s1
Event 2	f2	s2	f2 x s2

Normally;

$$Risk = Consequence \times Frequency\ of\ Consequence$$

However, risk of an event occurring as a result of another event involves the calculation of conditional probability. Conditional probability is the probability of some event A, given the occurrence of some other event B. In this case, the event frequency is calculated as [36]:

$$\begin{aligned}&Frequency\ of\ the\ Given\ Outcome\\&\qquad = Frequency\ of\ initiating\ event\\&\qquad \times Conditional\ Probability\ of\ a\ Given\ Outcome\end{aligned}$$

After the risks are quantitatively determined, they are ranked according to their quantitative value. Semi-quantitative risk assessment methods which are suitable for ranking could also be used for this purpose. For instance, the matrix method is a good technique to rank risks of present hazards.

Mitigation measures should then be suggested for the medium and high risk items. All stages from initiation to suggestions for risk reduction should be communicated with the facility.

The methodology explained above is compatible with the methodology suggested by the IPPC Guidance Document for Textile Sector prepared by the Scottish

Environment Protection Agency, Environment and Heritage Service and Environment Agency. It also forms the basis for methodology of this study. The the methodology which exists in the guidance document is mainly comprised of three segments:

• Identification of the hazards posed by the installation/activity,
• Assessment of the risks of accidents and their possible consequences,
• Implementation of measures to reduce the risks of accidents, and contingency plans for any accidents that do occur [8].

2.2.3. Semi-Quantitative Risk Assessment Techniques

Risk assessment procedure is implemented through certain techniques. Some qualitative hazard identification and risk analysis techniques are highly convenient for semi-quantitative risk evaluation methods through a risk matrix approach. These techniques include:

- Screening Level Risk Analysis (SLRA),
- Guide word Hazard and Operability (HAZOP) study,
- Failure Modes and Effects Analysis (FMEA),
- Checklist,
- What-if,
- Matrix Method.

2.2.4 Screening Level Risk Assessment

The focus of a screening level risk assessment is identification of major hazards. Screening Level Risk Assessment (SLRA) can be applied to both new and existing facilities and also to major modifications in existing facilities.

A process-focused approach is used during SLRA to identify potential undesirable events. The technique mainly relies on walk-through physical inspections, as well as document study. Spreadsheets are typically used to facilitate information management. During the identification of potential hazards, they are prioritized according to the risk receptor. SRLA should be followed by more detailed analyses of hazards if needed [37].

2.2.5. Hazard and Operability Study

Hazard and Operability Study (HAZOP) is an investigation of the processes of a facility to assess the hazard potential that arise from deviation in design specifications and the consequential effects on the facility as a whole. The results of the study can lead the team to decide whether redesign or slight changes in the design is necessary. It can identify and eliminate potential hazards and their effects at each and every stage of the activity. Focusing on sensitive areas of the facility, HAZOP is suitable for chemical processes [38].

It is possible that a solution becomes apparent; this is accepted as a part of HAZOP study. Performance of the method depends on the accuracy of data and technical skills and abilities of the team [21].

Advantages:

- It identifies and eliminates/mitigates potential hazards and their effects at every stage of production,
- The method focuses on the sensitive areas of the facility.

Disadvantages:

- It provides no numeric ranking of hazards,
- HAZOP focuses on one-event failures,
- It is time consuming,

- It requires an inter-disciplinary, skilled and experienced team [39].

2.2.6. Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) is a procedure by which each potential failure mode in a system is examined to determine its effect on the system and to classify it according to its severity [38].The analysis investigates all probable failures of the system and examines the results of these failures. It also suggests mitigation measures to diminish the probability of these failures. The results of the FMEA generally bring forth improvements in equipment design [21].

Advantages:

- The method is very structured and rigorous.

Disadvantages:

- Hazard ranking is not possible with this method, unless used with a risk ranking matrix,
- It is limited to identification of single failures; the method cannot integrate multiple causes [38].

2.2.7. Checklist Analysis

Checklist analysis is a method which cannot be used on its own, but it is generally used with another method. Checklist analysis is a list of items and questions to be answered as yes and no. The preparation of questions and answering them requires experience and confident knowledge about the facility [38]. The questions are prepared before visiting the plant and the person who conducts risk analysis continuously asks questions to the employees of the facility.

Checklist which is prepared appropriately draws the road map of the risk analysis. It is easy to detect common hazards in a facility through checklist analysis as well as to decide whether current or forthcoming regulations on safety and health at work are met or not. Checklists should be updated regularly [21]. A sample checklist is shown in Figure 2.2.

Company: **Participants:** **By:**
Location:
Date:

Hazard Review Section:

Materials, Chemicals, or Components	Physical State (Liq, gas, liquefied gas, solid, powder...)	Quantity (Throughput or Inventory)	Range of Operating Pressure	Range of Operating Temperature	Compressed or Liquefied Gas	Fire	Explosion	Detonation	Oxidizer	Toxic - Acute	Toxic - Chronic	Corrosive	Reactive	Smell/Fumes	dust/Mist	Radiation	Other	Air Pollutant	Water Pollutant	Ground Contaminant	Hazardous Waste

Figure 2.2: An example format for hazardous materials checklist [37]

Advantages:

- It is easy to use,
- It can be conducted faster.

Disadvantages:

- It is limited by the experience and knowledge of the team,
- It yields minimum level of hazard identification,
- It is able to identify the existing hazards; it may not identify the new hazards [38].

2.2.8. What If Analysis

This method approaches to the facility with a brainstorming mentality. Participants in risk assessment roam around the facility and repeatedly ask the question “What if” to seek what could go wrong in there.

This method can give definite results if workers in the facility know well what they are doing. Workers inside the plant will answer these questions and then according to the results important hazard items will be highlighted. The questions which experts will ask should be prepared very carefully. An example question to be asked during “What if” analysis could be: “What if the raw material is fed in with the wrong concentration?” [21]. If the answer to this question is like “If the concentration of the raw material increases, an exothermic reaction which is very hard to control may occur” then a precaution necessity will be highlighted for raw material feeding [21].

Advantages:

- It is easy to use,
- It works well for new & unusual scenarios.

Disadvantages:

- It is limited by the experience and knowledge of the participant,
- It is pretty unstructured, challenging to retain focus.

2.2.9. Matrix Method

Risk assessment matrix is a simple tool for ranking different risks of possible events in a facility. As the frequency and consequences of the possible hazards are identified or estimated, they could be categorized using category definitions such as those presented earlier in Table 3.3 and Table 3.4. Then, a risk matrix such as in Figure 3.3 can be used to classify each event into a risk category. The possible hazardous events which are ranked through the matrix method are identified with other methods listed above, e.g. the checklist, what-if, HAZOP or FMEA methods.

Possible hazards are listed according to their frequencies and consequences and they are placed in the matrix [40]. Top-right parts of the matrix (high consequence, high frequency) show higher risks and the bottom-left parts of the matrix show very low risks, (VL: Very Low, L: Low, M: Medium, H: High).

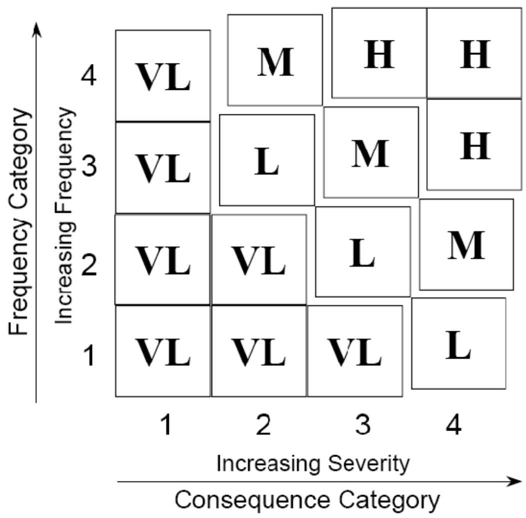

Figure 2.3: Risk Matrix example [40]

Advantages:

- The matrix evaluation and ranking technique is a very powerful technique, because it is simple and it can easily lead to decisions in terms of actions required immediately and further studies required for more detailed understanding.

- It is very suitable to be used by everybody in the facility: operators, supervisors, management, engineering personnel, safety and environmental coordinators.
- The matrix approach mainly focuses on aggregate consequences and risk of specific events.

Disadvantages:

- If the consequences and frequencies of events are not examined carefully first, and then be integrated into this matrix, overestimation or underestimation of the risk may occur [41].

2.3. Types of Accidents of Interest in the Risk Assessment

Major industrial accidents with a large radius of effect generally result from fire or explosion involving a chemical release. The mechanisms of chemical releases and their outcomes like fires or explosions have been studied intensely and these studies still continue. It is very important to comprehend the hazards associated with chemical releases.

There are several hazards linked to hazardous chemical substances. These include small scale injuries of employees as a result of inhaling or physically contacting the chemicals. As most of these chemicals are corrosive, asphyxiating, reactive, carcinogenic, etc. in nature, close contact with these chemicals while working may arouse health problems for employees. However, in terms of major industrial accidents the hazards resulting from these chemicals could be defined as fire and explosion hazards. Classical study of Doyle, 1969 indicates that two major causes of losses as a result of accidents are fires (42% frequency and 30% financial loss) and explosions (53% frequency and 69% loss) [21]. It should be noted that "explosion" term used by Doyle include chemical runaway reactions [21].

2.3.1. Hazardous Properties of Chemicals

As it is seen in Table 2.6, certain chemicals carry hazards and produce outcomes like fire, explosion or toxic gas clouds. This fact is dependent on certain characteristics of chemicals. These characteristics and the mechanism behind fires, explosion or toxic gas clouds led by chemical releases are explained in this section.

Table 2.6: Hazards which hazardous chemicals present and their potential outcomes [34]

Hazard Category	Potential Outcome
Flammable Liquids, including those liquefied by refrigeration	Pool fire
	Flash fire
Flammable gases, liquefied by compression	Boiling Liquid Expanding Vapour Explosion (BLEVE)
	Fireball
	Jet fire
	Vapour Cloud Explosion (VCE)
	Flash Fire
	Pool Fire
Flammable Gases, Gas under pressure	Fireball
	Flash Fire
	Jet Fire
Toxic Liquids, including those liquefied by refrigeration	Toxic Gas Cloud
Toxic gases, liquefied by compression	Toxic Gas Cloud
Toxic gases, gas under pressure	Toxic Gas Cloud
Toxic combustion products	Toxic Gas Cloud
Explosive Dusts	Dust Explosion

2.3.2. Flammability and Combustibility

The concept is related to flammable properties of the chemical, its flash point, explosive limits and ignition temperatures. Flash point is the minimum temperature at which an ignitable mixture exists above a liquid surface [41]. The determination of whether a chemical is flammable or highly flammable is usually governed by the arbitrary flash point values of 67^{o}C (153^{o}F) and 23^{o}C (73^{o}F) [42].

There are other specific technical criteria and test methods for identifying flammable and combustible liquids. For example, under the Workplace Hazardous Materials Information System (WHMIS) used by Canada, flammable liquids have a flashpoint below 37.8°C (100°F). Combustible liquids have a flashpoint at or above 37.8°C (100°F) and below 93.3°C (200°F) [43].

The minimum requirements for a flame to occur are:

- A fuel (either gas or liquid) in certain limits of concentration (the fuel and air should have mixed in proper ratios)
- A supply of oxygen above certain minimum concentration (this is generally met by air)
- An ignition source of minimum temperature, energy and duration (ignition sources can include sparks from electrical equipment or welding and cutting tools, hot surfaces, open flames from heating equipment, smoking materials etc. [44].

Necessary limits of concentration for flame to occur are generally expressed as flammability limits. Below a certain concentration of the flammable gas, the lower flammability limit (LFL), the mixture is too 'lean'; while above a certain concentration, the upper flammability limit (UFL) it is too rich [14]. As defined by Carson P.A., Mumford C.J, a concentration of vapour can be reached below which a flame will not propagate; this concentration is the Lower Explosive Limit (LEL)

[41]. Conversely, the vapour concentration can be made so “rich” that there is insufficient oxygen for combustion; this is the Upper Explosive Limit (UEL). The intermediate range is Flammable Range [41]. It should be noted that, “a material's flammable or explosive limits also relate to its fire and explosion hazards. These limits give the range between the lowest and highest concentrations of vapour in air that will burn or explode [45]”. All three represent the “fire triangle” in Figure 2.4.

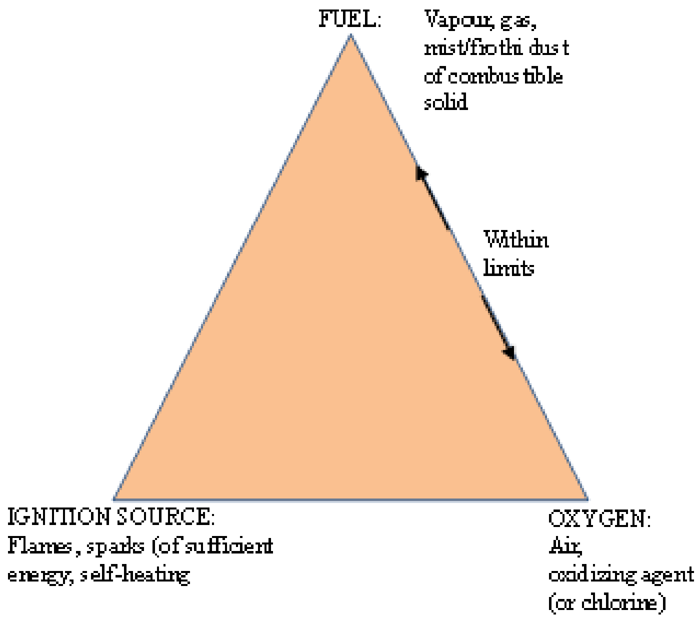

Figure 2.4: Fire triangle [41]

The ignition temperature is the temperature at which a small amount of material will spontaneously ignite in a given atmosphere and burn without a further heat input, [41]. When a gas or vapour, or a dust cloud burns in a confined place heat of combustion causes rapid expansion of the gaseous combustion products which are restrained by the confined place. The pressure depends on the composition of the flammable mixture. A mixture just above the flammability limits would result in a pressure rise which is far below that of a stoichiometric mixture (with correct quantity of air for complete combustion). Ignition of a stoichiometric mixture could result in pressure exceeding 100 psi (700 kN/m^2) [41].

2.3.3. Toxicity

Release of a toxic chemical is one of the biggest major industrial hazards, after fire and explosion. A toxic release has a probability of occurrence higher than that of a fire or explosion [20].

Toxicity of a substance is its ability to lead to harmful effects on the health of living organisms. These effects can attack a single cell, a group of cells, an organ system, or the entire body. All of the chemicals may cause harm. However, when a large amount of chemical is needed to cause damage, the chemical is considered to be relatively non-toxic. But if even a small amount can be harmful, the chemical is considered toxic [46].

Toxic chemicals enter the body through inhalation, ingestion and external (dermal) contact. Generally, gases, vapours, fumes and dusts are inhaled and liquids and solids are ingested [20]. When considered in terms of major industrial accidents to affect the public, it could be stated that toxicity effects reach to the public via gases, vapours, fumes and dusts. A release of a toxic compound could occur via release of a toxic liquid and its evaporation or release of a toxic gas so that the toxic vapour or gas can reach the public.

2.3.4. Corrosivity

Corrosive chemicals can attack and chemically destroy exposed body tissues. Corrosives can also damage or even destroy metal. They begin to cause damage as soon as they touch the living tissue or the metal. Most corrosives are either acids or bases [47].

2.3.5. Potential Outcomes of a Chemical Release

Several outcomes occur as a result of flammable, combustible or toxic chemical releases. These are mainly Pool Fire, Flash Fire, Boiling Liquid Expanding Vapour Explosion (BLEVE), Fireball, Jet Fire, Vapour Cloud Explosion (VCE), Dust Explosion or Toxic Gas Clouds as indicated in Table 4.6. Theories of these undesired events will be investigated in this section.

2.3.6. Pool Fire

A pool fire is a turbulent diffusion fire burning above a horizontal pool of vaporising hydrocarbon fuel where the fuel has zero or low initial momentum [48]. A pool fire occurs when a flammable liquid spills onto the ground and is ignited as it is shown in Figure 2.5.

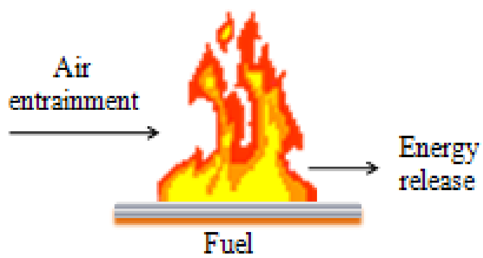

Figure 2.5: Pool fire dynamics [48]

Upon ignition, fire spreads rapidly over the surface of the liquid spill area. The flame may cause damage by direct impingement or by radiation. Pool fires may also occur on water or land (for example steel) [20]. Pool fires may be static or running. Static pool fires burn within the boundaries of the pool [48].

“For a given amount of fuel, spills with a large surface area burn with a high Heat Release Rate for a short duration, and spills with a smaller surface area burn with a lower Heat Release Rate for a longer duration” [49].

2.3.7. Flash Fire

A leaked flammable gas may be in a number of forms. If it is ignited at the point of release, it behaves like a flame on a Bunsen burner. This flame may be directed to another part of the plant in some cases. If the leaked material does not ignite as soon as it is released, then it forms a vapour cloud which grows for a period before it is ignited. This effect is called as a flash fire if the gas cloud burns, but does not explode. An evaporating liquid can also result in a similar gas cloud and flash fire. People caught in flash fire will likely die. Flash fires may cause extensive destruction to an industrial plant, particularly to vulnerable items such as electric cabling, but may leave the main plant equipment relatively unharmed. However, a flash fire does also cause a sudden depletion of oxygen, and this effect can be lethal to personnel [20].

2.3.8. Boiling Liquid Expanding Vapour Explosion (BLEVE)

A BLEVE generally occurs when a pressure vessel containing a pressure-liquified gas is exposed to fire. Under such a condition, the liquid heats up and the vapour pressure increases. This rise leads to a pressure increase in the vessel. When this pressure exceeds the set pressure of the pressure relief valve, the valve operates. The liquid vapour is released to atmosphere and liquid level decreases. The liquid in contact with the vessel can provide sufficient cooling to keep the metal intact, but the vapour cannot. Therefore, as the liquid vaporizes and is lost through the pressure relief valve, the proportion of vessel wall which has the advantage of liquid cooling decreases. After a time, metal which is not any more cooled by liquid becomes exposed to the fire. Then, the metal loses strength and ruptures. This leads to a BLEVE, which is simply a pressure wave resulting from the very rapid expansion of the pressurized liquid in to vapour as it depressures when the vessel disintegrates. BLEVEs can occur with an appropriately operating pressure relief valve.

Flammable (e.g., propane, butane liquefied under pressure) as well as non-flammable materials (e.g., water-steam mixture under high pressure) can result in BLEVEs if the containment disintegrates rapidly for any reason. If the material is flammable, and it ignites, a fireball follows the BLEVE. Often, the term BLEVE is incorrectly used to mean both the pressure wave and the fireball.

Most BLEVEs involve a pressure storage vessel or transportation tanker carrying a flammable liquid, typically a liquefied flammable gas. The development of BLEVE is demonstrated in Figure 2.6 [20].

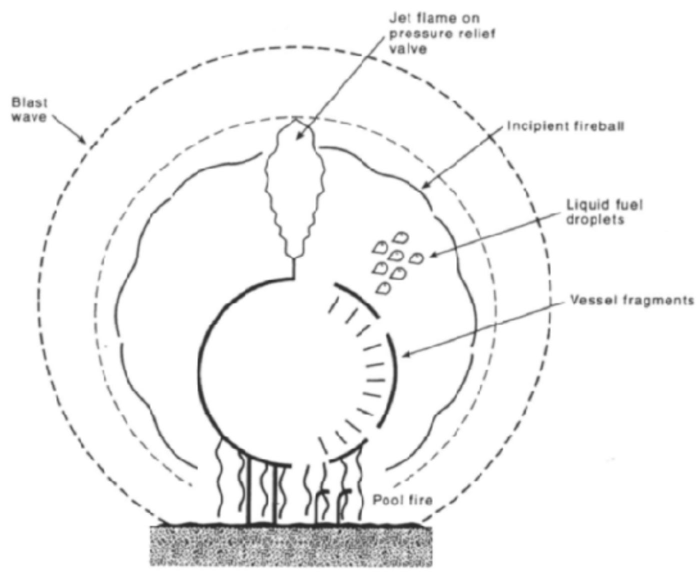

Figure 2.6: Development of BLEVE [20]

As illustrated in Figure 2.6, a BLEVE causes blast wave, and metal fragments; if the material involved is flammable, it will also lead to a fireball. The radiant heat resulting from the fireball is generally considered to be the principal hazard, but also, fragments of the vessel can be thrown a considerable distance and shock waves are generated by the explosive rupture of the vessel [50].

2.3.9. Fireball

If a flammable material is released and fire engulfment of a vessel occurred; a fireball may be formed [20]. Most treatments of fireballs relate to liquefied gas. Fireballs may result from bursting of a pressurized vessel and from formation of a vapour cloud. There are two other types of event which may lead to a fireball. One is the ignition of a release from liquefied or pressurized gas pipeline, where the jet flame is preceded by a fireball. The other one is an eruption in hot oil giving rise to a release of burning vapour. Particular interest is paid to fireball occurring as a part of BLEVE. In fact, the other types of fireballs are rarely seen [20].

2.3.10. Jet Fire

Release of flammable material from a vessel or pipeline under pressure may give rise to a jet fire if the material ignites upon release [20] & [50]. Jet fires may involve releases of gaseous, flashing (two phase) liquid and pure liquid chemicals [51]. Scenarios involving jet fires may have substantial flame lengths, sometimes up to several hundred metres.

2.3.11. Vapour Cloud Explosion

For vapour cloud explosion (VCE) to occur a flammable cloud should burn and the combustion should give rise to an overpressure. Not all the times that flammable vapour combustion results in overpressure. If there is no overpressure, the event is called as vapour cloud fire or flash fire. However, in case there is an overpressure resulting from the combustion, the event is named as VCE, which is one of the most serious hazards in industries. Combustion of a vapour cloud with the occurrence of overpressure occurs due to at least partial confinement, such as due to plant vessels, equipment and pipe racks, even though there may not be any building as a containment.

VCEs are not very common, but their consequences tend to be highly destructive. Vapour Cloud Explosion threatens a considerable area, with its effects drifting from the leak source [20]. Several devastating Vapour Cloud Explosions occurred since the 1970s. As a result, a considerable degree of attention and research effort has been focussed on this subject. To assess damage, models are necessary to calculate the magnitude of an explosion as a function of distance from the centre [52].

Vapour cloud explosion may have devastating results; it is known that severe damage to the immediate surroundings with window breakage up to 4.5 km from the source can be seen [53]. Hence, it is vital to set overpressure values with respect to distances whilst modelling vapour cloud explosions mathematically.

The large radius of effect of VCE makes inspection of domino effect crucial. Salzano and Cozzani [54] not only draw the relationship between overpressure and distance, but also form a link between overpressure vs. distance and domino effect. The 'Seveso-II' Directive (96/82/EC) extended its requirements also to the assessment of possible domino effects outside the site under consideration (e.g. to nearby plants). The study of Salzano and Cozzani [54] is hence important in terms of underlining the damage of VCE on surrounding industrial plants.

2.3.12. Toxic Gas Cloud

Many toxic releases disperse instantaneously, causing relatively few casualties. Historical data show that there are small number of fatalities resulted from toxic vapour clouds. However, in 1984, Methyl isocyanate release from an industry in Bhopal caused 4000 fatalities. This event may require giving some weight to more pessimistic estimates [20].

In order to experience a toxic cloud, the toxic chemicals may either be in form of gas or they should be liquid chemicals with low evaporation temperatures. Upon release, the chemical forms a cloud and this cloud can travel long distances. Exposure to some chemicals results in temporary or permanent damage to organs of the body, which is called as poisoning. Toxic effects may be acute and/or chronic. Acute effects are seen as a result of single exposure to a high concentration of the toxic chemical whereas chronic effects are experienced as a result of exposure to low concentrations, perhaps over a large part of a working lifetime [20]. Obvious effects may not be seen in the latter case, the toxic effects may become visible in years while acute effects may be observed instantaneously.

2.3.13. Dust Explosion

Many solid materials are combustible in nature, if there is a source of ignition with convenient energy, they can burn. Solids can get ignited and burn easily when their size decreases [55] as it is illustrated in Figure 2.7.

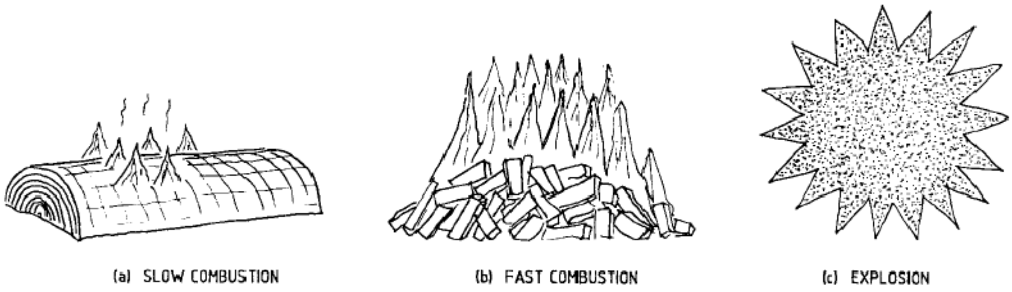

Figure 2.7: As surface area of solid substance increases, combustion rate increases [56]

Hazard of explosion of combustible dust has been well known for several centuries. The first scientific report of a dust explosion was given in Morozzo di Bianze [57], about the explosion of a silo of flour. Many other reports on accidents involving dust explosion have been reported in literature [58]. A significant study on dust explosion is published by K.N. Palmer (1973) [55]. 28 years later, an overview of the explosive characteristics of dusts is given in Cashdollar [59], whilst their importance for the risk analysis requirements and data to be collected were discussed by Siwek [60]. There are many other books on the topic which have been published [58].

This is because of the fact that oxygen gets easier access to the whole mass if the solid material is in dust form. Also, heat cannot be drained from burning surfaces into the inner part of solid material if the substance is in dust form. Optimum condition for dust explosion occurs when particles are away from each other to let air come into contact with each particle; however they are not too distant so that heat release supports the burning of adjacent particles. This describes particulate suspension of dusts [55].

Dust explosion may be defined as combustion of a dust cloud which leads to rapid build-up of pressure and consequently explosion if this overpressure occurs in a confined space. The expansion effects in dust explosions result from the heat developed via the combustion and, in some cases, result from the dust itself because gases evolve from the dust due to high temperatures [55]. Dust explosions arise from rapid release of heat due to the chemical reaction:

Fuel + Oxygen → Oxides + Heat

This means that only materials which are not already stable oxides can give rise to dust explosions. Natural organic materials like flour, grain, linen, sugar, sulphur, starch, etc., synthetic organic materials like plastics, organic pigments, pesticides, etc., coal and metals like aluminium, magnesium, zinc, iron, etc. may cause dust explosion [56].

Dust explosion may occur when the conditions for a powder explosion, known as the ‘‘explosion pentagon’’ exist [61]. These conditions should be present simultaneously for dust explosion to occur:

- fuel
- cloud
- oxidizer
- ignition source
- confinement [58].

The first three requirements can be found in industries easily. Fuel is the combustible dust used for the manufacturing process; cloud can be formed deliberately or accidentally. Oxidizer is the air inside the working area. Mostly, the minimum energy (MIE) required for ignition is so low that preventing ignition is very difficult. Confinement can be provided by the areas of the plant (ducts, hoppers, reactors), but often the building itself can act as a confining device [58].

A primary explosion in processing equipment or in an area were fugitive dust has accumulated may shake accumulated dust. As a result, if ignited, the additional dust dispersed into the air may cause one or more secondary explosions. These can be far more destructive than a primary explosion due to the increased quantity and concentration of dispersed combustible dust. Figure 2.8 illustrates primary and secondary explosion occurrence mechanism [62].

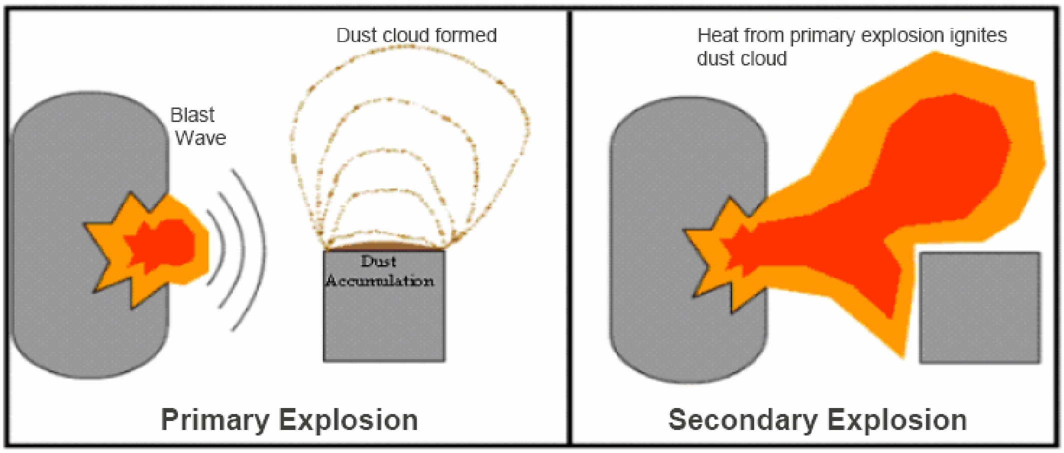

Figure 2.8: Primary and secondary dust explosion [62]

It is very important to model dust explosion effects as consequences may be very severe. Marmo et al. [58] presented a risk analysis method in their study that can be applied to factories where combustible dust is handled. The study investigates the dust explosion risk of aluminium, however, demonstrates a very good example of mathematical modelling of dust explosion. This study is an illustration of integrated industrial risk assessment as it identifies the hazards, utilizes checklist method, defines the probable consequences, suggests preventive techniques and uses mathematical models to predict magnitude of effect of explosions [58].

Marmo uses TNT Equivalence Method as a mathematical model to predict the damage as a result of blast waves caused by aluminium dust explosion [58]. TNT Equivalence Method can reveal whether the consequence of dust explosion may lead the domino effect or the magnitude of the damages calculated, for instance, in terms of human loss. Mathematical models are explained in the next section.

2.4. Mathematical Models

Markowski states that "the severity of an explosion or fire is described by the damages (or consequences) occurring due to the impact of the explosion or fire scenario" [63]. Markowski also emphasized that fast realization of risk assessment for potentially explosive atmospheres is a very time- and expense-consuming exercise. This complex task necessitates the application of fire/explosion effect models. There are several methods to model fires and explosions mathematically. In this section only the models which are used in this study are explained.

2.4.1. TNT Equivalence Method

Basic assumption behind TNT Equivalence Method which is used for modelling effects of vapour cloud explosions is a proportional relation between the amount of fuel present in the cloud and TNT-charge weight expressing the explosive potential of the cloud [64]. The proportionality factor is called as TNT equivalency, yield factor or efficiency factor. For vapour cloud explosions, this factor is deduced from damage patterns observed in major vapour cloud incidents in comparison with TNT explosions [65].

In order to apply the method, heat of combustion of the fuel in the cloud should be of the same magnitude of hydrocarbons. TNT Equivalence Method enables the modelling of blast effects resulting from vapour cloud explosion much easier and practical. The model mainly identifies the empirical relation between charge weight of TNT and the resulting structural damage [64].

Values of TNT-equivalency are obtained via statistical analysis from the damage observed in a limited number of vapour cloud explosion incidents. Statistical data show that characteristic values between 4% and 10% should be used so as to predict hazards arousing from vapour cloud explosions. TNT equivalency of 4% represents the majority of accidents, like accidental release of fuels. It can be stated that by using TNT equivalence method, blast effects of an average major incident will be extrapolated to an actual situation. Thus, TNT Equivalency Methods are most successful at predicting blast effects of actual conditions which are very much similar to “average major incident conditions” [64].

TNT Equivalence Method is widely accepted for predicting the blast effects of high explosives. The method can also be used to model the effects of chemical explosions like VCE. In fact all high explosives tend to produce similar blast waves and the blast wave may be visualized to appear at a point, as high masses of explosives contain a very small volume. On the contrary, VCE release energy from a very large volume and their blast waves differ from the ones produced by high explosives. This behaviour led to the following criticisms of TNT Equivalence Method to model VCEs [66]. If TNT Equivalence Method is used to predict structural response, the model would be less satisfactory. In order to decide for blast resistant structures, blast model utilization would be more appropriate [67].

In summary, TNT equivalence models:

- TNT Equivalence Model uses a point source to approximate the explosion. In vapour cloud explosion, there is a three dimensional non-homogenous cloud. Hence, it is difficult to justify the choice of location for origin of the blast wave.

- The peak overpressure isopleths are spherically symmetric; they bear no relationship with the geometry of the cloud.
- As the distance from the origin of blast wave approaches to zero, the peak overpressure approaches infinity.
- It is difficult to select and defend an explosion yield factor.
- The model cannot predict the blast wave duration or impulse.
- Blast waves produced by vapour cloud explosions and by high explosives are different in their nature. For a given peak overpressure, a VCE blast wave will typically have a longer positive phase duration, resulting in a larger positive impulse, which increases its damage potential [65].

Determination of Charge Weight and Predicting the Blast Overpressure:

The equivalent charge weight of TNT is calculated via the stepwise procedure below:

a. <u>Determine the Charge Weight</u>

After calculating weight of fuel in the cloud W_f, equivalent weight of TNT could be calculated through the equation below:

$$W_{TNT} = \alpha_e \frac{W_f H_f}{H_{TNT}} \tag{2}$$

where

W_{TNT} = equivalent weight of TNT (kg)
W_f = weight of fuel in the cloud (kg)
H_f = heat of combustion fuel (MJ/kg)
H_{TNT} = blast energy of TNT = 4.68 (MJ/kg)
α_e = TNT – equivalency / yield factor [65]

Blast energy of TNT currently in use ranges from 4.19 and 4.65 MJ/kg according to Brasie and Simpson [68]. This value is taken as 4.68 MJ/kg by Center for Chemical Process Safety (CCPS) [65]. α_e is the value of yield factor, which is suggested by CCPS as 0.03 and by US EPA as 0.1 [64, 69]. Reported values of TNT-equivalency range from a fraction of one percent up to some tens of per cent. Braise and Simpson [69] and Brasie [70] recommend TNT equivalencies of 2% for near field and 5% for far field effects. Exxon [65] suggests TNT equivalences of 3% for a vapour cloud covering an open terrain and 10% for a vapour cloud that is partially confined or obstructed [64].

b. Determine the Blast Effects

After calculating the TNT charge weight, the blast characteristics in terms of the peak side-on overpressure of the blast wave dependent on the distance is known from published information. The side on blast wave peak overpressure produced by a detonation of a TNT charge is graphically represented in Figure E.1 in Appendix E. The graph provides overpressure values with respect to distances as dependent on the Hopkinson-scaled distance from the charge. The relation between real distance and Hopkinson-scaled distance is provided in the equation below [65]:

$$\check{R} = \frac{R}{W_{TNT}^{1/3}} \tag{3}$$

where

$\check{R}$ = Hopkinson-scaled distance (m/kg$^{1/3}$)
W_{TNT} = charge weight of TNT (kg)
R = real distance from charge [65]

The overpressure values at certain distances then can be read from Hopkinson-scaled TNT charge blast graph in Figure E.1. Overpressure values at different distances will determine the radius of effect, hence the dimensions of the area of damage from a vapour cloud explosion. Overpressure effects are shown in Table 2.7

Table 2.7: Effects of side-on overpressure [71]

Peak Side-On Overpressure, bar	**Consequences to Building**	**Consequences to Building Occupants**
0.0138	Threshold of glass breakage	No injury to occupants
> 0.0345	Significant repairable cosmetic damage is possible	Possible occupant injury from glass breakage and falling overhead fixtures.
>0.069	Possible minor structural damage to buildings and severe damage to un-reinforced masonry load-bearing wall buildings	Personnel injury from debris is likely
>0.138	Local failure of isolated parts of buildings and collapse of un-reinforced masonry load-bearing wall buildings	Possible serious injury or fatality of some occupants
>0.207	Collapse of buildings	Probable serious injury or fatality of some occupants
>0.69	Probable total destruction of non-blast-resistant buildings	Probable 100% fatalities

2.4.2. Multi-Energy Vapour Cloud Explosion Model

Multi-Energy Model developed by TNO overcomes some of the criticisms for TNT Equivalence Method. In this model, peak side-on overpressure does not approach to infinity at the centre of the cloud. Overpressure is relatively constant near field, and then it decays with increasing distance. It can also model the blast wave which is produced. Therefore, the model is more successful at predicting the overpressure effects resulting from VCEs. Positive phase duration of a VCE can be modelled by TNO Multi-Energy Vapour Cloud Explosion model. However, the model cannot overcome the criticism towards TNT Equivalence Method regarding to the relation between geometrical shape of cloud and justification of the origin of blast wave [66].

For vapour cloud explosions, TNO Multi-Energy model is often used to determine overpressure as a function of distance. Lees also makes reference to this method in his textbook [52]. According to Fernando D´ıaz Alonso et al. [52], the Multi-Energy model is widely used for consequence analysis and for domino hazard.

If detonation of unconfined parts of vapour can be ignored, strong blast is generated only by those cloud portions which burn under intensely turbulent conditions [66]. Partially confined and/or obstructed clouds carry appropriate conditions for deflagrative explosion [65].

Deflagration: An explosion produces a pressure wave that spreads out into the surrounding area, causing damage to people and property. The greater the speed of front part of the flame, the more intense the overpressure, and the greater the destructive force of the explosion. For most accidental explosions, the flame front will travel relatively slowly in what is called a "deflagration". A typical deflagration flame front (for hydrocarbon combustions) travels about 1 metre per second.

Detonation: In intentional explosions and worst-case accidental explosions, the flame front travels rapidly in what is called a detonation. A typical detonation flame front (for hydrocarbon combustions) travels about 2,500 m per second [72].

Other portions of the cloud which are under turbulent conditions while the cloud is ignited may also develop explosive and blast generating combustion. Conditions such as intensely turbulent fuel-air jets resulting from a high pressure release could form a source of blast in a flammable vapour cloud. The rest of the cloud may burn slowly, without contributing to the strong blast effects. This concept is the base of Multi-Energy concept and underlines the blast modelling for VCEs [64]. The consequence is that vapour cloud explosion blast should be handled as a number of sub-blasts corresponding with the number of potential blast volumes identified in the cloud [65].

The most important parameter like side-on overpressure, peak dynamic pressure and positive phase duration of the blast wave are dependent on dimensionless distance representation (Sachs-scaled). Initial strength of the blast varies between 1 to 10, from very low to detonative strength. The blast charts are prepared for vapour cloud explosions having a heat of combustion of 3.5 MJ/m^3, combustion energy for most hydrocarbon and air mixtures at stoichiometric concentrations [64].

Before applying the Multi-Energy Method, the volume and location of the flammable vapour cloud should be known or assumed. Then, energy-scaled distance R will be used, initial strength of the blast will be selected and corresponding overpressure values will be read from the graphic illustrated in Figure F.7.

$$\overline{\mathrm{R}} = \frac{R}{(E/P_0)^{1/3}} \tag{4}$$

where

$\overline{\mathrm{R}}$ = Sachs Scaled Distance from Charge Centre (-)
R = Real Distance from Charge Centre (m)
E = Charge Combustion Energy (J)
P_0 = Ambient Pressure (Pa) [65]

After calculation of Sachs-scaled distance initial blast strength should be used to read the side-on overpressure value. For a safe and conservative estimate of the strength of 10 should be chosen; however, a source strength of 7 seems to represent the actual event more accurately in case of building explosion. For the rest of the cloud which is unconfined or unobstructed, an initial strength of 2 would be suitable [65].

Corresponding Sachs-scale side-on blast overpressures are illustrated in Figure F.1 in Appendix F. They are converted to side-on blast overpressure values through the equation below:

$$\Delta P_s = \Delta \overline{P}_s P_0 \tag{5}$$

ΔP_s = Side-on blast overpressure (Pa)

$\Delta \overline{P}_s$ = Sachs scale side-on blast overpressure (-)

P_0 = Ambient pressure (Pa) [65]

2.4.3. Point Source Fire Model

The most hazardous outcome of jet fires is heat radiation. General approach towards jet fire modelling is to accept the fire as a point of heat source via assuming its geometrical shape. Vertical jet fire models are commonly used to assess the hazards from flares. The model of Chamberlain has been extended to horizontal jet fires by Johnson et al. [73, 74, 75]. Mathematical modelling of jet fire with point source fire modelling approach represents a fire at a point and the average heat flux resulting from that fire through the equation below:

$$\dot{Q} = \frac{x_E \times m \times \Delta H}{4 \Pi r^2 t} \tag{6}$$

$\dot{Q}$ = Average heat flux (Watts/m^2)

x_E = fraction of heat generation in fire that is radiated (-)

m = mass of fuel (kg)

ΔH = heat of combustion (J/kg)

r = distance from the point source to the receiver (m)

t = duration of fire (s) [42]

x_E is generally 0.2 to 0.4. This equation is incorrect for distances which are very close to fire. For point approximation to hold, the distance to the receiver should be at least 5 times the characteristic length scale of the fire [42].

In the literature, there are many software programmes which can model jet fires. Among them “Areal Locations of Hazardous Atmospheres” (ALOHA) model of EPA is one of them. ALOHA can estimate threat zones associated with hazardous chemical releases, including toxic gas clouds, fires, and explosions. ALOHA models key hazards—toxicity, flammability, thermal radiation (heat), and overpressure (explosion blast force) related to chemical releases that result in toxic gas dispersions, fires, and/or explosions via employing several different models, including an air dispersion model that it uses to estimate the movement and dispersion of chemical gas clouds [76]. Model basically defines a threat zone for jet fire where thermal radiation exceeds certain Level of Concerns.

ALOHA assumes that jet fire release is oriented vertically, although the wind can tilt the flames in the downwind direction. Thermal radiation is the primary hazard associated with a jet fires. Other potential jet fire hazards include smoke, toxic by-products resulting from the fire, and secondary fires and explosions in the surrounding area; however, ALOHA does not model these hazards [76].

CHAPTER 3

LITERATURE REVIEW

This chapter revises the literature with respect to present studies on industrial safety and risk assessment. Different views on these topics are inspected. An overview of these topics is given from the literature.

3.1. Industrial Safety Concept

With industrial revolution and technical developments, risks in industries have raised to such an extent that the consequences of industrial accidents sometimes dominatethe design and operation in certain enterprises, like the nuclear and aerospace industries. Prevention and mitigation of such accidents has also had foremost impacts on process industries for over a century. However, industrial safety concept has only recently been brought together in a coherent form [20].

Perhaps, the most important contribution to industrial safety concept is made by the excellent work of Frank Lees. This study is published in 1996, with the title "*Loss Prevention in Process Industries (2nd Edition, Butterworth)*" [72]. The science of risk analysis has emerged as a major branch of knowledge only in recent years [77]. Lately, there occurred numerous studies towards developing the concept. In fact, industrial safety is a living concept according to Benerjee [20] and the concept should continue developing. It is also the heart of wellbeing of process industry.

Industrial safety is a process which involves learning from past experience and comprehending the mechanisms of accidents so that prevention and control methods could be developed, according to Khan and Abbasi [78]. However, industries seem to be reluctant in revealing the truth behind accidents and suppress their mistakes. This behaviour is also discussed by Badoux; Marshall; Kletz and Lees [78]. Kletz states that the industrial accidents are mostly because of repetition of same or similar mistakes [79, 80]. Khan and Abbasi [78] states that it has been hard to understand the mechanisms and to develop methods to prevent these incidents, mainly due to the reluctance of industries to reveal the truth behind industrial accidents.

One school of thought disputes that the prevention of incidents requires strict discipline and the attribution of blame for error whereas the other argues that incidents resulting from human error should be analysed via the free flow of information which is inhibited by a blame culture [21]. This is the main clash behind placement of industrial safety culture.

Lacking of appropriate risk assessment studies in industries are explicated by many scientists. Maron˜o et al. [81] affirms that the effort spent on research activities towards risk assessment in industries has increased significantly during the last decades. However, they argue that industrial implementation of the models and systems developed did not proceed at the same rate. Harms-Ringdahl et al. also agree with this determination, especially when considering the Small and Medium Sized Enterprises (SME), where compliance with current legislation and company image still are the main drivers of activities related to safety, health and environment at the Plants [82]. Loupasis et al. [83] and O. Salvi et al. [83] explain the insufficient implementation of new methodologies in the industry with the limiting factors like availability of enough human resources at the plants and the lack of validated methods.

3.2. Risk Assessment

Risk is commonly defined as the combination of probability and consequences [84]. Risk assessment is a structured science-based process to estimate the likelihood and severity of risk with attendant uncertainty, according to Coleman and Marks [85]. Lees also draw attraction to the subjection of risk to uncertainty [20]. Risk assessments which are prepared by experts do not provide an explicit and reproducible measure of risk according to this argument. Validity of risk assessment is highly dependent on how it is derived. A study by Lathrop and Linnerooth [86] prove this argument by presenting widely differing assumptions underlying three separate studies of the same proposed facility in the United States. Scenna and Cruz [87] explain the stochastic uncertainty with the natural variability of parameters related to the physical processes involved. For instance, the natural variability of the weather affects diffusion processes of pollutants, and consequently influences risk calculation [87]. However, Kaplan [88] declares that "good practice for risk assessors would include elicitation of the evidence from the experts and creation of a consensus state-of-knowledge curve as a means to address data gaps so that uncertainty and variability can be computed".

In fact, even though it is agreed that there is attendant uncertainty in risk assessment, there have been serious improvements in the risks, especially which are related to explosions and fires [89]. It is possible to obtain numerical risk values as a result of risk assessment, especially regarding to fires and explosions as a result of quantitative risk assessment. Similar to the common definition of risk, quantitative risk assessment is described as analysis combining the likelihood of accidental events with their consequences in a systematic manner [89].

Even though the certainty of risks are mostly discussed and given importance, the starting point of risk analysis does not need to be risk assessment. Instead of putting assessment at the first stage, risk communication is being increasingly accepted as a starting point. According to Coleman and Marks [85] who state this trend, upon tracking risk communication with decision makers in the first step, the results of risk assessment are weighed by risk managers with other factors to support decision-making processes. There, disadvantages of uncertainty in risk assessment could be eliminated to an extent. Coleman and Marks [85] argue that, if risk communication is not conducted appropriately, the judgements and opinions of experts may impose on the risk assessment significant bias and overconfidence that could misinform decision makers about the magnitude of risk and attendant uncertainty.

New trend on risk communication should of course be followed with risk assessment study. Lagadec [90] states the forward-looking risk analysis as an exhaustive identification of potential hazardous sources to prevent accident scenarios and to assess potential impact on targets in order to propose prevention or protection. Gadd et al. [91] state the purpose of risk assessment as to determine whether the level of risk arising from workplace activities is acceptable, or whether more needs to be done to control or reduce the risk. The process of risk assessment should therefore be carried out in a rational, logical and structured manner.

The study of Tixier et al. [92] analyzes more than 60 risk analyses which were developed by industrialists and competent authorities so as to shape a methodology of risk assessment. This study revealed that risk assessment is composed of three main steps:

- "An identification phase based on a site description (hazardous activities, products and equipment). Those data are necessary to develop the processes of the methodologies.
- An evaluation phase to realise a quantification of the risk. There are two ways to lead this—a deterministic approach and/or a probabilistic approach. This evaluation gives the previously found consequences of scenarios and enables their impacts on the industrial site or on its vicinity to be taken into account.

- A hierarchisation phase which aims at ranking some results, obtained through the two previous phases, in order to put preponderant risks forward. Thanks to this hierarchisation, the most important risks could be solved first" (review of methods)" [92].

Identification step highlights hazards in order to define the scope and structure of the safety document. Typically, general types of hazards (e.g., chemical, physical, electrical, kinetic energy) are first identified, and then hazards which are specific to processes and activities are detected for subsequent hazard analysis. Hazard identification may include the use of a check list, inventory and other screening criteria to help determine the extent of the Hazard Analysis that should be performed [93].

Evaluation of risk necessitates combining input parameters, the consequence and the frequency of the present hazard. Input parameters are mainly fed by historical incidents and models. Marono et al. declares that on one hand, accidents have been, and unfortunately still are, a continuous source of information. On the other, an increasing number of models and methods are being developed to identify new factors and/or to integrate all of the available knowledge [81]. For instance, evaluation of flammability risks contains understanding the processes that occur following the ignition of chemical release. This can be achieved through investigation of past incidents. Thermal radiation and overpressure can be calculated via mathematical models are used to determine the severity of the consequence [94].

Hierarchisation of risks could be conducted via a risk matrix. Risk matrices have been used by the industry and the US military for several years to rank different risks in the order of importance [95]. Matrix method allows the decision maker to set priorities for the implementation of control measures and hence a very important tool According to Donoghue, another advantage of risk matrices is that managers in large organizations are becoming more and more familiar with their use in safety [95].

CHAPTER 4

MANUFACTURING PLANT

Denim manufacturing plant where this study is conducted is in Kayseri, a city located at Central Anatolia, Turkey. The integrated plant, established at 1953, produces denim fabric (to be used in jeans) from raw cotton as a result of complex production chain. The facility is listed among top five denim producers in Europe and among top 10 in the world producing approximately 20,000 tons of cotton fibre and 40 million m of denim fabric is per year.

4.1. Plant Layout

The plant resides on an area of 156,000 m^2. There is another factory and an industrial zone which are both 20 m away from the factory. Residential area is just about 350 m to the mill. Currently, 900 employees work in the textile plant. The layout of the facility viewed with Google Earth software is presented in Figure 7.9. The figure also illustrates industrial zone, other textile mill and the residential area.

Figure 4.1: Facility layout figure taken from Google Earth software

4.2. Process overview

The production chain inside an integrated textile mill generally contains numerous complex processes. This section describes the process in the studied mill. Certainly, there are tens of major and intermediate processes and applications, however, an outline of the process of the sketched in this section. Information regarding to the process overview are compiled by the help of several inspections at the plant.

Denim fabric production process starts with cotton in the integrated facility. Different types of cotton which are stored in cotton warehouse of 7500 m^2 are blended in cotton mill. Cotton warehouse can store up to 6000 tonnes of cotton. This warehouse is mainly a single stored building with one large door open. Automatic fire extinguishing system with water is present in that warehouse.

Cotton bales, pressed and baled with metal or plastic wires are transported to the cotton mill where they turn into fibre. Cotton mill is a large and closed area where the climate inside is formed via ventilation system. There, cotton fibres enter into blenders which comb and take different cotton types inside. Blending process mixes these different types of cotton bales and removes impurities of cotton. Cotton sequentially passes through several other machines where fibres are parallelized and then turn into yarn via the yarn manufacturing process. As soon as yarn is produced, spinning process is applied to make yarn thinner. Lastly, they are conveyed to the rest of the process sections as bobbins after being exposed to steam for the fixation of yarn.

Yarns are dyed according to the colour desired via a wet process in indigo section. Indigo section is a closed segment in the facility with no air entrance. There is a chemical warehouse which only contains chemicals used in indigo line. Minimum storage principles are applied here, only chemicals to be enough for a week are stored. Nearby the warehouse, in a large and open vessel, recipe of each indigo/dye solution is prepared via using a bunch of some other chemicals like caustic, indigo dye and/or some other types of dyes. Indigo solution is generally at high temperatures. Yarns are dipped into the tanks of indigo solution after they are treated with several chemicals to be ready for dyeing. Dyed yarns go under a several more steps like softening and drying.

Dyed yarns are to be weaved. However, weaving with automatic machines may usually cause yarns to detach. To strengthen the yarns, they are washed with sizing solution in sizing department. Sizing department includes a kitchen where sizing solution is present. Even though there is no structural arrangement inside the kitchen, it is also used as a warehouse. A portion of the ground surface in the entrance of the room is spared for storage of starch bags and auxiliary chemicals to prepare sizing solution. There, starch to be enough for a week of production is stored. Sizing solution includes starch, auxiliary chemicals and enzymes. Sizing solution is cooked inside pressurized tanks. Starch is provided to these tanks via a hopper. The hopper helps starch to get dispersed inside the machine so that starch is mixed inside the solution more homogenously.

Sized yarns are weaved in weaving department. This is also an enclosed space with a high moisture ratio. There are numerous weaving machines which work on electricity. As a result of weaving in machines, cotton fibres emerge and fill in the atmosphere inside the department. There are vacuum cleaners around the machines to pump in these fibres. As a result of weaving process fibres turn into denim fabric.

Finally, finishing process is applied to give desired quality and characteristics to the denim fabric. With the utilization of numerous chemicals and extensive amount of water, various properties are given to the fabric. Final product may be water-proof, fire-proof or resistant to crease and shrink via different applications inside finishing department. Finishing department where journey of cotton to denim fabric ends contains a chemical warehouse and a kitchen. The chemicals necessary for two days of consumption are stored at the warehouse which is located near the storage area denim fabric rolls. Chemical solutions in different process lines are prepared inside the pressurized tanks found in the kitchen.

Process scheme of the plant is demonstrated in Figure 4.2.

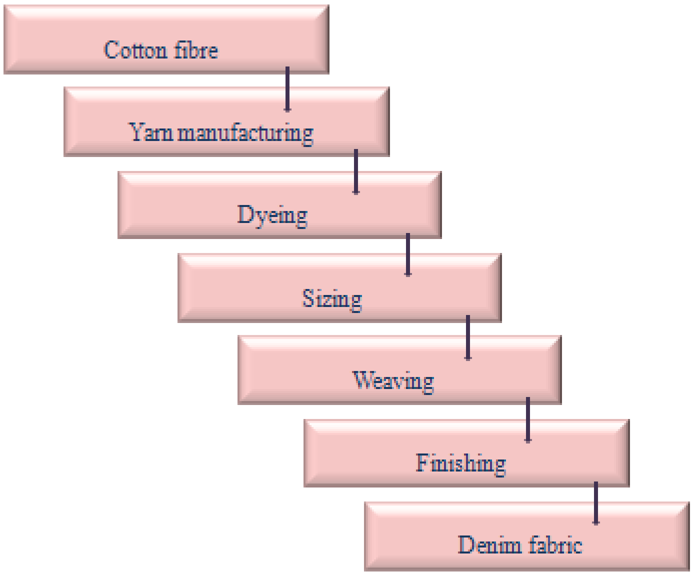

Figure 4.2: Process scheme inside the mill

Hot water and steam are required for the above-mentioned processes. The energy essential for heating up water and obtaining steam is obtained from the cogeneration unit inside the department. Natural gas line pipelines reach through cogeneration unit where there are turbines to produce power, evaporators to produce hot water and steam and a control room. The plant produces 5 MW power/day.

All chemicals used in processes explained above are stored in larger amounts in the main warehouse which has a volume of 3760 m^3. Chemicals are transported to the plant and loaded via trucks to the entrance of the warehouse. Then, forklifts are used to locate these chemicals inside the warehouse. There are approximately 130 different types of chemicals which are present in main warehouse. There is no ventilation inside this depository. Chemicals which present a major fire or explosion risk are stored in a separated space. There are no chemical substances which are in gaseous form or under pressure.

CHAPTER 5

METHODOLOGY

This study assesses the risks in the denim manufacturing plant which result from the chemicals used inside the facility and natural gas utilized to generate power and steam in cogeneration unit. The methodology applied while conducting the study is composed of five main steps which will be explained in this chapter. This methodology is compatible with risk assessment methodology described in IPPC Guidance Document for Textile Sector prepared by Scottish Environment Agency Environment and Heritage Service and Environment Agency [8].

First step is *initiation*; it is conducted in order to set a framework for the risk assessment study. In next step, *hazard identification,* potential hazards in the plant were identified. Then, *consequence* and *frequency analyses* were done to quantify the present risk via *quantitative risk analysis*. During the study, risks are communicated with the manufacturing plant and several suggestions are proposed.

5.1. Initiation

Before starting to carry out a risk analysis, the scope and the objective of the analysis should be determined. There are numerous risks that a facility poses, like carcinogenic risk, toxicity risk, fire and explosion risk, ecological risk, etc. Each different class of risk assessment requires different approaches during risk analysis, i.e. the activities/situation to present the risk will vary accordingly. Hence, this decision should be made before site investigations.

Furthermore, it is indeed advantageous to determine the receptor(s) of risk before initiating risk assessment. Risk receptors may vary from aquatic environment to reputation of the company. Implementation of the study differs for different concepts or parties affected from the hazard if potential risk occurs.

In this study, initiation phase of risk assessment was carried out before paying a visit to the denim manufacturing plant. To draft the scope of the study, the IPPC Directive, the Textile Industry and manufacturing process of denim plant was carefully analyzed.

5.2. Hazard Identification

In order to carry out hazard identification, it is necessary to understand which sort of hazards may be present within the mill or not. In this study, hazard identification is conducted on-site. On-site studies were composed of two segments: on-desk inspection and walk-through inspection. On-desk inspection phase was mainly composed of reviewing related documents of the manufacturing plant, like the incident statistics, contingency plans, present risk assessment studies, inventory of chemicals utilized in the mill, etc. and interviews with risk assessment team to identify their gaps and necessities. Checklist method was used to identify hazards during walk-though examination within the facility. A set of checklist on hazardous chemicals question the presence of toxic, corrosive, or flammable sprays, fumes, mists, or vapours, a potential of the chemical to lead fire, explosion or toxic gas clouds was prepared. On-desk inspection showed that none of the chemicals had the tendency to evaporate under standard temperature and pressure. This fact eliminated the examination of toxic gas cloud risk. Hence, the risk assessment will focus on fires and explosions resulting from a hazardous substance release.

While carrying walk-through inside the manufacturing mill, so as to determine hazards present, mainly incident statistics of the plant and feedback from employees were used. Walk-through inspection contained comprehending the detailed process overview, awareness of employees, utilization practices of chemicals via asking “what if” question continuously to predict what may go wrong. After walk-through site investigation, the scope of the study was determined as risk analysis of major industrial accidents.

The receptor of the study was determined as “people” both the employees of the facility and the public around the manufacturing plant, after consulting with the plant management. As major industrial accidents generally entail people living or working inside or around the facility, it can be comprehended better why the receptor in the study was selected as the people. This decision was also consulted to the facility management board and agreement was made. Also, it is important to state that risk assessment study towards other risk receptors and towards other risk categories like ecological risk, occupational accident risk, etc. were already conducted by the risk assessment team.

After defining the scope of the study, consequence and frequency categories were defined via the aid of literature, incident statistics of the manufacturing plant, experiences of employees, historical incidents and logical judgement. This definition was also conducted via communicating the categories to the facility and via maintaining a consensus.

5.3. Consequence Analysis

Hazard identification step revealed several activities/situations which might lead to undesired consequences. Categorization for consequence and frequency values which were prepared specific to the plant formed a guideline whilst carrying out consequence analysis. The appropriate categories for present hazards were labelled by incident statistics inside the plant, experiences of employees, historical incidents and logical judgement based on background on fire and explosion mechanisms. Level of severity of the event consequence was questioned throughout this analysis.

5.4. Frequency Analysis

In this study, plant specific categories which had been defined before consequence and frequency analysis (categorization issue will be elaborately explained in the next chapter) were used for carrying out frequency analysis of present hazards. The appropriate frequency values were determined by incident statistics inside the plant, experiences of employees, historical incidents and logical judgement based on background on fire and explosion mechanisms. The event frequency and the likelihood of consequence levels for each event were questioned throughout the analysis.

5.5. Quantitative Risk Assessment

Semi-quantitative risk assessment reveals a numerical risk value through multiplication of consequence and frequency categories. In this study, aggregate risk was calculated. The sum of aggregate risk values for each event gave aggregate facility risk. Consequence and frequency analysis were conducted on risk evaluation forms, which are used as a tool for risk assessment study. Risk evaluation forms present hazardous activities/situations, consequence and frequency analyses of them along with quantitative risk calculation and suggestions to reduce risk level. In this study, mitigation measures are expressed within the risk evaluation forms not only for medium and high risk representing items, but also for some items which represent low risk. These suggestions are presented to the facility management and some of them were realized immediately. Then, matrix method is used to rank these risks.

CHAPTER 6

RESULTS AND DISCUSSION

6.1. Initiation Phase

As described in the Methodology Chapter of the study, before paying a visit to the denim manufacturing mill, an initiation study was conducted. This study covered comprehension of what "prevention of accidents" scope of the IPPC Directive covers. With the light of the Directive, a preliminary study including a site visit to the plant towards industrial risk was carried out to be prepared to examine hazardous events within the plant.

During the site visit, issues were clarified towards the scope of the risk analysis. Just before walk-through site inspection, risk assessment team of the facility gave an outline of the risk assessment and risk prevention studies that are already being conducted in the plant. These included risk assessment towards small accidents, unintentional releases, environmental pollution, abnormal operation and occupational health and safety risks. However, an elaborative study on major industrial risks was lacking. Therefore, via communicating with the facility management it was agreed that present study would fill a gap in risk analysis towards major industrial risks. As indicated before, major industrial losses result from fire, explosion or toxic gas cloud. All of these three events which can be classified as chemical hazards could lead to destruction in the public as led the historical industrial accidents some of which are illustrated in Table 2.1 in and they are mainly resulting from chemical releases.

6.2. Hazard Identification

6.2.1. On-desk Inspection

Due to above-mentioned reasons, hazards identification step focused on chemical hazards. During hazard identification, chemicals which are stored, transported and utilized in the plant were studied via Checklist Method. Checklist Method is very helpful in terms of understanding the potential hazards presented by chemicals. The checklist formed during the initiation phase of the present study is presented in Appendix A. A snapshot of this checklist can be seen in Table 6.1.

Table 6.1: A snapshot of the Checklist which is prepared for the pilot plant

MSDS ID	Materials, Chemicals, or Components	Physical State (Liq, gas, liquefied gas, solid, powder...)	Quantity (Throughput or Inventory)	Range of Operating Pressure	Range of Operating Temperature (Bulk Tempetarure)	Range of Operating Temperature (Process Tempetarure)	Fire (FLammable or Combustible)	Explosion/ Detonation	Oxidizer	Toxic - Acute	Toxic - Chronic	Asphyxiant	Corrosive	Reactive	Smell/ Fumes	Dust/ Mist	Radiation
1	Chemical 1	Liquid	-	1 atm	15oC-45oC	15oC-90oC	C	-	-	-	-	-	-	-	-	-	-
3	Chemical 2	Liquid	-	1 atm	15oC-45oC	15oC-90oC	C	-	-	+	+	-	-	-	-	-	-
4	Chemical 3	Liquid	1125 kg	1 atm	15oC-45oC	15oC-90oC	C	-	-	+	+	-	-	-	-	-	-
5	Chemical 4	Liquid	450 kg	1 atm	15oC-45oC	15oC-90oC	C	-	-	+	+	-	+	+	-	-	-

Flammable	Combustibles	Corrosives	Explosive Liquids	Toxic Materials
	Oxidizers	Reactives	Less Hazardous Materials	

The checklist is comprised of serious questions on properties of the chemicals used in the mill like the quantity, flammability, explosivity and corrosivity. The checklist is prepared specific to the scope of the study, hence does not include air pollutant, water pollutant and hazardous waste characteristics of the chemical substances. Information inside the checklist is gathered from inventory statistics of the facility and Materials Safety and Information Sheets (MSDS) of the chemicals which are again provided by the facility.

The basic logic behind the checklist is to put + or – according to the presence of hazardous properties of substances. Detailed investigations of chemical MSDS are carried out so as to reveal the hazardous properties and they are systematically used to fill in the checklist. This gives the opportunity at visualizing all properties of chemicals together and via paying attention to + symbols inside the list identifying the most hazardous chemicals in terms of fire and explosion.

The reason behind toxic gas cloud hazard not being analyzed in this study is mainly the information gathered through the checklist. As can be seen from the whole list in Appendix A, none of the chemicals except for natural gas is flammable, which is not toxic [97]. This means that none of the chemicals are in vapour state under room temperature. In fact, these substances have boiling points around 100 ^oC and they do not evaporate significantly till the temperature values are close to their boiling points. A toxic cloud can only be formed in this facility as a result of temperature raise of toxic chemicals due to a fire or explosion or as a result of toxic combustion products of fire and explosion itself. These scenarios involve complex physicochemical and thermodynamic events and they will not be a focus in this study.

It is not only the chemical properties carrying a potential risk, but also the incompatibilities between different sort of chemicals. These incompatibilities are also studied before walk-through inside the plant. This study is very advantageous in terms of realising dangerous activities (like storing incompatible chemicals next to each other inside the plant) during site inspection. A classification among chemicals according to their hazardous properties was also done by checklist method. This classification is very much helpful to determine the incompatibilities between different categories of chemicals. The compatibility study with respect to substances in the mill is presented in Table 6.2.

Table 6.2: Incompatibilities between different categories of chemicals

	Combustible Dusts	Oxidizers	Corrosive Materials	Reactives	Explosive Liquids	Less hazardous materials	Toxic Materials
Combustible Dusts	-	+	+	+	+	-	-
Oxidizers		-	+	+	+	-	-
Corrosive Materials			-	+	+	-	-
Reactives				-	+	-	-
Explosive Liquids					-	-	-
Less hazardous materials						-	-
Toxic Materials							-

As it is presented in Table 6.2, same categories of chemicals do not present a hazard, as their properties are similar to each other and are not incompatible. Incompatible chemicals (chemicals which may present a hazard when they are in contact) are shown by a plus in Table 6.2. However, there is a probability of exothermic reaction formation between combustible dusts and oxidizers, corrosive materials, reactives and explosive liquids.

Fire risk inside the plant is intensely studied by the risk assessment team of the plant; however, the studies did not cover fire resulting from chemical release. Instead, fires emerging from cotton fibre and electricity shortcuts were inspected. Consequent to on-desk hazard identification studies through checklist, chemical categorization and incompatibility list, it is exactly determined that the scope of the study is defined as fire and explosion hazard presented by hazardous substances and fires resulting from cotton fibres and electricity short cuts, etc. inside the plant. The fire and explosion of interest concern a large hazard radius. The receptor of the study is selected as people, both covering the employees of the facility and the public around the mill.

6.2.2. Walk-through Inspection

With the guiding light of initiation phase and on-desk inspection, a walk-through examination was conducted within the facility. The walk-through inside the facility took five working days. In the first day, process scheme was studied as an overview to the facility. Then, each department were paid a visit. During the examination, employees in risk assessment team, process managers, and responsible employees of process lines were also present. The procedure involved question and answer phase with accompanying representative from the facility and "what if" question were always asked to identify what may go wrong.

Walk-through inspection focused on main chemical warehouse, cotton mill, indigo, sizing, weaving and finishing departments and cogeneration unit. These focus points are mainly determined according to the hazards presented by the chemicals or cotton fibres inside the departments.

There were many hazardous activities/situations observed inside these departments. These hazardous activities were discussed with the employees of the facility. Activities or situations which may present a risk were conveyed to the process workers, process managers, quality assurance team, risk assessment team and facility manager and their opinions and comments were also evaluated. In the proceeding paragraphs inspection results for different departments of the plant are presented.

Main Warehouse

Chemicals inside the warehouse are stored on numerous shells which are approximately 5-6 m tall. In order to reach chemical shelves at the top, forklifts are used. These forklifts operate on either electricity or diesel. Forklifts may be a source of ignition inside the warehouse. Diesel forklifts should not enter inside; electricity forklifts should be completely isolated. Forklifts which run on electricity in the warehouse are not isolated well. There is no strict rule on banning the entrance of electrical appliances inside the warehouse. Also, lighting appliances are not isolated and they may be an ignition source, too.

Quality assurance tests are conducted in other departments and samples are taken from chemicals on a routine basis by the Research & Development Department of the plant. However, during the walk-through inspection, it was observed that chemicals tanks are left open after taking samples.

Starch and indigo dye used for manufacturing processes are in dust form and stored in packages on shelves at high elevations. During their transfer to process departments they may burst and dust explosion may occur.

Liquids which are known as flammable are contained in a separate section in the main warehouse. However, the walls of this section are not fire or pressure resistant. It is also not known if the main walls of the chemical warehouse are built via pressure and fire resistant walls or not. This knowledge gap may present an important hazard, as there is industrial zone and another textile mill only 20 m away from the main warehouse.

Some chemicals require being stored at certain temperature and relative humidity (RH) values. Outside the necessary range of temperature or RH values chemical may go decomposition or other types of chemical reactions. However, temperature and RH values are not checked regularly in the main warehouse. Moreover, storage in warehouse is not done according to this categorization.

In the checklist provided in Table A.1 in Appendix A, there are eight chemical categories presenting incompatibilities. Table 6.2 presents these incompatibilities between different categories of chemicals. Also, chemical information sheets to notify employees about the hazards are not present inside the warehouse.

During the walk-through inspection, it was also seen that there are many corroded vessels of which the expiration dates are over. As some of these vessels are already cracked, they may easily deliver decomposition products or chemical vapour. The corrosive effects of these chemicals were apparent. Although there is spill containment system at the bottom of some shelves; however, some shelves lack it. This allows the spilled chemical to spread on the ground directly.

Another observation in the main warehouse is that the employee responsible from the warehouse is not well informed about the properties of chemicals, chemical characterization, storage according to properties of chemicals, contingency plan of the facility and what should be done in case of an emergency. This observation is noted to be serious.

Finishing Department

Finishing department is composed of number of connected halls. In these halls there are mainly four sections: i) chemical storage, ii) denim fabric storage iii) process halls and iv) finishing kitchen. There is no ventilation inside the whole finishing department. Chemical barrels inside finishing kitchen are usually left open. The same hazard present in chemical warehouse is also present for finishing kitchen.

Similar to the main chemical warehouse, finishing chemical depository also do not contain chemical information sheets on shelves. Moreover, storage of chemicals is not conducted according to the properties stated in their MSDS. Incompatible chemicals may get into contact as a result of inappropriate storage.

Finishing warehouse, inside which finishing chemicals are stored, does not have surrounding walls, but instead chemical shelves are in the middle of an open space. This space is also open to denim fabric storage. Intense amount of cotton fibres are present in this section. Packages of chemicals existing in finishing warehouse are observed to be covered with approximately 5-6 mm of cotton dust. Furthermore, storage space was found to be not enough for plentiful chemicals and several barrels were directly on the ground, not even on a shelf.

Finishing kitchen involves pressurized tanks to prepare process solution. These tanks are in poor condition; their regular maintenance checks are not conducted. It can be easily seen that the outer metal part of the pressurized tank is torn off. Employees of finishing department are not well informed about the properties of chemicals, their potential hazards, emergency plans of the facility.

Indigo Department

Indigo solution is used by adding certain chemicals into a tank according to different recipes and then this solution is fed into process lines. During the preparation of this solution indigo dust is also fed into the reactor. This procedure involves scattering of indigo dust. Indigo dye includes mainly sulphur; hence the dust could be accepted as sulphur dust.

Indigo department has a warehouse. Inside this department storage is not conducted according to different categories of chemicals. There are no tanks at all present underneath the chemical shelves. Shelves do not carry information labels on. Also, there are no absorbent materials to suck up chemicals in case of a chemical spill.

Employees do not know much about chemical properties and potential hazards presented by them. Emergency plans of the facility are not known as well. There occurred unintentional chemical reactions in past, and no measures were taken against. Luckily, no one was hurt during these incidents.

Sizing Department

Sizing department contains pressurized tanks where sizing solution is prepared. The main ingredient of this solution is starch. Starch is scattered and dispersed inside the hopper. As sizing solution is prepared in Sizing Department, expectedly, it is the dustiest place within the mill. Starch which is used to prepare the sizing mixture is loaded, transported and processed inside this department. Starch gathers on the ground and on the edges (e.g. on the top of pipelines, on the equipments, etc.).

Weaving Department

There are not much information labels in weaving department. Each weaving machine is connected to electricity. However, electricity cables are not well isolated. Due to weaving process cotton fibres are present and they gather on non-isolated electricity cables. Electricity control cabinets and electrical appliances are not isolated as well. Moreover, there are objects which block the access to control cabinets. There is a dust collection channel which curls around weaving department and cotton mill. Chemical fibres are present everywhere, even around the entrance point of this dust collection channel. On the other hand, there is a battery charging area which is open to cotton dust access.

Cotton Mill

Cotton mill is a large area with lots of closed machines inside which cotton is mixed, homogenized and purified. The department was found to be full of cotton fibre, hard to walk without inhaling cotton. Electricity cables are not well insulated in this department. Also, closed machines have engines which continuously operate. These engines heat up and cause cotton fibres to catch fire due to the lack of ventilation inside machines. There are metal wires around cotton bales. Occasionally, these wires are not totally removed and metal pieces remain in the bales. Cotton bales can also contain metal pieces as impurity. These pieces then enter into the long process chain which occurs inside closed machines. There are huge fans inside these machines. Just before the entrance point of the fans, there are magnets to remove metal pieces inside cotton. However, they may not eliminate all pieces. These pieces and the fan are both composed of metal. Collision of metal pieces with the parts of the fan results in spark and causes fire. This is examined from the fire statistics of the facility and also from the interview made with the workers.

Cotton warehouse, which is a unit close to the cotton mill, is also 20 m away to the main chemical warehouse. It seems that any fire/explosion resulting from cotton warehouse or main chemical warehouse may affect each other. Also, forklifts running on electricity and diesel are being used inside cotton warehouse. Electrical insulation of these forklifts is not checked regularly.

Cotton bales are transferred to the cotton mill through an entrance door with a metal grounding. However, heat resulting from friction between the metal grounding and metal wares around cotton bales and the spark formation due to this friction cause cotton bales to catch fire. This fire generally involves a few cotton bales and is generally extinguished fast.

There is a cotton dust collection canal which curls around the weaving department and cotton mill. Fire catches frequently inside this canal in cotton mill. Luckily, cotton fire has a distinguishable smell and it is easily detected. Employees in this section are very well trained and they are used to these fires so that these fires are generally extinguished without their scales getting larger.

Cogeneration

Cogeneration unit is the electricity and steam supplier to the facility. Hot water is also produced Natural gas, which is used to produce power, arrives in the cogeneration unit via the pipelines. Natural gas is not distributed inside the facility, but instead only to the cogeneration unit. There, 5 MW/day of power is produced along with hot water and steam. Hot water is sent to a pool afterwards for process utilization and steam is fed into process lines.

The unit is comprised of two separate rooms. One is the turbine compartment and the other one is the control room. Economizers and evaporators are also placed inside the control room.

As indicated before, natural gas is not toxic [96], but it is flammable. Any leak of natural gas could lead to fire or explosion in the cogeneration unit. The effects of such an explosion could reach up to hundreds of metres.

Through the inspection carried out in each department, hazards are identified. In order to list the hazards present inside the whole plant, risk evaluation forms are utilized. These forms contain hazardous activities/situations, consequence and frequency analysis and quantitative risk as well as specific suggestions for each hazard.

A sample risk evaluation form which is prepared for a hazard item in the sizing department is presented in Table 6.3. Full version of risk evaluation forms can be found in Appendix B. Risk Evaluation forms are prepared for each department mentioned above and several items observed during inspection are listed one under the other.

Table 6.3: A sample item from risk evaluation forms

RISK EVALUATION FORM

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)	Suggested Precautions	Explanations
S-1	Sizing	Pressurized tanks are utilized under high temperatures to prepare the sizing mixture.	Pressurized tanks carry the risk of exploding in case their regular checks are not carried out.	Sufficient								

The empty cells seen in Table 6.3 will be filled according to the category definitions, consequence and frequency analysis. Hence, risk evaluation, comments and suggestions about each item will be seen in the same form in an integrated manner.

6.3. Category Definitions

Categories should be defined before conducting the consequence and frequency analysis so that the risk can be calculated mathematically giving a meaningful result. In this study category, definitions for consequences are arranged according to the fact that receptor in this study is the people. Hence, the consequence category is organized according to the number of people to be affected from the event. This categorization also includes the magnitude of the effect.

On the other hand, frequency categorization is conducted according to the statistical analysis of incident records of the facility. The facility has been alive for over 50 years and average working life of an employee is approximately 30 years. Categorization of frequencies is made via considering these facts.

A summary version of categorization for consequence and frequency classes can be seen in Table 6.4. Full version of the categorization prepared specific to the plant can be found in Appendix B. These categories will be used as a guiding tool while predicting or projecting the consequence and frequency values of potential hazards.

Table 6.4: Risk Categorization

Lower Boundary of Likelihood Categories	Likelihood of Event or Consequence (Frequency Guidelines)	Description	Category	Weight per year	Risk Matrix (Risk=Frequency x Consequence)					
3/yr	More than 3 times per year	Extremely likely	6	6	0,018	0,18	1,8	180	1800	18000
1/yr	1 to 3 times per year	Extremely likely	5	2	0,006	0,06	0,6	60	600	6000
1/3yr	More often than 1 in 3 years	Very likely	4	0,6	0,0018	0,018	0,18	18	180	1800
1/10yr	Once in 3 to 10 years	Not likely	3	0,2	0,0006	0,006	0,06	6	60	600
1/30 yr	Once in 10 to 30 years	Not likely	2	0,06	0,00018	0,0018	0,018	1,8	18	180
	Less than once in 30 years	Not likely	1	0,02	0,00006	0,0006	0,006	0,6	6	60
Step	**Using the Risk Matrix**	**Consequence (of one type of event)**								
1	For a given event, select the highest possible "Consequence"			Category	1	2	3	4	5	6
2	Move up into Risk Matrix to appropriate "Likelihood" category			Weight 10^3\$	0,003	0,03	0,3	30	300	3000
3	Intersection of Consequence and Likelihood gives the Risk Level	**Impact on Persons (Safety and Health)**			Below regulatory concern or Administrative only	Minor injury(ies), health impact (1 person) that is reversible	Lost time injury(ies), public safety/ human health impact (>1 to 10 people) that is reversible	Some public safety/ human health impact (>1 to 10 people) that is lethal or severe in effect	Significant public safety/ human health impact (>10 to 100 people) that is lethal or severe in effect	Widespread public safety/human health impact (>100 people) that is lethal or severe in effect
4	Move on to the next highest Consequence category and repeat until the highest Risk Level is identified.									

In Table 6.4, it can be seen that the frequencies and consequences of the possible risks in the plant were categorized into six groups. The first category for frequency which is the most probable is expressed as Category 6 and it was set as more than three occurances per year. Frequency of event category was defined as "More than 3 times per year", "1 to 3 times per year", "More often than 1 in 3 years", "Once in 3 to 10 years", "Once in 10 to 30 years" and "Less than once in 30 years". Also, consequence category categories are defined as "Below regulatory concern", "Minor injury(ies) of 1 person that is reversible", "Lost time injury(ies), public safety/ human health impact (>1 to 10 people) that is reversible", "Some public safety/ human health impact (>1 to 10 people) that is lethal or severe in effect", "Significant public safety/ human health impact (>10 to 100 people) that is lethal or severe in effect" and lastly "widespread public safety/human health impact (>100 people) that is lethal or severe in effect".

In order to highlight the importance of more frequent events and higher consequences, certain weights were appointed for categories. These weights are higher for frequent events and events with a consequence on more people and involving irreversible effects. The "weight" value set for Category 6 risks is 3000 which physically means a consequence of this category may cost 3,000,000 \$/year ($3000x10^3$ \$/year) to the facility if the risk is not properly managed [97].

Consequence is expressed as \$/year, because both reversible and irreversible effects are reflected in this risk assessment. In order to combine fatalities and injuries and consequences below regulation limits under one expression, cost of the risk to the plant is used. This value gives the \$/year which the plant may pay if it does not change the situations/activities causing risk to the infinity.

Monetary value reflection of consequence categories are based upon the approximate indemnification values in Turkey [98]. When it comes to implementation, these values should be discussed with stakeholders. The consequence categories increase according to $\log_{10}$ and its times. However, the reversible effect on 1-10 people and the irreversible effect on 1-10 people differ 100 times instead of 10. This is due to the fact that the indemnification amount is much higher when the effect is irreversible. Risk matrix is also illustrated in Table 9.11, higher consequences and higher frequencies combine to give a higher risk value. Risk matrix ranks the present risks according to their severity and likelihood.

These definitions are prepared specific to the plant and they guided the risk assessment study. They will also help the assessment to carry a relative objectivity as all of the consequences and frequencies will be sorted according to a present categorization. Also, in order to decrease the subjectivity, categories were also shared with the facility management and a consensus was made.

6.4. Consequence and Frequency Analysis and Quantitative Risk Assessment

In this study, consequence, frequency analysis and quantitative risk assessment were all carried out in a coherent manner. They were conducted simultaneously. These studies are explained in this section. Analyses were done in seven departments, main warehouse, finishing, indigo, sizing, weaving departments, cotton mill and cogeneration unit.

6.4.1. Main Warehouse

MW -1:

MW-1 stands for Main Warehouse hazard item 1. The same abbreviation style will be used throughout this section. Forklifts running on diesel or electricity are used in main warehouse. Insulation of forklifts is not very well managed. Regular control is not applied for the electrical insulation. Equipment fire can occur inside the main warehouse, which can heat up stored chemicals and trigger an exothermic reaction of chemicals. Also, these equipments can act like sources of ignition.

The frequency of event is described as once in 3-10 years (Category 3) according to the historical statistics and experiences of employees. The frequency of a consequence of Category 6 as a result of equipment fire in the main warehouse is not described as it is not forecasted.

Liquids evaporate at any temperature, for example a water body evaporates without its temperature reaching to the boiling point. However, as liquids do not tend to evaporate intensely in room temperature and atmospheric pressure, it can be said that formation of a flammable chemical vapour cloud inside the main warehouse is not very likely.

There is one worker in main warehouse; the number of people may increase from time to time. In case of an equipment fire, 1-10 people may be influenced, but this has a very low frequency value, less than once in one's working life. However, the frequency of 1-10 people getting influenced from such a fire reversibly is higher; 0-30 years. Minor injuries of one people may be observed more frequently; hence its frequency value is defined as once in 3-10 years, the same as the event frequency.

Risk is calculated as multiplying values of consequence and frequency. There, weights of categories are taken into account (e.g. weight of irreversible effects like deaths are higher than reversible impacts). Risk is then numerically expressed. Table 6.5 shows the risk evaluation form, filled accordingly.

Consequence unit is 10^3 \$ and frequency unit is per year. Therefore, risk level which is expressed as weight (0,62 for MW-1) should be multiplied by 10^3 \$/year. This multiplication will be done at the end of risk evaluation, summation of all risk weights will be converted to \$/year.

Table 6.5: Risk Evaluation Form of Main Warehouse for Item 1

Item No	**Activity Department**	**Activity / State Description**	**Potential Event**	**Current Precaution**	**Frequency of Event**	**A Consequence Category (1-6)**	**B Frequency Category (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
MW-1	Main warehouse	Fork lifts (electrical and diesel) are used inside the warehouse.	Equipment (fork lift) fire may occur inside the warehouse leading to ignition of stored flammables and combustibles.	Insufficient	3	6		3000		0,0000
						5		300		0,000
						4	1	**30**	**0,02**	**0,60**
						3	2	0,3	0,06	0,02
						2	3	0,03	0,2	0,01
						1	3	0,003	0,2	0,00
Total Risk Weight										0,62

MW-2:

The same logic which is followed in Item 1 will be followed throughout the risk evaluation. There are electrical appliances like lighting inside the warehouse. They may act as sources to lead fire or explosion. In fact, flammable vapour formation is not very likely due to the chemical properties at STP. However, these sources of ignition could lead to severe results in special cases like chemical spill.

Category of event frequency is detected as 2. This is due to the statistical data and experiences of employees. Also, according to the study of Zeeuwen, electrical appliances form 2.5% of all ignition sources [99]. This also shows that the frequency of electrical ignition is rather low.

As can be seen in Table 6.6, such an accident is not expected to affect more than 10 people irreversibly. Upon ignition of a chemical spill, it is predicted to be extinguished as soon as possible. Hence, the frequency of slighter consequences is of Category 1. The probability of this incident having results below regulatory concern is higher.

Table 6.6: Risk Evaluation Form of Main Warehouse for Item 2

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-2	Main warehouse	There are electrical appliances inside the warehouse.	Electrical appliances may create a spark. This spark could lead to a fire or an explosion inside the warehouse.	None	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,61

The logic behind frequency and consequence analysis is that, the frequency decreases as the consequence increases. To exemplify, an earthquake of magnitude 7.0 occurs once in several decades. However, earthquakes of lower magnitudes, like 3.0 occurs approximately once in several days. In Item 2, consequence categories 2, 3 and 4 have the same frequency category values. This is due to low resolution of categorization set in this study. If more sensitive categorization was conducted, i.e. more consequence categories were defined; consequence categories would then have different frequency values.

MW-3:

By the personnel in Research &Development Department of the plant for several purposes, samples are collected from chemical tanks regularly. However, after sample collection, usually the chemical tanks are left open. Open containers may be exposed to an ignition source, or there is a probability they may spill and catch fire Event frequency is 1 as the chemicals are not intensely evaporating under STP. This decreases the probability of a fire or explosion due to flammable vapour gathering inside the main warehouse. However, this is not very likely.

Event frequency can never be exceeded; hence the frequency category is always 1 with respect to different categories. It is not predicted that an incident resulting in irreversible effects on more than 10 people. Results can be seen in Table 6.7.

Table 6.7: Risk Evaluation Form of Main Warehouse for Item 3

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-3	Main warehouse	Chemical tanks are left open during sample collection.	Fire / explosion may occur.	Insufficient	1	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,61

MW-4:

There are many packages of chemicals which are in solid phase. These finely divided combustible solids (starch or indigo dust mainly) are stored on shelves at higher elevations. Then, they are carried to process lines with forklifts. During transportation, packages of dust may fall down and burst. Dispersed dust may lead to dust explosion.

Frequency of dust explosion is small, because historical data indicates that dust explosion has a low frequency, [99]. Also, a dust explosion had not occurred in the plant before. However, the results may be devastating. Hence, here it is possible that more than 100 people are irreversibly affected. Results of the analysis can be found in Table 6.8.

Table 6.8: Risk Evaluation Form of Main Warehouse for Item 4

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-4	Main warehouse	Dusts are stored on shelves at higher elevation.	During taking dust packages they may burst. Dust explosion may occur.	None	1	6	1	**3000**	**0,02**	**60**
						5	1	300	0,02	6
						4	1	30	0,02	0,6
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										66,61

MW-5:

The section in which most hazardous chemicals with respect to flammability and combustibility are stored is not isolated from the main warehouse with a fire and pressure resistant wall. In case a fire or explosion occurs in this section, this may spread to the main warehouse simultaneously.

As there has not been any fire inside the more hazardous materials zone during the lifetime of warehouse (18 years), to assume the worst scenario, we can take the frequency of initiating event as 1/19=0.053/year. It is assumed that only 60% of fires/explosions inside this zone will affect the main warehouse. Then the event frequency is;

$$0.053\ per\ year\ \times 60\% = 0.0318\ per\ year$$

According to the scale of frequency and consequence given in Section 6.4, this frequency number fits to Category 2. Hence, frequency of event is determined as Category 2. The possibility of such a fire which has spread from the more hazardous zone to the main warehouse to affect more than 100 people severely is assumed as 5%:

$$0.0318\, per\ year\ \times 5\% = 0.00159\, per\ year \rightarrow \text{ (Category 1)}$$

The possibility of influencing between 10 and 100 people (severely) is assumed as 10%:

$$0.0318\, per\ year\ \times 10\% = 0.00318\ \ per\ year\ \rightarrow \text{ (Category 1)}$$

The possibility of influencing between 1-10 people (severely) is assumed as 15%:

$$0.0318\, per\ year\ \times 15\% = 0.00477\, per\ year \rightarrow \text{ (Category 1)}$$

The possibility of such a fire to affect between 1-10 people reversibly is assumed as 95%:

$$0.0318\, per\ year\ \times 95\% = 0.03021\, per\ year\ \rightarrow \text{ (Category 2)}$$

Possibility of influencing one people reversibly is assumed as 99%:

$$0.0318\, per\ year\ \times 99\% = 0.031482\, per\ year \rightarrow \text{ (Category 2)}$$

The possibility of having results below regulatory concern is assumed as 100% (such a fire would definitely have some negative results below regulatory concern):

$$0.0318\, per\ year\ \times 100\% = 0{,}0318\, per\ year \rightarrow \text{ (Category 2)}$$

Results are shown in Table 6.9.

Table 6.9: Risk Evaluation Form of Main Warehouse for Item 5

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-5	Main warehouse	Section for hazardous chemicals is not isolated with a resistant wall.	A probable fire/explosion emerging from this section could spread to the main warehouse.	None	2	6	1	**3000**	**0,02**	**60**
						5	1	300	0,02	6
						4	1	30	0,02	0,6
						3	2	0,3	0,06	0,018
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										66,62

MW-6:

In the main warehouse, there are certain chemicals which have to be stored at certain relative humidity and temperature values. Although there is a RH and temperature monitor; it is not regularly checked. The values may be out of the required scale and this might not be recognised if regular check is not conducted. Then, it is possible that some chemicals existing in the main warehouse may decompose and produce some other chemicals or chemical vapour. Some chemicals may go through some exothermic reactions if the temperature is not controlled properly.

However the frequency of such an event is considered to be low as it had never happened inside the plant before. Hence, the frequency of event is in Category 1. Also, such an event is not forecasted to irreversible effects. This is because it involves a limited number of chemical packages. It is very likely that the reaction will be intervened before it worsens. The evaluation is shown in Table 6.10.

Table 6.10: Risk Evaluation Form of Main Warehouse for Item 6

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-6	Main warehouse	RH and temperature of the main warehouse are not regularly checked.	Chemicals could deterioriate, undergo different reactions which might as a result lead to fire.	Insufficient	1	6		3000		0
						5		300		0
						4		30		0
						3	1	**0,3**	**0,02**	**0,006**
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,01

MW-7:

Storage of chemicals is not done according to the chemical properties which are stated in MSDS. There are certain incompatibilities of chemicals which are stated in Table 6.2. In case incompatible chemicals come into contact, undesired reactions may occur, leading to fire or explosion [9].

The frequency of chemicals on the shelves coming into contact is not predicted to be higher. For this to occur either both incompatible chemicals should spill at the same time or their packages should be corroded to leak the materials simultaneously. The consequence of such an event is not predicted to have irreversible effects, because it involves certain chemical packages, hence intervention to the event is easier. The evaluation is shown in Table 6.11.

Table 6.11: Risk Evaluation Form of Main Warehouse for Item 7

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-7	Main warehouse	Storage is not conducted according to chemical properties of MSDS documents.	Physical contact may lead to a fire or an explosion.	None	1	6		3000		0
						5		300		0
						4		30		0
						3	1	**0,3**	**0,02**	**0,006**
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,01

MW-8:

There are many chemicals with corroded containers. Expiration dates for some of these chemicals are over. Most probably, substance inside the containers started to deteriorate. Some of them are already cracked and leaking the substance. Leaked materials may catch fire.

As the containers are already in corroded phase, it is easier for incompatible chemicals to get into contact. The frequency category is higher, 2. The probability of 1-10 people getting irreversible affected from such an event is low; the category is defined as 1. This is because the event will involve only certain packages and controlling the event is easier. The frequencies of lower consequences should be higher in that case, Category 2 is attached to them. Evaluations are shown in Table 6.12.

Table 6.12: Risk Evaluation Form of Main Warehouse for Item 8

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-8	Main warehouse	There are many chemicals with corroded vessels.	Leaked chemical may catch fire or incompatible chemicals may contact, leading to fire or explosion.	None	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	2	0,3	0,06	0,018
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,62

MW-9:

Chemicals do not contain information sheets on storage shelves about their properties, potential hazards they carry, how their hazards should be mitigated. Thus, workers using these chemicals may not know all about each chemical. Misuse of these chemicals due to insufficient information provided on the shelves may lead to fire or explosion (exothermic reactions, incompatible chemicals, etc.).

Event frequency is determined as Category 2. This is selected as so because these types of accidents occurred in the manufacturing plant. According to the interviews conducted with different employees, it is confirmed that this type of incidents occur once in 10-30 years. Instant intervention to prevent the accident scale getting larger may not be possible, due to lack of information. Hence, it could lead to more severe consequences. The frequency of 1-100 people being severely affected from such an event has the Category 1. The frequency increases for slighter consequences as can be seen in Table 6.13.

Table 6.13: Risk Evaluation Form of Main Warehouse for Item 9

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-9	Main warehouse	Chemical tanks do not include chemical information sheets on.	Misuse of may lead to fire/explosion.	None	2	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	1	30	0,02	0,6
						3	2	0,3	0,06	0,018
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										6,62

MW-10:

As indicated before, employee of the main warehouse is not very well informed about the hazard chemicals represent, contingency plan of the mill or what should be done to prevent the accidents. In case a fire or explosion occurs, the responsible employee may not take appropriate precautions and hence the scale of the accident may enlarge. The evaluation of risk entails conditional probability. Such an event has never occurred throughout the life time of main warehouse. Hence, the likelihood of such an event according to the worst case scenario (conservative estimate) is 1/19=0.053/year Assuming that worker inside the warehouse will not take the appropriate measures with a probability of 50%; then the probability of such an event is;

$$0.053\,per\ year\ \times 50\% = 0{,}0265\,per\ year \rightarrow (\text{Category } 1)$$

(Frequency of accident scale enlarging due to insufficient actions of workers)

The possibility of an enlarged accident in the main warehouse to affect more than 100 people severely is assumed as 5%:

$$0.0265\ per\ year\ \times 5\% = 0.001325\ per\ year\ \rightarrow\ \text{(Category 1)}$$

As both of these frequencies fall into Category 1, it is important to explain the importance of resolution of categorization here. Six categories were defined in frequency categorization. Adding a few more frequency categories would have given a better resolution of the risk levels on the matrix. To exemplify, if the number of categories for frequency values were 15 instead of 6, the categories of probability of the event and the possibility of more than 100 people getting irreversibly affected would be different.

The possibility of influencing between 10 and 100 people (severely) is assumed as 10%:

$$0.0265\ per\ year\ \times 10\% = 0.00265\ \ per\ year\ \rightarrow\ \text{(Category 1)}$$

The possibility of influencing between 1-10 people (severely) is assumed as 15%:

$$0.0265\ per\ year\ \times 15\% = 0.003975\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The possibility of such an event to affect between 1-10 people reversibly is assumed as 95%:

$$0.0265\ per\ year\ \times 95\% = 0.02518\ per\ year \rightarrow\ \text{(Category 1)}$$

Possibility of influencing one people reversibly is assumed as 99%:

$$0.0265\ per\ year\ \times 99\% = 0.02623\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The possibility of having results below regulatory concern is assumed as 100% (such a fire would definitely have some negative results below regulatory concern):

$$0.0265\ per\ year\ \times 100\% = 0.0265\ per\ year\ \rightarrow\ \text{(Category 1)}$$

Results are inserted in Risk Evaluation Forms as shown in Table 6.14. Instead of using Category Definitions for the frequency values, calculated frequencies are inserted for a better risk assessment.

Table 6.14: Risk Evaluation Form of Main Warehouse for Item 10

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-10	Main warehouse	The responsible worker may not take appropriate actions in case of a fire/explosion.	The scale of the accident could enlarge instantaneously.	Insufficient	1	6	1	**3000**	0,001325	**3,975**
						5	1	300	0,00265	0,795
						4	1	30	0,003975	0,119
						3	1	0,3	0,02518	0,0075
						2	1	0,03	0,02623	0,00078
						1	1	0,003	0,0265	0,000079
Total Risk Weight										4,90

MW-11:

There are some chemical shelves which do not contain chemical collective tanks at the bottom. Each shelf should have spill containment system at the bottom so that in case chemicals leak, they do not directly spill on the ground; prone to ignition sources. The probability of such an incident is estimated as Category 2.

It is not very likely that such an incident would cause irreversible effects on more than 10 people. The frequency of irreversible effects on 1-10 people is rather low. Because, spilled chemical will involve certain chemical packages, thus it is easier to intervene. The lower consequences have higher frequency values as can be seen in Table 6.15.

Table 6.15: Risk Evaluation Form of Main Warehouse for Item 11

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-11	Main warehouse	Some chemical shelves do not contain collective tanks.	Leaked chemical could lead to fire/explosion.	Insufficient	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	2	0,3	0,06	0,018
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,62

MW-12:

The distances between main warehouse, cotton warehouse, industrial zone and another textile mill are too low, approximately 20 m. This makes a domino effect possible. In case a fire or explosion occurs inside the main warehouse can affect the surrounding buildings. Risk calculation for this event entails conditional probability.

Such an event has never occurred throughout the life time of main warehouse. Hence, the likelihood of such an event according to the worst case scenario is 1/19/year=0.053/year. It is assumed that a fire or explosion in the main warehouse will spread to the surrounding buildings with a 20% probability.

$$0.053\ per\ year\ \times 20\% = 0.0106\ per\ year$$

(Frequency of spreading fire– Category 1)

The possibility of such a fire which has spread from the main warehouse to affect more than 100 people is assumed as 5%:

$$0.00106\, per\ year\ \times 5\% = 0.00053\, per\ year\ \rightarrow\ \text{(Category 1)}$$

The possibility of influencing between 10 and 100 people (severely) is assumed as 10%:

$$0.0106\, per\ year\ \times 10\% = 0.00106\ \ per\ year\ \ \rightarrow\ \text{(Category 1)}$$

The possibility of influencing between 1-10 people (severely) is assumed as 15%:

$$0.0106\, per\ year\ \times 15\% = 0.00159\, per\ year \rightarrow\ \text{(Category 1)}$$

The possibility of such an event to affect between 1-10 people reversibly is assumed as 95%:

$$0.0106\, per\ year\ \times 95\% = 0.01007\, per\ year\ \rightarrow\ \text{(Category 1)}$$

Possibility of influencing one people reversibly is assumed as 99%:

$$0.0106\, per\ year\ \times 99\% = 0{,}0105\, per\ year \rightarrow\ \text{(Category 1)}$$

The possibility of having results below regulatory concern is assumed as 100% (such a fire would definitely have some negative results below regulatory concern):

$$0.0106\, per\ year\ \times 100\% = 0{,}0106\, per\ year\ \rightarrow\ \text{(Category 1)}$$

Results are shown in Table 6.16.

Table 6.16: Risk Evaluation Form of Main Warehouse for Item 12

Item No	Activity Department	Activity / State Description	Potential Event	Current Precaution	Frequency of Event	A Consequence Category (1-6)	B Frequency Category (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
MW-12	Main warehouse	Main warehouse, cotton warehouse, industrial zone and another textile mill are only 20 m away from each other.	An accident in main warehouse may instantaneously affect the other buildings.	None	1	6	1	**3000**	**0,00053**	**1,59**
						5	1	300	0,00106	0,318
						4	1	30	0,00159	0,048
						3	1	0,3	0,01007	0,003
						2	1	0,03	0,0105	0,0003
						1	1	0,003	0,0106	0,00003
Total Risk Weight										1,96

6.4.2. Finishing Department

F-1:

There are various chemical tanks with their caps open in finishing department. They may spill onto the ground and catch fire, lead to an explosion. The event frequency is described as Category 2; this is higher than that of Item 3 in the main warehouse. The reason behind is that there are more ignition sources in the finishing department than there are in main warehouse. As process lines are in the finishing warehouse, there is a continuous flow of motion and various equipments, cables, electricity control panels, etc. inside this section.

Also, the consequence values are predicted as higher than that of warehouse. This is due to crowded personnel of finishing department. The event is not forecasted to influence more than 100 people as seen in Table 6.17.

Table 6.17: Risk Evaluation Form of Finishing Department for Item 1

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-1	Finishing	Chemical tanks which are used for finishing process are frequently left with their caps open.	Chemicals inside the tanks can easily spill, which might lead to a fire or an explosion.	Insufficient	2	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	1	30	0,02	0,6
						3	1	0,3	0,02	0,006
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										6,61

F-2:

Chemical packages do not carry information labels on. Event frequency is set as the same as Item 9 of the main warehouse. However, a fire or explosion resulting from misuse of chemical is not expected to have the same consequence as main warehouse. This is because of the huge amount of chemicals stored at the main warehouse and the location of it. Table 6.18 illustrates the analysis:

Table 6.18: Risk Evaluation Form of Finishing Department for Item 2

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-2	Finishing	Chemical tanks do not carry information labels on.	Misuse of chemicals may lead to fire/explosion.	None	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	2	0,3	0,06	0,018
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,62

F-3:

Chemicals are not stored according to their properties defined in MSDS and their incompatibilities. The analysis is very similar to Item 7 in the main warehouse. Though, similar accident in finishing warehouse could irreversible consequences on 1-10 people. This is because of the fact that there are more employees in the finishing department whereas there is only one permanent employee in the main warehouse. Moreover, during walk-through inspection it was observed that safety information of finishing staff is rather poor. Facility management also agreed with that observation; and stated they had recently started to work in that department and planned to train the finishing staff. Analysis can be seen in Table 6.19.

Table 6.19: Risk Evaluation Form of Finishing Department for Item 3

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-3	Finishing	Chemicals are not stored according to their MSDS documents.	Chemicals which goes under hazardous reactions may easily be in physical contact.	None	1	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,61

F-4:

As indicated before, finishing warehouse is inside the process halls. There are no walls to separate the warehouse from the process. Nearby the warehouse, fabric rolls are stored. Any fire or explosion resulting from the process halls can easily spread to the warehouse and fires/explosions emerging from the warehouse can influence process halls. Fabric rolls would make spreading easier.

According to statistics taken from the mill, approximately there occur 2 fires inside finishing process halls in a year. It is assumed that the possibility of a fire in finishing department to spread is 2% (Throughout the history such a spread is never seen).

$$2\, fires\ per\ year\ \times 2\% = 0.04 \ \rightarrow\ (\text{Event frequency} - \text{Category 2})$$

The possibility of such a fire which has spread to the finishing warehouse to affect more than 100 people is assumed as 5%:

$$0.04\, per\ year\ \times 5\% = 0.002\, per\ year\ \rightarrow\ (\text{Category 1})$$

Possibility to affect between 10 and 100 people (severely) is 10%:

$$0.04\, per\ year\ \times 10\% = 0.004\, per\ year\ \rightarrow\ (\text{Category 1})$$

Likelihood of affecting between 1-10 people severely is 15%:

$$0.04\, per\ year\ \times 15\% = 0.006\, per\ year\ \rightarrow\ (\text{Category 1})$$

Possibility that between 1 and 10 is influenced reversibly is 95%:

$$0.04\, per\ year\ \times 95\% = 0.038\, per\ year\ \rightarrow\ (\text{Category 2})$$

Likelihood of one people getting affected reversibly is assumed as 99%:

$$0.04\, per\ year\ \times 99\% = 0.0396\, per\ year\ \rightarrow\ (\text{Category 2})$$

Probability that effects below regulatory concern will occur is assumed as 100% (such a fire would definitely have some negative results below regulatory concern):

$$0.04\ per\ year\ \times 100\% = 0.04\ per\ year\ \rightarrow\ (\text{Category }2)$$

Table 6.20 demonstrates the analysis.

Table 6.20: Risk Evaluation Form of Finishing Department for Item 4

Item No	**Activity Department**	**Activity / State Description**	**Risk Definition**	**Current Precaution**	**Frequency of Event**	**A Consequence (1-6)**	**B Frequency (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
F-4	Finishing	No walls are present to separate the warehouse from the process where fabric rolls are stored.	Fires emerging from process can spread to finishing warehouse or vice versa.	None	2	6	1	**3000**	**0,002**	**6**
						5	1	300	0,004	1,2
						4	1	30	0,006	0,18
						3	2	0,3	0,038	0,0114
						2	2	0,03	0,0396	0,0012
						1	2	0,003	0,04	0,00012
Total Risk Weight										7,4

F-5:

As indicated before, fabric rolls and finishing warehouse are very close to each other. Chemical packages contain intense amount of cotton dust on them. Cotton dust is a very flammable material. In case cotton dust catches fire, chemicals may also catch fire or explode.

In case cotton fibres on chemical packages catch fire, the probability of chemicals catching fire is assumed as 40%. The cotton fibres on chemical packages have never caught fire before, during the lifetime of finishing warehouse.

$$1/30\ per\ year\ \times 40\% = 0.0133\quad (\text{Event Frequency}\ -\ \text{Category 1})$$

The possibility of such a fire to affect more than 100 people is assumed as 0%, it is predicted that the fire/explosion will be intervened before the scale enlarges. The possibility of affecting between 10 and 100 people (severely) is assumed as 5%:

$$0.0133\ per\ year\ \times 5\% = 0.00067\ per\ year\ \rightarrow\ (\text{Category 1})$$

The likelihood of influencing between 1-10 people severely is 15%:

$$0.0133\ per\ year\ \times 15\% = 0.0020\ per\ year\ \rightarrow\ (\text{Category 1})$$

The possibility of influencing between 1 and 10 reversibly is 20%:

$$0.0133\ per\ year\ \times 20\% = 0.0027\ per\ year\ \rightarrow\ (\text{Category 1})$$

The probability of one people being affected reversibly is assumed as 60%:

$$0.0133\ per\ year\ \times 60\% = 0.008\ per\ year\ \rightarrow\ (\text{Category 1})$$

The likelihood that results below regulatory concern will occur:

$$0.0133\ per\ year\ \times 100\% = 0.0133\ per\ year\ \rightarrow\ (\text{Category 1})$$

Results are illustrated in Table 6.21.

Table 6.21: Risk Evaluation Form of Finishing Department for Item 5

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-5	Finishing	Cotton fibers gather on chemical tanks.	In case the cotton fibers catch fire, this may affect the flammable chemicals	None	1	6		3000		0
						5	1	**300**	**0,00067**	**0,201**
						4	1	30	0,002	0,06
						3	1	0,3	0,0027	0,00081
						2	1	0,03	0,008	0,00024
						1	1	0,003	0,0133	0,00004
Total Risk Weight										0,26

F-6:

Finishing warehouse does not have enough places for chemical storage. Hence, many chemical packages are not even on shelves, but they are on the ground. It is easier for these chemicals to fall over and spill on the ground. Also, in case chemical leaks, it will directly leak on the ground. Chemical on the ground is prone to ignition sources and it may catch fire.

However, such a fire has never happened before. Hence, the frequency of event is determined as Category 1. Such an incident is not forecasted to affect more than 10 people irreversibly. Because, it will involve some chemical packages only and it is likely that the spill will be intervened before it catches fire. As the resolution of categorization is not selected as high for this study, the rest of consequence categories will have frequency Category 1 as illustrated in Table 6.22.

Table 6.22: Risk Evaluation Form of Finishing Department for Item 6

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-6	Finishing	The finishing warehouse do not have enough place for chemicals.	Chemicals may leak directly on the ground and they might catch fire.	None	1	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,61

F-7:

Finishing department has the highest number employees among all departments and many of them have not received safety training; thus do not know very well what to do in case of an emergency. In case of a fire or explosion in the finishing department, the scale of accident may enlarge due to this fact.

This scenario entails conditional probability. It is assumed that in case a fire or explosion occurs, workers may not take appropriate actions 50%. According to statistics, approximately 3 incidents occur per year in finishing department (2 fires and one exothermic chemical reaction).

$$3\ per\ year\ \times 50\% = 1.5\ per\ year$$

(This means that a fire in which workers do not take appropriate measures will occur frequently)

The percentage of fires which enlarge because the workers do not take appropriate measures is assumed as 10%. Here it is assumed that for the rest of fires, either fire brigade in the mill or the other agents will intervene in the fire before they enlarge.

$$1.5\ per\ year\ \times 10\% = 0.15\ per\ year\ \rightarrow\ \text{(Category 2)}$$

The possibility of such an incident to affect more than 100 people is assumed as 0%
The probability of affecting between 10 and 100 people irreversibly is 5%:

$$0.15\ per\ year\ \times 5\% = 0.0075\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The likelihood of influencing between 1 and 10 people severely is 30%

$$0.15\ per\ year\ \times 30\% = 0.045\ per\ year \rightarrow\ \text{(Category 2)}$$

The possibility of affecting between 1 and 10 people reversibly is 60%:

$$0.15\ per\ year\ \times 60\% =\ 0.09\ per\ year \rightarrow\ \text{(Category 2)}$$

The likelihood of influencing one people reversibly is 70%:

$$0.15\ per\ year\ \times 70\% = 0.105\ per\ year \rightarrow\ \text{(Category 3)}$$

The possibility of such an incident to have results below regulatory concern is assumed as 100%:

$$0.15\ per\ year\ \times 100\% = 0.15\ per\ year \rightarrow\ \text{(Category 3)}$$

Results are demonstrated in Table 6.23.

Table 6.23: Risk Evaluation Form of Finishing Department for Item 7

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-7	Finishing	Workers are not well informed on safety issues.	In case of a fire or explosion, necessary actions may not be taken and scale of accident may enlarge	Insufficient	2	6		3000		0
						5	1	**300**	**0,0075**	**2,25**
						4	2	30	0,045	1,35
						3	2	0,3	0,09	0,027
						2	2	0,03	0,105	0,0031
						1	2	0,003	0,15	0,00045
Total Risk Weight										3,63

F-8:

Pressurized tank explosion is frequently seen in several industries. There are pressurized tanks in finishing department utilized for process mixture preparation. Their conditions are in poor state, the corrosion of the tanks can easily be seen. Maintenance checks of these tanks are done under higher pressures than operating pressure to ensure the safety of pressurized tanks. The explosion risk increases if the maintenance checks are not conducted.

It is predicted that frequency of event is Category 3. This is predicted according to the frequent explosions seen in history and the fact that such an explosion have not occurred before in finishing department. Such explosion generally has severe effects on employees working nearby the tanks. Hence, the event is not forecasted to affect more than 100 people irreversibly. The frequency of between 10 and 100 people to be affected from such an accident is of Category 1 whereas the frequency category of affecting between 1 and 10 people is forecasted as 2. The frequency of influencing less people is higher, Category 3, illustrated in Table 6.24.

Table 6.24: Risk Evaluation Form of Finishing Department for Item 8

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
F-8	Finishing	Finishing kitchen contain pressurized tanks whose maintanance checks are not conducted.	Tanks which are corroded can explode.	None	3	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	2	30	0,06	1,8
						3	3	0,3	0,2	0,06
						2	3	0,03	0,2	0,006
						1	3	0,003	0,2	0,0006
Total Risk Weight										7,87

6.4.3. Indigo Department

I-1:

Indigo dust, a combustible dust, is handled while preparing indigo mixture for process lines. The preparation of the mixture is done in a vessel manually. During this action, indigo dust is scattered. Dispersed indigo dust may cause dust explosion upon contact with an ignition source, which can easily be found in the kitchen and process halls as there are various equipments, electricity cables and electricity control panels.

Dust explosion is not frequently seen in industries; therefore the event frequency category is selected as 1. Dust explosions may have devastating results; this is why it is predicted that it may affect more than 100 people. In fact, frequency categories should increase for decreasing consequences. In this study, though, resolution is kept low and frequency categories for all results are the same (Category 1). Results can be seen in Table 6.25.

Table 6.25: Risk Evaluation Form of Indigo Department for Item 1

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
I-1	Indigo	Indigo dust is scattered during preparation of indigo mixture.	Dust explosion may occur due to combustible dust dispersion in the process halls.	Insufficient	1	6	1	**3000**	**0,02**	**60**
						5	1	300	0,02	6
						4	1	30	0,02	0,6
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										66,79

I-2:

Chemicals are not stored according to their properties and incompatibilities. Chemical contact may result in fire or explosion. The event frequency is predicted the same as Item 3 of Finishing Department.

As demonstrated in Table 9.33 below, the incident is not forecasted to affect more than 10 people reversibly. This is due to the fact that number of employees in indigo department is less than that of finishing department. Chemical contact due to improper storage will affect a limited number of chemicals and therefore intervention will be easier. Results can be seen in Table 6.26.

Table 6.26: Risk Evaluation Form of Indigo Department for Item 2

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
I-2	Indigo	Chemicals are not stored according to their properties which are stated in their MSDS documents in the indigo warehouse.	Physical contact may occur; emerging a possibility of fire or explosion.	None	1	6		3000		0
						5		300		0
						4		30		0
						3	1	**0,3**	**0,02**	**0,006**
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,01

I-3:

There are no chemical collection tanks at the bottom of some chemical storage shelves. Chemicals may leak onto the ground directly in case of a spill and catch fire. It is not very frequent to have chemical fires inside indigo department. Hence, it is assumed that the probability of such a fire is 1/20 years=0.05 per year (Category 2). Intervention in such incidents involving only a limited number of chemicals is easier. It is not predicted that such a fire will affect more than 10 people irreversibly. The frequency of influencing one people reversibly is higher than the frequency of more severe consequences as illustrated in Table 6.27.

Table 6.27: Risk Evaluation Form of Indigo Department for Item 3

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
I-3	Indigo	There are no tanks to catch the chemical leakes in the indigo warehouse.	Chemicals may directly leak on the ground and catch fire.	Insufficient	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,61

I-4:

There are no chemical information sheets present on chemical packages. Employees may misuse the chemicals and hence cause a fire or explosion. The evaluation of this risk is very similar to Item 9 of main chemical warehouse. This incident in indigo department is not predicted to affect more than 10 people severely whereas the consequences of similar item may be more severe in the main warehouse. Evaluation is demonstrated in Table 6.28.

Table 6.28: Risk Evaluation Form of Indigo Department for Item 4

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
I-4	Indigo	Indigo warehouse does not contain information sheets on chemical tanks.	Fire / explosion may occur due to misuse of chemicals.	Insufficient	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,61

I-5:

In indigo chemical warehouse, there are no absorbent materials to be used upon chemical spills. This increases the duration chemical is on the ground and prone to ignition sources. The chemical on the ground may catch fire. Evaluation of this item is very similar to Item 3 of indigo department and it is illustrated in Table 6.29.

Table 6.29: Risk Evaluation Form of Indigo Department for Item 5

Item No	**Activity Department**	**Activity / State Description**	**Risk Definition**	**Current Precaution**	**Frequency of Event**	**A Consequence (1-6)**	**B Frequency (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
I-5	Indigo	There are no absorbant materials to be used in case of a chemical spill.	Probable spill might directly enter into the working atmosphere. This may cause the spilled chemical to catch fire.	Insufficient	2	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,61

I-6:

Employees of indigo department do not know well about safety issues. They are lacking information especially on fire and explosion. Compared to the employees of finishing department, it is observed that the employees in indigo department are in poorer condition with regards to safety information. Hence, the event frequency is determined as Category 3. Evaluation results are attached in Table 6.30.

Table 6.30: Risk Evaluation Form of Indigo Department for Item 6

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
I-6	Indigo	Workers are not well informed.	In case of a fire or explosion, necessary actions may not be taken, the scale of accident may enlarge instantaneously.	Insufficient	3	6		3000		0
						5	1	300	0,02	6
						4	2	30	0,06	1,8
						3	2	0,3	0,06	0,018
						2	3	0,03	0,2	0,006
						1	3	**0,003**	**0,2**	**0,0006**
Total Risk Weight										7,82

6.4.4. Sizing Department

S-1:

Pressurized tanks are utilized at high temperature and pressure values to prepare sizing solution. There is a probability that these high pressure tanks explode. However, regular maintenance checks of tanks are conducted in sizing department. The evaluation is very similar to Item 8 of Finishing Department. The frequency of event is of Category 1 because the maintenance checks are regularly done in this department. The results are attached in Table 6.31.

Table 6.31: Risk Evaluation Form of Sizing Department for Item 1

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
S-1	Sizing	Pressurized tanks are utilized under high temperatures to prepare the sizing mixture.	Pressurized tanks carry the risk of exploding in case their regular checks are not carried out.	Sufficient	2	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	1	30	0,02	0,6
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	2	0,003	0,02	0,00006
Total Risk Weight										6,61

S-2:

Pressurized tank explosion would increase the pressure inside the sizing department. There is intense amount of dust in the department. Pressure rise resulting from pressurized tank explosion may lead to dispersion of all present dust gathered on surfaces. These tanks have never exploded before (sizing department is present for about 30 years); hence the probability of tanks to explode is 1/30=0,033/year. The probability of tank explosion resulting to dust explosion is assumed as 50%:

$$0.033\,per\ year\ \times 50\% = 0.0166\,per\ year$$

(Frequency of Event – Category 1)

The possibility of a dust explosion to affect more than 100 people irreversibly is assumed as 40%:

$$0.0166\,per\ year \times 40\% = 0.0066\,per\ year\ \rightarrow\ (\text{Category 1})$$

The likelihood of influencing between 10 and 100 people irreversibly is assumed as 60%:

$$0.0066\ per\ year \times 50\% = 0.0033\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The possibility of the incident to affect between 1 and 10 people irreversibly is 75%:

$$0.0066\ per\ year \times 75\% = 0.0050\ per\ year\ \rightarrow\ \text{(Category 1)}$$

Likelihood of the incident to influence between 1 and 10 reversibly is 90%:

$$0.0066 per\ year\ \times 90\% = 0.0060\ \rightarrow\ \text{(Category 1)}$$

Possibility of one people to get affected reversibly is 95%:

$$0.0066\ per\ year\ \times 95\% = 0.0063\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The incident would certainly have results below regulatory concern:

$$0.0066\ per\ year\ \times 100\% = 0.0066\ per\ year \rightarrow\ \text{(Category 1)}$$

Evaluation results are shown in Table 6.32.

Table 6.32: Risk Evaluation Form of Sizing Department for Item 2

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
S-2	Sizing	Pressurized tanks are utilized under high temperatures to prepare the sizing mixture.	In case the pressurized tanks explode, the pressure may arise and dust explosion can occur.	None	1	6	1	**3000**	**0,0066**	**19,8**
						5	1	300	0,0033	0,99
						4	1	30	0,0050	0,15
						3	1	0,3	0,0060	0,0018
						2	1	0,03	0,0063	0,00019
						1	1	0,003	0,0066	0,000019
Total Risk Weight										20,9

S-3:

Starch is a combustible dust which is used in process. It gathers on the surfaces like the edges of the walls, on the top of pipelines, etc. Dust explosion may occur in sizing department. This can start with the bursting of starch packages fed into the hopper. If an ignition source is present, primary dust explosion occurs and as there is intense amount of dust gathered around this would most probably be followed with a secondary dust explosion. Evaluation of risk is very similar to that of Item 2. Results can be seen in Table 6.33.

Table 6.33: Risk Evaluation Form of Sizing Department for Item 3

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
S-3	Sizing	Starch, a combustible dust, is utilized and gathered inside the sizing (on the ground, on the edges, pipes, etc.) department.	Dust explosion may occur.	Insufficient	1	6	1	**3000**	**0,02**	**60**
						5	1	300	0,02	6
						4	1	30	0,02	0,6
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										66,61

S-4:

Starch is fed in to the pressurized tanks via the hopper for preparation of sizing mixture. Hopper is used to disperse starch so that it is easily solved in the mixture. The frequency of hopper dust explosion is stated as 5% in the study of Zeeuwen [99]. Hence, the frequency event category is 1. Results are illustrated in Table 6.34.

Table 6.34: Risk Evaluation Form of Sizing Department for Item 4

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
S-4	Sizing	Starch is dispersed in hopper.	Dust explosion may occur inside the hopper.	Insufficient	1	6	1	**3000**	**0,02**	**60**
						5	1	300	0,02	6
						4	1	30	0,02	0,6
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										66,61

6.4.5. Weaving Department

W-1:

There are no information signboards present in weaving department. This may cause lack of information. There are electrical cables, electricity control panel and intense amount of cotton fibres which may cause fire or explosion. However, the frequency of the incident is predicted as Category 1 since fire in weaving department has never occurred due to lack of information of workers. As the fire of cotton dust can easily be detected, they are usually extinguished instantaneously. Therefore, it is not forecasted that such an incident will affect more than 10 people irreversibly as seen in Table 6.35.

Table 6.35: Risk Evaluation Form of Weaving Department for Item 1

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
W-1	Weaving	Information signboards regarding to the operating conditions inside the weaving halls are insufficient.	Fire may occur due to lack of information in the weaving department.	Insufficient	1	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	1	0,03	0,02	0,0006
						1	1	0,003	0,02	0,00006
Total Risk Weight										0,61

W- 2:

Electrical control panels are not very well isolated, which creates arcs and causes ignition of cotton fibres. According to incident statistics of manufacturing plant, fire emerging in weaving department due to electrical causes is approximately one per year. Event frequency is very high, Category 5. Even through, these fires occur very frequently, their consequences tend to be low. Employees in the department are used to such fires; thus they are usually extinguished instantaneously. Results are attached in Table 6.36.

Table 6.36: Risk Evaluation Form of Weaving Department for Item 2

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
W-2	Weaving	Electrical control panels are not well isolated.	Fire may occur due to sparks emerging from electrical control panels.	Insufficient	5	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	1	30	0,02	0,6
						3	2	0,3	0,06	0,018
						2	5	0,03	0,06	0,0018
						1	5	0,003	0,06	0,00018
Total Risk Weight										6,62

W-3:

Electrical control panels are blocked by objects. In case of a fire, the electricity should be cut from control panels so that the scale of the accident does not enlarge. As they are blocked in weaving department, a potential fire may enlarge instantaneously.

The frequency of fires which involve electrical connections is approximately one per year according to the incident statistics of the manufacturing plant. The probability of inaccessibility to electrical control panel is assumed as 30%:

$$1\,per\ year\ \times 30\% = 0.3\,per\ year$$

The probability of fire scale enlarging due to this inaccessibility 15% (most probably firemen, etc. will get involved):

$$0.3\,per\ year\ \times 15\% = 0.045\,per\ year$$

(Event Frequency - Category 2)

The possibility of a dust explosion to affect more than 100 people irreversibly is assumed as 5%:

$$0.045\,per\ year\ \times 5\% = 0.0034\,per\ year\ \rightarrow\ (\text{Category } 1)$$

Likelihood of influencing between 10 and 100 people irreversibly is assumed as 7%:

$$0.045\,per\ year\ \times 7\% = 0.00315\,per\ year\ \rightarrow\ (\text{Category } 1)$$

Possibility of affecting between 1 and 10 people irreversibly is 15%

$$0.045\,per\ year\ \times 15\% = 0.0068\,per\ year\ \rightarrow\ (\text{Category } 1)$$

Likelihood of influencing between 1 and 10 reversibly is 50%:

$$0.045\,per\ year\ \times 50\% = 0.0225\,per\ year\ \rightarrow\ (\text{Category } 1)$$

The probability of one people reversibly is 80%:

$$0.045\,per\ year\ \times 80\% = 0.036\,per\ year\ \rightarrow\ (\text{Category } 2)$$

The possibility of having results below regulatory concern:

$$0.045\ per\ year\ \times 100\% = 0.045\ per\ year\ \rightarrow\ (\text{Category } 2)$$

Results are illustrated in Table 6.37.

Table 6.37: Risk Evaluation Form of Weaving Department for Item 3

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
W-3	Weaving	Electrical control panels are blocked by materials standing in front of them.	In case of a fire, the scale of any accident may enlarge.	None	2	6	1	**3000**	**0,0034**	**10,2**
						5	1	300	0,0032	0,96
						4	1	30	0,0068	0,204
						3	1	0,3	0,0225	0,0068
						2	2	0,03	0,036	0,00108
						1	2	0,003	0,045	0,00014
Total Risk Weight										11,37

W-4:

Electrical equipments inside weaving department are not very well isolated. There is an intense amount of cotton dust present, electrical arcs may result in fire. To exemplify, there are weaving machines which produces fabric. These machines have lots of cotton fibres around. There are electrical cables of these machines. Several machines have cables which are not insulated. Plastic covers around cables are molten.

The event frequency is Category 5, as that of Item 2. This sort of fires is not expected to affect more than 10 people irreversibly. The frequency of influencing between 1 and 10 people irreversibly is predicted as very low (Category 1). Such fires will surely have effects below regulatory concern. Results are attached in Table 6.38.

Table 6.38: Risk Evaluation Form of Weaving Department for Item 4

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
W-4	Weaving	Electrical equipments inside weaving halls are not isolated well.	Electrical arcs may emerge from electrical equipment and they may cause fire.	None	5	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	2	0,03	0,06	0,0018
						1	5	0,003	0,2	0,0006
Total Risk Weight										0,61

W-5:

Cotton fibres present in weaving department are collected by dust collection canals which curl around weaving department and cotton mill. Fire occurs inside these canals very frequently, several times per month. However, employees in these departments are used to these types of fires, they know what to do. Moreover, it is easier to detect cotton fire because of its significant smell. Consequently, a major part of fires in dust collection canals are extinguished instantaneously.

There is a probability that the fire caught in weaving department spreads to cotton mill if it is not extinguished at once, because, cotton fibre collection canals link these departments. Inside canal intervention is not possible, therefore the scale of accident may enlarge immediately.

Frequency of such an event is determined as Category 3 as a result of inspecting incident statistics. Such an incident is not forecasted to affect more than 100 people (even though the fire spreads, firemen inside the manufacturing mill would intervene). However, there is a possibility that between 10 and 100 people may get irreversibly affected. This frequency is low, most probably employees would get out of halls. The frequency of between 1 and 10 people getting reversibly influenced is higher, which is demonstrated in Table 6.39.

Table 6.39: Risk Evaluation Form of Weaving Department for Item 5

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
W-5	Weaving	There are cotton fibers gather around dust collection canals.	In case of a fire inside these canals, the scale of fire may enlarge instantaneously as these canals curl around many halls.	None	3	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	1	30	0,02	0,6
						3	2	0,3	0,06	0,018
						2	3	0,03	0,2	0,006
						1	3	0,003	0,02	0,00006
Total Risk Weight										6,62

W-6:

There is a battery charging area for electrical equipments. This is an open place where there is intense amount of cotton fibres. The section is not isolated. Electrical arcs occur during battery charging and these arcs may cause cotton fibres to catch fire. Event frequency is determined as Category 3 as a result of interviews conducted with employees. This fire is not predicted to affect more than 10 people irreversibly. The results are demonstrated in Table 6.40.

Table 6.40: Risk Evaluation Form of Weaving Department for Item 6

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	A Consequence (1-6)	B Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
W-6	Weaving	Battery charging area is not closed and isolated and there are cotton fibers all around.	Cotton fibers may catch fire easily as it is probable that electrical arcs occur in the battery charging area.	None	3	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	2	0,3	0,06	0,018
						2	3	0,03	0,2	0,006
						1	3	0,003	0,2	0,0006
Total Risk Weight										0,62

6.4.6. Cotton Mill

CM-1:

Electricity cables in Cotton Mill are not very well isolated. Cotton fibres in the department may cause fire. The incident statistics revealed that event frequency is of Category 3 for the cotton mill. Such fires are not predicted to cause consequences of Category 5 and 6. The frequency of such an incident to affect between 1 and 10 people irreversibly is of Category 1. However, the likelihood of one people getting affected reversibly is higher as can be seen in Table 6.41.

Table 6.41: Risk Evaluation Form of Cotton Mill for Item 1

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	B Consequence (1-6)	A Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
CM-1	Cotton Mill	Electricity cables inside the cotton mill are not well isolated.	Electrical arcs may cause cotton fibres to catch fire.	Insufficient	3	6		3000		0
						5		300		0
						4	1	**30**	**0,02**	**0,6**
						3	1	0,3	0,02	0,006
						2	2	0,03	0,06	0,0018
						1	3	0,003	0,2	0,0006
Total Risk Weight										0,61

CM-2:

Cotton warehouse is only 20 m to the main chemical warehouse. In case a fire occurs inside cotton warehouse, it may affect chemical warehouse. The evaluation entails conditional probability. Such a fire has never occurred in cotton warehouse up to now. Cotton warehouse has sprinkle system to extinguish fire automatically. Spreading probability is assumed as 5%.

$$1/53\ per\ year\ \times 5\% = 0.25$$

(Event Frequency - Category 1)

The possibility of a spread to affect more than 100 people is assumed as 5%:

$$0.25\ per\ year \times 5\% = \ 0.0125\ per\ year \rightarrow \text{(Category 1)}$$

Likelihood of influencing between 10 and 100 people irreversibly is assumed as 10%:

$$0.25\ per\ year\ \times 10\% = 0.025\ per\ year\ \rightarrow \text{(Category 1)}$$

Probability of affecting between 1 and 10 people irreversibly is 15%:

$$0.25\ per\ year \times 15\% = 0.0375\ per\ year \rightarrow (\text{Category } 2)$$

Possibility of influencing between 1 and 10 people reversibly is assumed as 60%:

$$0.25\ per\ year\ \times 60\% = 0.15\ per\ year\ \rightarrow (\text{Category } 3)$$

Likelihood of affecting one people reversibly is 90%:

$$0.25\ per\ year\ \times 60\% = 0.225\ per\ year\ \rightarrow (\text{Category } 3)$$

Possibility of having results below regulatory concern:

$$0.25\ per\ year\ \times 100\% = 0.25\ per\ year\ \rightarrow (\text{Category } 3)$$

Results are shown in Table 6.42.

Table 6.42: Risk Evaluation Form of Cotton Mill for Item 2

Item No	**Activity Department**	**Activity / State Description**	**Risk Definition**	**Current Precaution**	**Frequency of Event**	**B Consequence (1-6)**	**A Frequency (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
CM-2	Cotton Mill	Cotton warehouse is very close to the main chemical warehouse.	Fire occuring inside cotton warehouse may affect chemical warehouse.	Insufficient	3	6	1	**3000**	**0,0125**	**37,5**
						5	1	300	0,025	7,5
						4	2	30	0,0375	1,125
						3	3	0,3	0,15	0,045
						2	3	0,03	0,225	0,0068
						1	3	0,003	0,25	0,000075
Total Risk Weight										46,2

CM-3:

Engines of machines heat up if they are not ventilated regularly and cotton fibres inside these machines catch fire. This happens very frequently, nearly once in a month. Employees in cotton mill are used to these fires and they extinguish them as soon as they occur. Thus, high consequences are not predicted for such fires. Evaluation results are presented in Table 6.43.

Table 6.43: Risk Evaluation Form of Cotton Mill for Item 3

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	B Consequence (1-6)	A Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
CM-3	Cotton Mill	Engines of machines are not ventilated regularly.	Engines of machines heat, cotton fibers which enter into the engines catch fire.	Insufficient	6	6		3000		
						5		300		
						4		30		
						3	1	0,3	0,02	0,006
						2	3	0,03	0,06	0,0018
						1	6	**0,003**	**6**	**0,018**
Total Risk Weight										0,03

CM-4:

Cotton bales contain metal wires around. Entrance ground for cotton bales is also made of metal. Metal pieces contact causes sparks and this ends up with fire of cotton bale. These fires occur very frequently, several times per month. As these fires only involve limited numbers of cotton bales, consequences are very low. Evaluation results are attached in Table 6.44.

Table 6.44: Risk Evaluation Form of Cotton Mill for Item 4

Item No	**Activity Department**	**Activity / State Description**	**Risk Definition**	**Current Precaution**	**Frequency of Event**	**B Consequence (1-6)**	**A Frequency (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
CM-4	Cotton Mill	The entrance ground where cotton bales enter is made of metal.	The contact of metal wires with the metal ground emerge sparks and cotton bales catch fire.	Insufficient	6	6		3000		0
						5		300		0
						4		30		0
						3		0,3		0
						2	1	0,03	0,02	0,0006
						1	6	**0,003**	**6**	**0,018**
Total Risk Weight										0,02

CM-5:

Cotton fibres gather around dust collection canals and catch fire. As these canals curl around many halls, the fire has a probability to spread. The evaluation is very similar to that of Item 5 of weaving department. Results are illustrated in Table 6.45.

Table 6.45: Risk Evaluation Form of Cotton Mill for Item 5

Item No	**Activity Department**	**Activity / State Description**	**Risk Definition**	**Current Precaution**	**Frequency of Event**	**B Consequence (1-6)**	**A Frequency (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
CM-5	Cotton Mill	There are cotton fibers gathered around the collection canals.	Dust / Fiber collection canals may catch fire.	Insufficient	3	6		3000		0
						5	1	**300**	**0,02**	**6**
						4	1	30	0,02	0,6
						3	2	0,3	0,06	0,018
						2	3	0,03	0,06	0,0018
						1	3	0,003	0,06	0,00018
Total Risk Weight										6,62

CM-6:

Forklifts working with electricity or with accumulator are used inside the cotton warehouse. Electrical arcs may emerge from these sources and cause fire. These fires are not predicted to have irreversible effects. This is due to the fact that there are not many employees in the cotton warehouse, there is automatic sprinkler system and the fire brigade of the plant is located nearby the cotton warehouse. Evaluation results are shown in Table 6.46.

Table 6.46: Risk Evaluation Form of Cotton Mill for Item 6

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	B Consequence (1-6)	A Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
CM-6	Cotton Mill	Fork lifts working with accumulator or electricity are utilized inside the cotton warehouse.	Electrical arcs may emerge. These arcs may cause fire.	Insufficient	2	6		3000		0
						5		300		0
						4		30		0
						3	1	**0,3**	**0,02**	**0,006**
						2	2	0,03	0,06	0,0018
						1	2	0,003	0,06	0,00018
Total Risk Weight										0,01

CM-7:

Pieces of metal wires around cotton bales sometimes accidentally enter into the machines. There is a huge magnet to remove these metals, however they may not be hold by the magnet and enter into the fan. When pieces of metals hit the fan, sparks are created and cotton fibres in the machine catch fire. According to the interview conducted by the facility employees, the frequency of event category is determined as 5. These fires occur very frequently and hence employees are used to such fires;

they immediately extinguish them. Therefore, these fires are not predicted to have irreversible effects as can be seen in Table 6.47.

Table 6.47: Risk Evaluation Form of Cotton Mill for Item 7

Item No	Activity Department	Activity / State Description	Risk Definition	Current Precaution	Frequency of Event	B Consequence (1-6)	A Frequency (1-6)	A Consequence (Weight)	B Frequency (Weight)	Risk Level A*B (Weight)
CM-7	Cotton Mill	Metal wire pieces which could not be eliminated with the magnet enter into the fan.	Metals rubbing to each other cause sparks. Cotton fibers may inside the machines may catch fire.	Insufficient	5	6		3000		0
						5		300		0
						4		30		0
						3	1	**0,3**	**0,02**	**0,006**
						2	2	0,03	0,06	0,0018
						1	5	0,003	2	0,006
Total Risk Weight										0,01

Risk value is the same for Consequence Category 3 and 1. While ranking these risks, the one with the higher consequence will be of higher attention.

6.4.7. Cogeneration Unit

CU 1:

Natural gas fed into the cogeneration unit via the pipelines. Natural gas pipelines may leak natural gas and jet fire could occur. It is assumed that full bore rupture rate is 0.6/m pmpy [96]. Assuming that length of the pipeline is 5 km:

$$\frac{0.6}{1000000\,m}\,per\ year\ \times 5000\,m = 0.003\,per\ year\ \text{(Gas leak frequency)}$$

Even though there is a gas detection system and ignition sources are prevented, the leaked gas may catch fire. Gas detection system failure may occur or human error or any other type of failure may cause an ignition. This probability is assumed as 10%.

$$0.003\ per\ year\ \times 10\% = 0.0003\ per\ year$$

(Event frequency for jet fire – Category 1)

The likelihood of a jet fire to affect more than 100 people irreversibly is assumed as 40%:

$$0.0003\ per\ year\ \times 40\% = 0.00012\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The likelihood of a jet fire to influence between 10 and 100 people irreversibly is assumed as 70%:

$$0.0003\ per\ year\ \times 70\% =\ 0.00021\ per\ year \rightarrow\ \text{(Category 1)}$$

The possibility of influencing between 1 and 10 people irreversibly is assumed as 90%:

$$0.0003\ per\ year\ \times 90\% = 0.00027\ per\ year \rightarrow\ \text{(Category 1)}$$

The probability of affecting between 1and 10 people reversibly is 99%:

$$0.0003\ per\ year\ \times 99\% = 0.000297\ per\ year\ \rightarrow\ \text{(Category 1)}$$

The likelihood of having results below regulatory concern is 100%:

$$0.0003\ per\ year\ \times 100\% = 0.0003\ per\ year \rightarrow\ \text{(Category 1)}$$

Values above are assumed in order to have a picture of present risk. However, jet fire may have devastating results on the public. Therefore, elaborate analysis on the risk is necessary. It is important to decide the dimensions of the flaming cloud, because it can be said that fatality will be observed 100% in the cloud [96]. Results are attached in Table 6.48.

Table 6.48: Risk Evaluation Form of Cogeneration Unit for Item 1

<table>
<tr><th>Item No</th><th>Activity Department</th><th>Activity / State Description</th><th>Risk Definition</th><th>Current Precaution</th><th>Frequency of Event</th><th>A Consequence (1-6)</th><th>B Frequency (1-6)</th><th>A Consequence (Weight)</th><th>B Frequency (Weight)</th><th>Risk Level A*B (Weight)</th></tr>
<tr><td rowspan="6">CU-1</td><td rowspan="6">Cogeneration Unit</td><td rowspan="6">Natural Gas is delivered to cogeneration unit via pipelines.</td><td rowspan="6">Natural gas could leak from the pipelines and jet fire could occur.</td><td rowspan="6">Insufficient</td><td rowspan="6">1</td><td>6</td><td>1</td><td>3000</td><td>0,00012</td><td>0,36</td></tr>
<tr><td>5</td><td>1</td><td>300</td><td>0,00021</td><td>0,063</td></tr>
<tr><td>4</td><td>1</td><td>30</td><td>0,00027</td><td>0,00081</td></tr>
<tr><td>3</td><td>1</td><td>0,3</td><td>0,000029</td><td>0,0000087</td></tr>
<tr><td>2</td><td>1</td><td>0,03</td><td>0,0000297</td><td>0,00000089</td></tr>
<tr><td>1</td><td>1</td><td>0,003</td><td>0,0003</td><td>0,0000009</td></tr>
<tr><td>Total Risk Weight</td><td colspan="9"></td><td>0,42</td></tr>
</table>

CU-2:

Natural gas may leak from pipeline and gather inside the cogeneration unit without notice. Upon contact with an ignition source, Vapour Cloud Explosion may occur. For VCE to take place, gas detection system should not work appropriately. It is assumed that the possibility of this failure is 5% [96].

Unfortunately, there is no ventilation system inside the cogeneration unit, which increases the chance of vapour cloud gathering in. Even though there is no ignition sources present upon gathering of the cloud, VCE will most probably occur. This is because turbines may have hot surfaces above auto-ignition temperature [97].

$$0.003 \; per \; year \; \times 0.05 = \; 0.00015 \; per \; year$$

The likelihood of a jet fire to affect more than 100 people irreversibly is assumed as 50% because VCE is more destructive than jet fire:

$$0.00015\, per\ year\ \times 50\% = 0.00075\, per\ year\ \rightarrow\ (\text{Category } 1)$$

The likelihood of a jet fire to influence between 10 and 100 people irreversibly is assumed as 70%:

$$0.00015\, per\ year\ \times 80\% =\ 0.00012\, per\ year\ \rightarrow (\text{Category } 1)$$

The possibility of influencing between 1 and 10 people irreversibly is assumed as 95%:

$$0.00015\, per\ year\ \times 95\% = 0.000143\, per\ year \rightarrow\ (\text{Category } 1)$$

The probability of affecting between 1and 10 people reversibly is 99%:

$$0.00015 per\ year\ \times 99\% = 0.000149\, per\ year \rightarrow\ (\text{Category } 1)$$

The likelihood of having results below regulatory concern is 100%:

$$0.00015\, per\ year\ \times 100\% = 0.00015\, per\ year \rightarrow\ (\text{Category } 1)$$

The results are illustrated in Table 6.49.

Table 6.49: Risk Evaluation Form of Cogeneration Unit for Item 2

Item No	**Activity Department**	**Activity / State Description**	**Risk Definition**	**Current Precaution**	**Frequency of Event**	**A Consequence (1-6)**	**B Frequency (1-6)**	**A Consequence (Weight)**	**B Frequency (Weight)**	**Risk Level A*B (Weight)**
CU-2	Cogeneration Unit	Natural Gas is delivered to cogeneration unit via pipelines.	Natural gas may leak and vapour cloud explosion may occur.	Sufficient	1	6	1	**3000**	**0,00075**	**2,25**
						5	1	300	0,00012	0,036
						4	1	30	0,000143	0,0043
						3	1	0,3	0,00014	0,000042
						2	1	0,03	0,000149	0,0000045
						1	1	0,003	0,00015	0,00000045
Total Risk Weight										2,29

VCE may result in severe destruction. Therefore, it is very important to determine the radius of effect via mathematical modelling to decide its consequences. Overpressure vs. distances should be calculated to decide on the severity of outcomes so that decision on taking necessary precautions can be made accordingly.

6.5. Risk Matrix

Risk matrix is formed as a result of the so as to rank present risks in the denim manufacturing plant. The ranking is conducted according to consequence and frequency categories of hazardous events. Risk matrix is demonstrated in Figure 6.1 can clearly be seen, risk items are ranked as very low and low. Highest risks are identified as dust explosion, natural gas explosion, natural gas jet fire and the enlargement of scale in case of a fire or explosion.

Likelihood values which are calculated via conditional probability reveal better risk estimation (can be seen in MW-10, MW-12, F-4, F-5, F-7, S-2, W-3, CM-2, CU-1, CU-2). However, due to the low resolution of categorization, the calculated different risk values will be reflected in the same categories. This necessitates a higher resolution in risk assessment studies for better results.

Frequency Category	Frequency Weight (py)						
6	6	CM-3, CM-4					
5	2						
4	0,6						
3	0,2						
2	0,06						
1	0,02			MW-6, MW-7, I-2, CM-6, CM-7	MW-1, MW-2, MW-3, MW-8, MW-11, F-2, F-3, F-6, I-3, I-4, I-5, W-1, W-4, W-6, CM-1,	MW-9, F-1, F-5, F-7, F-8, I-6, S-1, W-2, W-5, CM-5	MW-4, MW-5, MW-10, MW-12, F-4, I-1, S-2, S-3, S-4, W-3, CM-2, CU-1, CU-2
Consequence Weight (10^3 \$)		0,003	0,03	0,3	30	300	3000
Consequence Category		1	2	3	4	5	6

Figure 6.1: Risk Matrix for the Manufacturing Plant

Risk Distribution among Manufacturing Plant

Mathematical risk value for each department is different. Sum of all items in a department will give the risk value of this department. Hence, comparison between different departments in the mill would then be possible. Figure 9.12 which illustrates risk values of departments is below.

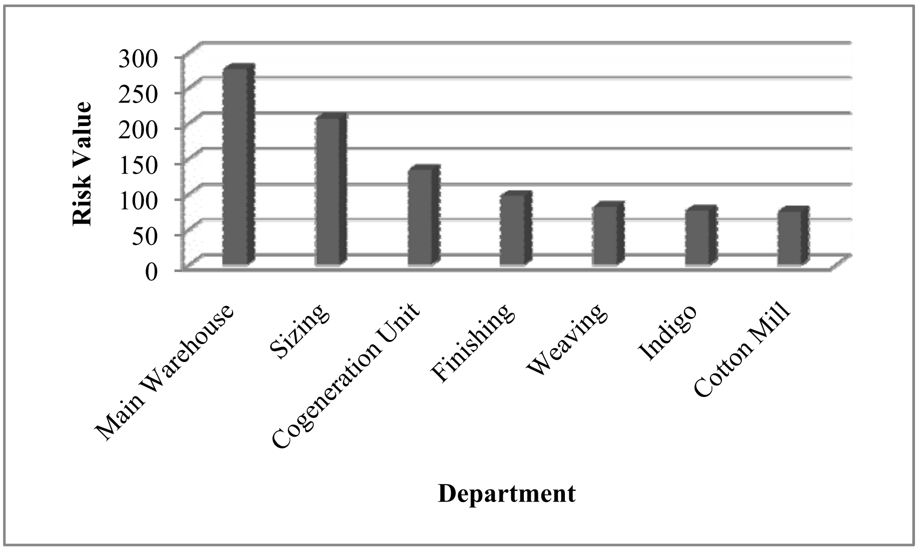

Figure 6.2: Comparison of risk values for departments of the plant

According to Figure 6.2, the highest risks are observed in the main warehouse. This is an expected result, because there are many chemicals stored, also electrical forklifts are used. The scale of a fire or explosion in the main warehouse is predicted to be large.

$$Aggregate\ Facility\ Risk\ = \sum Departmental\ Risks$$

Risk evaluation forms in Appendix B give event risks defined for each activity/situation. While utilizing these forms, estimated risk values are calculated by multiplication of consequence and frequency values. These values are statistical average values of the consequence and frequency spectrums. Facility aggregate risk is the summation of all event risks in all departments.

$$Aggregate\ Risk\ =\ 497{,}260\ \$/year$$

In this study numerical risk value is expressed as $/year; meaning that if the activities/situations posing a risk in terms of fire and explosion continue as they are till the infinity, i.e. no mitigation measure is implemented, the cost of the risk may be up to 497,260 $/year.

Risk is not expressed as fatality per year in this study, as there may also be injuries. Fatalities, injuries and damage to buildings are composed in $/year unit to illustrate the cost facility should pay to compensate the risk.

6.6. Suggested Precautions to Reduce Risk

Suggestions to reduce present risk levels are suggested to the facility management. Suggestions were specific to each activity/situation. These suggestions are also inserted in risk evaluation forms which are present in Appendix B.

Some of them are realized immediately. For example, chemical information sheets were places on each chemical shelf, safety training brochures were delivered to the employees and the visitors of the plant, chemical storage inside the warehouses were changed according to the chemical properties and dust accumulation was minimized via good housekeeping methods.

Current risk level of the plant is likely to be different than the risk level found as a result of this study, considering some suggestions are already implemented. Risk assessment and risk management for continual improvement necessitates repetition of the risk assessment regularly. This would give the opportunity of observing the suggestions on risk levels. Observation results may serve as a tool for decision makers as well as a cost-benefit analysis towards the cost of the present risk and the implementation of suggestions.

Suggestions to decrease risk level are built up specific to the plant. However, several of them could be used in various industries. Hence, these suggestions could be generalized and used in order to decrease risk levels in several industries. For example, the dust minimization principle could be used to prevent dust explosion in any industry handling dust.

CHAPTER 7

MATHEMATICAL MODELLING FOR HIGHEST RISKS

In this study, there are causes (like the presence of an ignition source) which triggers the intrinsic hazards (like flammability) to events (like dust explosion); these are all expressed in risk evaluation forms. Intermediate consequences as a result of this event (like the overpressure) and final consequences of interest (like the physical effects on people) are inspected in this study.

Risks are ranked with the risk matrix. In order to use the matrix, six categories were used for the consequence and frequency categories. Therefore, differentiation between very low risks could not be shown. Highest risks are determined as a result of risk matrix. Even though these risks are very low, the consequences will be modelled by mathematical models for the sake of public safety.

Highest risks in the plant are determined as a result of semi-quantitative risk assessment. These are dust explosion risk, natural gas jet fire risk, natural gas vapour cloud explosion risk and the risk of enlargement of a fire or explosion. Among these, dust explosion, vapour cloud explosion and jet fire can be mathematically modelled. In this chapter, they will be modelled based on different scenarios.

Modelling chapter is mainly composed of three segments. First, dust explosion in the main warehouse, sizing and indigo departments will be derived. Then, natural gas jet fire will be modelled and effects of natural gas vapour cloud explosion will be calculated.

7.1. Dust Explosion Modelling

Dust explosion may occur in main warehouse, sizing department and indigo department where starch and indigo dusts are utilized. In this study, different scenarios are developed for dust explosion modelling. These scenarios and effects of modelled scenarios will be given in this section. TNT Equivalence model will be used to model the overpressure effects of the dust explosion.

7.1.1. Main Warehouse

Two scenarios are developed for dust explosion modelling in the main warehouse. The first scenario is based on bursting one starch package. Explosion yield is used as 0.1 as EPA suggests [69]. Explosion yield of 0.03 is also used, but this scenario can be found in Appendix C. Second scenario is based on bursting 10 packages of starch upon the forklift falling down. Second scenario is also in Appendix C.

If only one package of starch is dropped, then 25 kg of starch would be spilled. Based on the assumption 1/5 of 25 kg of starch would form a cloud within the explosive concentration range:

$$M_{starch,dispersed} = 5 \text{ kg}$$
$$Q_{starch} = 17570 \text{ J/g}$$

The volume inside which starch will be dispersed will be smaller if only one package of starch is involved. This volume is assumed to be less than 1/10 of the main warehouse volume, as the amount of starch is much less. Dispersion volume is assumed as 1/30 of warehouse volume.

If 5 kg of starch is dispersed in main warehouse, with a volume of 3760 m^3; it would be dispersed in a space of approximately 125.3 m^3 then the dispersed starch concentration would be:

$\frac{5\times10^3 g}{125.3\ m^3} \cong 39.9\ \mathrm{g/m^3}$, which is above the lower explosion limit [57]

Calculation of side-on overpressure of a dust explosion resulting from 25 kg of starch inside the main warehouse is conducted. Assuming an explosion yield of 0.1, the equivalent charge weight of TNT is 1.88 kg. Overpressure effects can be read from the Hopkinson-scaled TNT charge blast graph in Figure E.1 in Appendix E. The results are shown in Table 7.1.

Table 7.1: Corresponding values of distance and pressure

Real Distance (m)	**Log Real Distance**	**Side-on Overpressure (bar)**	**Dimensionless Overpressure**	**Log Dimensionless Pressure**
5	0.70	0.6	0.59	-0.23
10	1.00	0.2	0.2	-0.70
22	1.34	0.07	0.07	-1.15
25	1.40	0.056	0.033	-1.48
30	1.48	0.048	0.028	-1.55
50	1.70	0.023	0.015	-1.82
84	1.92	0.013	0.013	-1.89

Distance vs. overpressure values are illustrated in Figure 7.1.

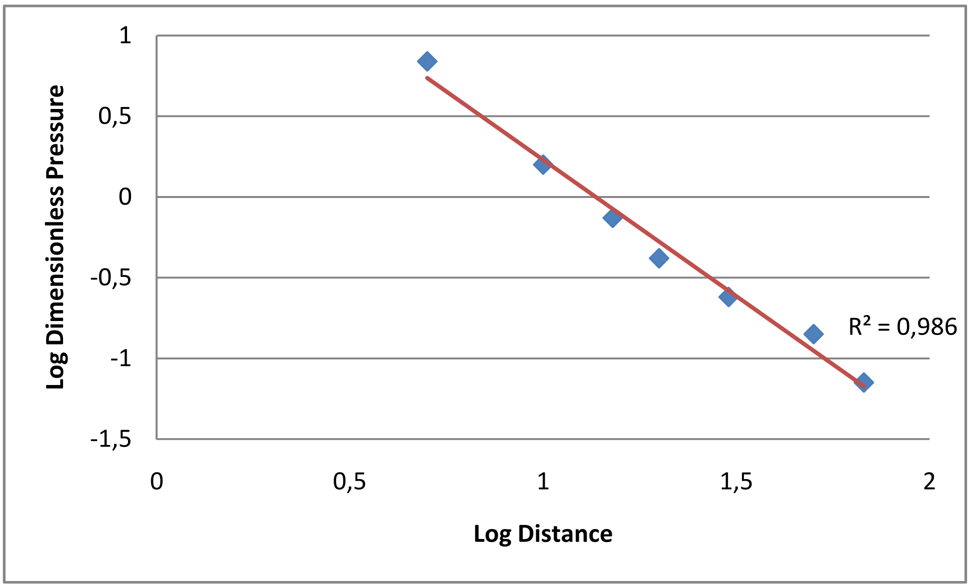

Figure 7.1: Side-on overpressure vs. distance

Based on the information in this table, results of modelled starch explosion where 5 kgof starch is involved in dust explosion with an explosion yield of 0.1 are illustrated in Table 7.2. Overpressure values here enable us for the vulnerability modelling.

Table 7.2: Summary results of modelled explosion

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
5	0.6	Collapse of buildings Probable serious injury or fatality of some occupants
10	0.2	Local failure of isolated parts of buildings and collapse of unreinforced masonry load bearing wall buildings Possible serious injury or fatality of some occupants

Table 7.2: Summary results of modelled explosion (cont'd)

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
22	0.07	Possible minor structural damage to buildings and severe damage to unreinforced masonry load-bearing wall buildings Possible serious injury or fatality to some occupants
30	0.048	Significant repairable cosmetic damage is possible Possible occupant injury from glass breakage and falling overhead fixtures
50	0.023	Threshold of glass breakage No injury to occupants
84	0.013	Below regulatory concern

According to Table 7.2, such an explosion is likely to kill workers within 22 m and destroy the buildings within the radius. Injury is potential at a distance of 30 m. Glass breakage threshold is exceeded up to a distance of 84 m.

7.1.2. Sizing Department

As indicated before, starch packages are carried by hand in sizing department. Therefore, one starch package bursting is modelled in sizing department. Accumulated dust exists in this department, hence effects of a secondary explosion is also modelled in this scenario. Explosion yield is taken as 0.1 as EPA suggests [69]. Dimensions of sizing department are shown in Figure 7.2.

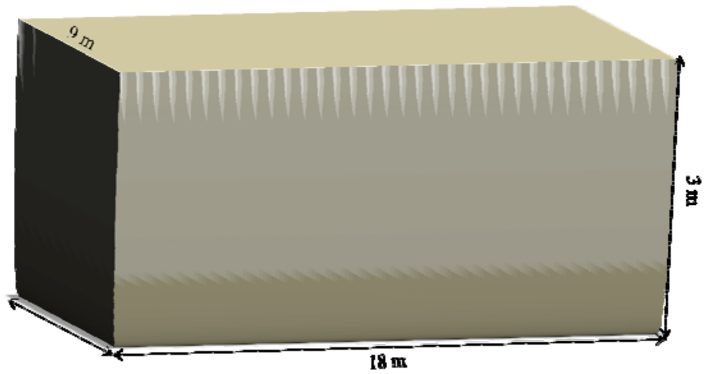

Figure 7.2: Dimensions of sizing department

$\forall_s = 9\ m\ \times 3m\ \times 18\ m = 486\ m^3$

It is assumed that 25 kg of one starch bag bursts and 1/5 of that starch is dispersed in the sizing department forming a cloud in the explosive concentration range. The volume in which starch dispersed is taken as 1/6 of the sizing department volume. This is assumed to be 1/6 as the volume of sizing department is not as big as volume of main warehouse; dispersed starch would instantaneously cover a significant portion of the department. Hence, the volume of dispersion is taken as 81 m^3 in the calculation.

$\frac{M_{starch,dispersed}}{\forall_{air}} = \frac{25/5\ kg}{486/6\ m^3} \cong 0.062 \frac{kg}{m^3} = 62\ g/m^3$ → above Lower Explosive Limit of starch

To calculate the overpressure effects of explosion, TNT equivalency method is used and to model the worst scenario, the yield factor is used as 0.1 as US EPA suggests and TNT Equivalence mass is calculated as 1.88 kg. Overpressure values with respect to different distances are read from Hopkinson scaled TNT charge blast graph in Figure E.1 in Appendix E. Results of this model is given in Table 7.3.

Table 7.3: Corresponding values of distance and pressure

Real Distance (m)	**Log Real Distance**	**Side-on Overpressure (bar)**	**Dimensionless Overpressure**	**Log Dimensionless Pressure**
1.5	0.18	9	8.88	0.95
3	0.48	2	1.97	0.29
5	0.70	0.66	0.65	-0.19
10	1.00	0.21	0.21	-0.68
22	1.34	0.07	0.07	-1.15
80	1.90	0.013	0.013	-1.89

Real distances and overpressure values are illustrated in Figure 7.3.

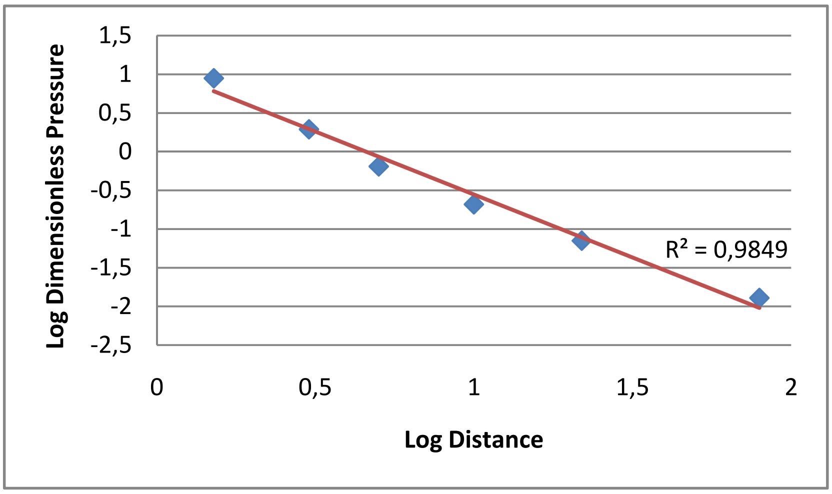

Figure 7.3: Side-on overpressure vs. distance

Table 7.4 summarizes probable results of the modelled explosion of 5 kg starch in sizing department with an explosion yield 0.1.

Table 7.4: Summary results of modelled explosion

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
1.5	9	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
3	2	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
5	0.66	Collapse of buildings Probable serious injury or fatality of some occupants
10	0.21	Collapse of buildings Probable serious injury or fatality of some occupants
22	0.07	Possible minor structural damage to buildings and severe damage to unreinforced masonry load-bearing wall buildings Personnel injury from debris is likely
80	0.013	Below regulatory concern

According to Table 7.4, such an explosion is likely to kill workers within the boundaries of the sizing department. Injuries may occur within a radius of 22 m. The effects of such an explosion may be present up to 80 m.

Such an explosion is also likely to resuspend the dust layers inside the space, i.e., a secondary dust explosion may occur. The amount of dust which is gathered as deposited dust layers are calculated below:

The area of the ground and edges can be calculated as follows:

$$\forall_g = 18\,m \times 9m = 162\,m^2$$

The edges and the sides cover approximately 1/8th of the department area:

$$\forall_e = 18\,m \times 9m \times \frac{1}{8} = 20.25\,m^2$$

Floor of sizing department is assumed to contain 1 mm of starch dust. Also, the edges and sizes which are not easily cleaned regularly may hold a starch dust up to 2 mm. Then, the volume of starch dust which is gathered inside the sizing department could be calculated as below:

$$\forall_{starch,ground} = 162\,m^2 \times \frac{1\,mm}{1000\,mm/m} = 0.162\,m^3$$
$$\forall_{starch,edges} = 20.25\,m^2 \times \frac{2\,mm}{1000\,mm/m} = 0.0405\,m^3$$
$$\forall_{starch,total} \cong 0.2025\,m^3 = 202.5\,L$$

Bulk density of starch is between 600 – 700 g/L [57]. To assume the worst scenario, bulk density of starch is taken as 700 g.

$$M_{starch} = 202.5\,L \times 700\ g/L = 141750\,g \cong 142\,kg$$

It is assumed that all resuspended starch is fully dispersed in the air. Hence, weight of fuel in the cloud, W_f is equal to 142 kg. Upon resuspension in the sizing department volume, the concentration of dust may be far beyond the Lower Explosive Limit as it is illustrated below:

$$C_{starch} = \frac{M_{starch,settled}}{\forall_{sizing\ department}} = \frac{142\,kg}{486\,m^3} = 0.292\,\frac{kg}{m^3} = 292\,g/m^3$$

TNT Equivalence Model will be used and in order to model the worst scenario, the yield factor will be used as 0.1 as US EPA suggests. TNT Equivalent mass is calculated as 53.31 kg. Overpressure values at different distances are read from Hopkinson scaled TNT charge blast graph in Figure E.1 in Appendix E. The results of modelling 142 kg (it is assumed that all resuspended starch is fully dispersed in the air) of dust explosion is presented in Table 7.5.

Table 7.5: Corresponding values of distance and pressure

Real Distance (m)	**Log Real Distance**	**Side-on Overpressure (bar)**	**Dimensionless Overpressure**	**Log Dimensionless Pressure**
5	0.7	7.1	6.88	0.84
10	1.0	1.6	1.58	0.20
15	1.18	0.75	0.74	-0.13
20	1.30	0.43	0.42	-0.38
30	1.48	0.24	0.24	-0.62
50	1.70	0.14	0.14	-0.85
68	1.83	0.07	0.07	-1.15
260	2.41	0.013	0.013	-1.89

Real distances and overpressure values are illustrated in Figure 7.4.

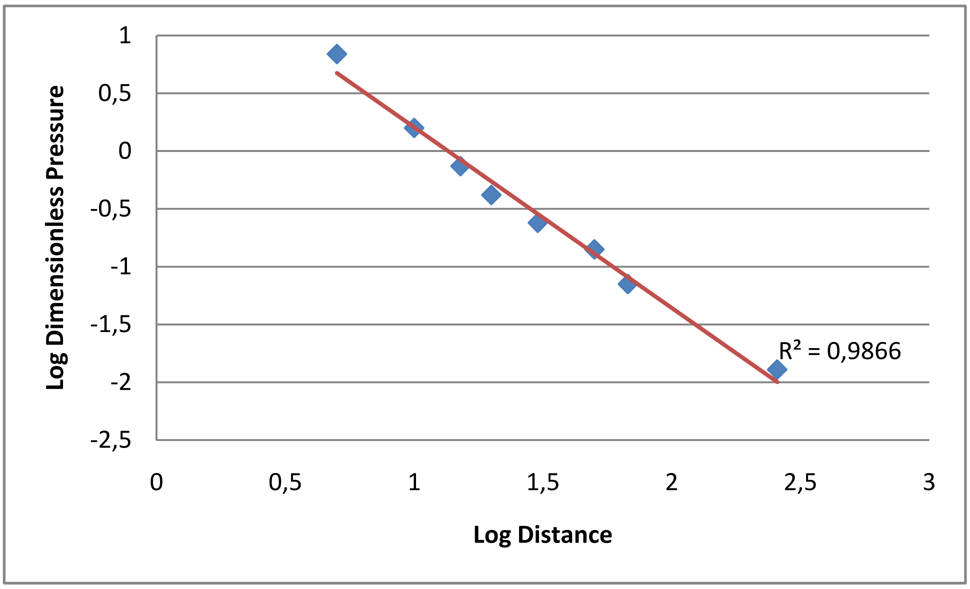

Figure 7.4: Side-on overpressure vs. distance

Table 7.6 summarizes probable results of the modelled starch explosion.

Table 7.6: Summary results of modelled explosion

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
5	7.1	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
15	0.75	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
30	0.24	Collapse of buildings Probable serious injury or fatality of some occupants

Table 7.6: Summary results of modelled explosion (cont'd)

Real Distance (m)	Overpressure (bar)	Probable Effect
50	0.14	Local failure of isolated parts of buildings and severe damage to unreinforced masonry load bearing wall buildings Possible serious injury or fatality of some occupants
68	0.07	Possible minor structural damage to buildings and severe damage to unreinforced masonry load-bearing wall buildings Personnel injury from debris is likely
260	0.013	Below regulatory concern

According to Table 7.6, such an explosion is much more destructive than primary dust explosion, having a larger radius of effect. It is likely to kill workers within 50 m, which is far beyond the boundaries of the denim manufacturing plant. Such an explosion could also affect the industrial zone and other textile mill which in vicinity. Injury can occur within a radius of 68 m. The effects of overpressure (glass breakage breakthrough point) reach upto 260 m

7.1.3. Indigo Department

As indicated before indigo dust is used to prepare indigo mixture. Indigo solution is prepared in a tank and indigo dust is added to this tank manually. Therefore, the scenario is based on a package of indigo dust bursting. Explosion yield will be used as 0.1 as EPA suggests [69].

Sulphur dust, which is among the most explosive industrial dusts, is intensely used in indigo department. In the following modelling, it is assumed that one package of indigo dust bursts.

$M_{indigo} = 25\ kg$

When indigo is dispersed in the section where indigo solution is prepared in the tank, it is assumed that 1/5 of this dust is well dispersed.

$M_{indigo,dispersed} = 5\ kg$

Volume of the space where indigo solution is prepared is approximately 24 m^3. Dust dispersion is assumed to occur within 6 m^3 of that volume. It is important to check whether the dust concentration is above Lower Explosive Limit which is specific to sulphur dust.

Lower Explosive Limit = 30 g/m^3
Upper Explosive Limit = 1400 g/m^3 [61, 62]

$C_{sulphur} = \frac{5\ kg}{6\ m^3} \cong 0.83\ kg/m^3\ = 830\ g/m^3$, Concentration of sulphur is between Lower and Upper Explosive Limits for Sulphur. To calculate the overpressure effects of explosion, TNT equivalency method will be used.

H_f for sulpur is 9.324 MJ/kg [63]

TNT Equivalent mass is calculated as 0.996 kg. Overpressure values at certain distances can be read from Hopkinson scaled TNT charge blast graph in Appendix E. Corresponding distance and pressure values are listed in Table 7.7.

Table 7.7: Corresponding values of distance and pressure

Real Distance (m)	Log Real Distance	Side-on Overpressure (bar)	Dimensionless Overpressure	Log Dimensionless Pressure
2	0.3	2.75	2.71	0.43
4	0.6	0.7	0.69	-0.16
10	1	0.16	0.16	-0.80
18	1.26	0.07	0.07	-1.15
20	1.30	0.06	0.06	-1.22
65	1.81	0.013	0.013	-1.89

Real distances and overpressure values are illustrated in Figure 7.5.

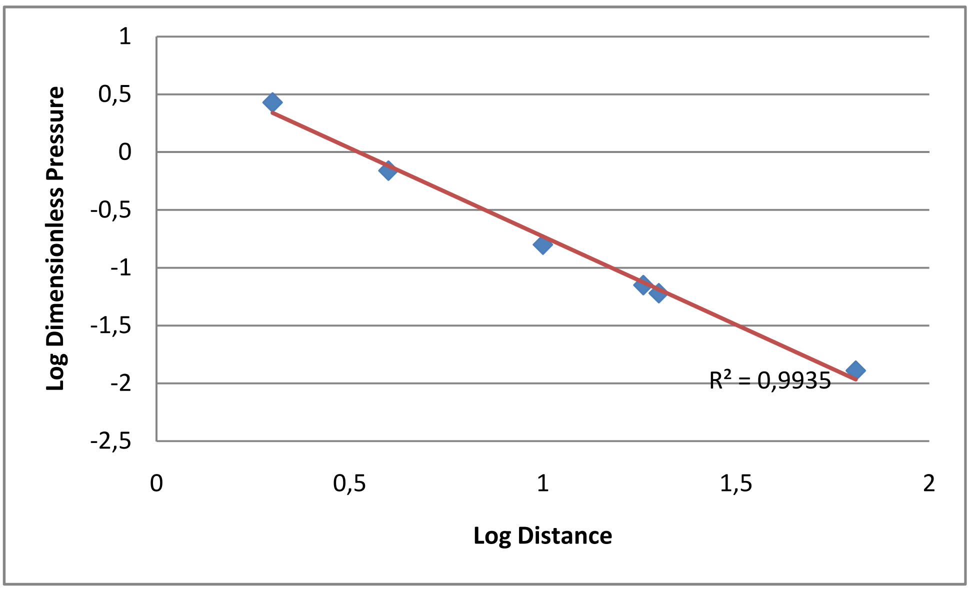

Figure 7.5: Side-on overpressure vs. distance

Table 7.8 summarizes probable results of the modelled starch explosion:

Table 7.8: Summary results of modelled explosion

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
2	2,75	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
4	0,7	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
10	0,16	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
20	0,07	Local failure of isolated parts of buildings and collapse of un-reinforced masonry load-bearing wall buildings Possible serious injury or fatality of some occupants
65	0,013	Below regulatory concern

According to Table 7.8, an indigo explosion would result in building destruction and fatalities within 20 m of effect radius. As indigo department is not a place where indigo dust is visibly gathered, a secondary explosion is not modelled for indigo department.

7.2. Natural Gas Jet Fire

Natural gas is composed of methane, ethane, propane, butane, carbon dioxide, oxygen, nitrogen, hydrogen sulphide and rare gases. As 70-90% of natural gas is methane. In its purest form, natural gas is approximately pure methane. Hence, natural gas modelling can be conducted via assuming natural gas as pure methane [100].

It is assumed that there occurs a pipe rupture inside cogeneration unit of the manufacturing plant, and natural gas starts to leak. There are two possibilities, natural gas could catch fire and result in a jet fire or the gas could fill the cogeneration department and lead to explosion. This modelling is conducted via the software programme ALOHA. There will be two scenarios, one is for high temperature average value and the other is for low temperature average value so as to show whether there is a difference in jet fire effects with respect to seasonal changes.

In order to model jet fire with ALOHA, certain input values should be provided for the software programme. Once the programme is run, it is necessary to select the location of the event as illustrated in Figure 7.6.

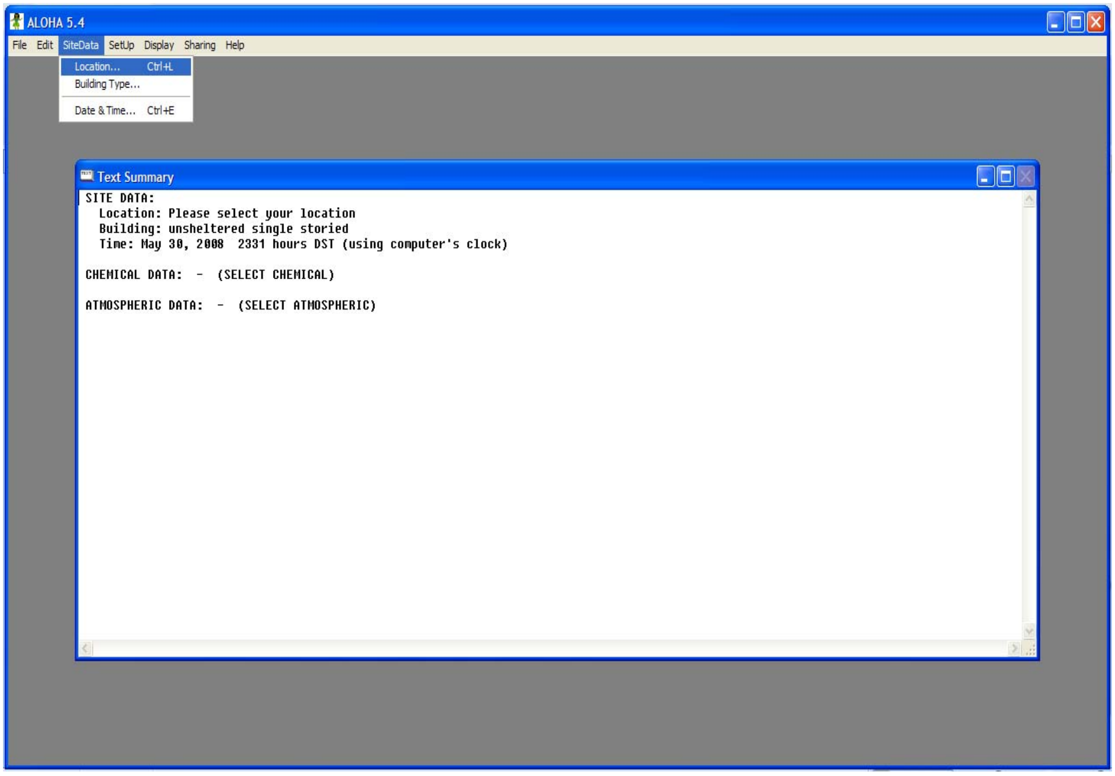

Figure 7.6: User interface of ALOHA software programme

Location input values for Kayseri where the plant is located are:

Elevation = 1043 m [101]

Coordinates = 38° 44′ 0″ N, 35° 29′ 0″ E [102]

After the data entry, location is selected as Kayseri. Then, atmospheric data are entered into the program as indicated in Figure 7.7.

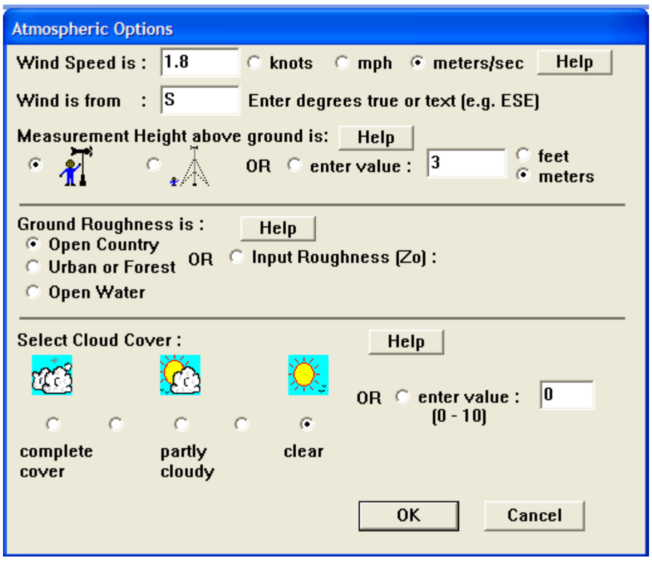

Figure 7.7: Atmospheric Data Entry to ALOHA software programme

Average wind speed in Kayseri is 1.8 m/s. The wind is mostly from south [103]. The plant is on open country and it is assumed that the day of the explosion is partly cloudy. Second part of data entry requires temperature values. Highest temperature values are observed in Kayseri during April, May, June, July, August and September. Lowest temperature values are observed during October, November, December, January, February and March. Average temperature between April to September is calculated as 17.5 ^{o}C and average temperature between October and March is calculated as 3.1 ^{o}C [104]. Modelling will be based on two different scenarios according to both temperature values.

Modelling for High Temperature Average Value

In the second part of the atmospheric data entry, temperature is selected as 17.5 ^{o}C, Stability Class is assumed to be F and Humidity is taken as medium, demonstrated in Figure 7.8.

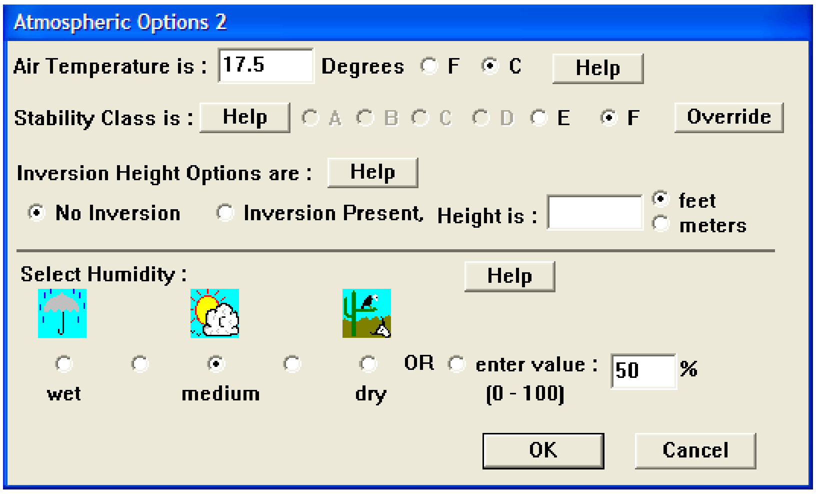

Figure 7.8: Data entry of atmospheric values

Chemical to be used in the modelling is selected as methane. Source of methane is entered as gas pipeline. Figure 7.9 shows the input information.

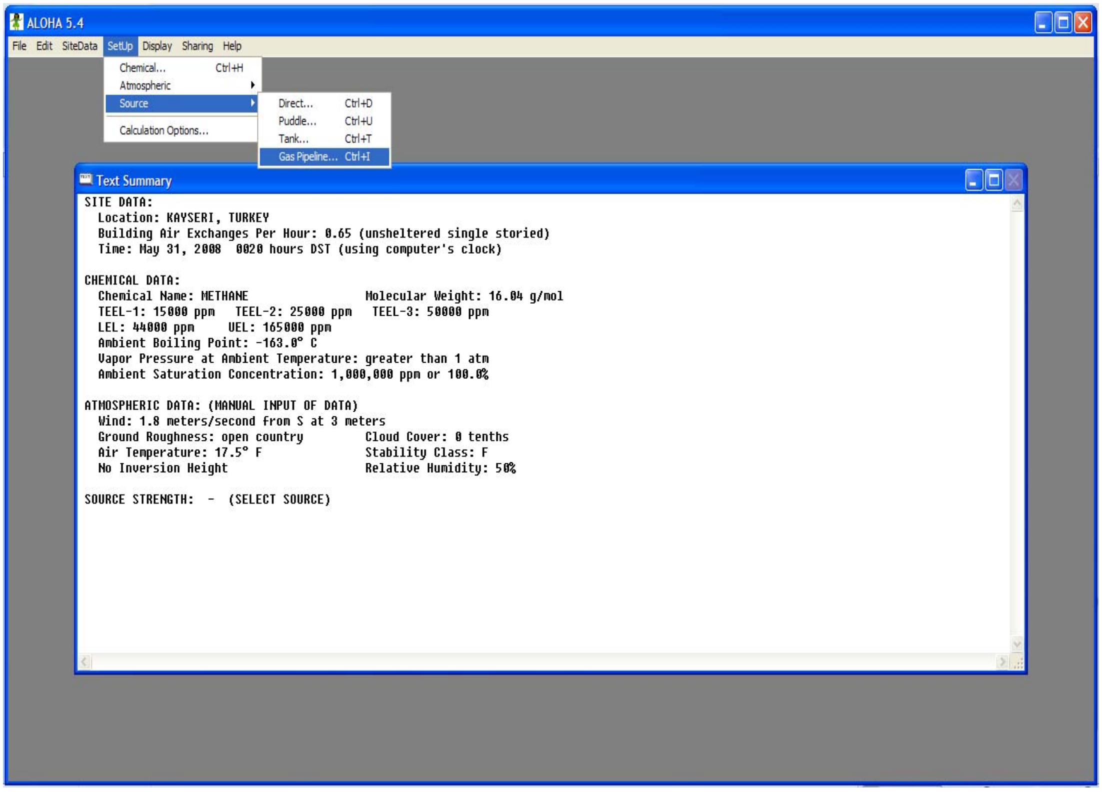

Figure 7.9: Input information regarding to jet fire modelling of methane

Model allows the user to prefer either methane which is not burning or jet fire of methane leak. When jet fire modelling is selected, the user interface is as shown in Figure 7.10.

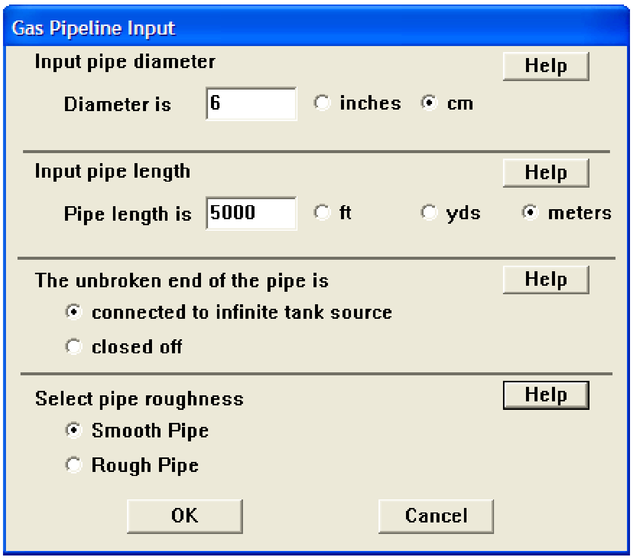

Figure 7.10: Input to be supplied by user for jet fire from natural gas pipeline rupture

Diameter of pipeline to carry natural gas to the cogeneration unit is approximately 6 cm. Pipe length from the section of the pipe where there is a whole till the natural gas supply point is assumed as 5 km. It is also assumed that the pipeline is not closed off, but connected to an infinite source, so that the worst case scenario can be modelled. Pipe roughness is selected as natural gas network was installed a few years ago and they may be assumed as non-corroded smooth pipes.

In Turkey, natural gas enters into the cities at 20 bar, it is further decreased for household consumption, but industrial natural gas pressure is mostly 20 bar if there is not a pressure regulator [105]. This value is rather low compared to 60 bar pressure of similar power plants in other regions of the world [106]. Temperature of the natural gas is considered to be at Standard Temperature and Pressure (STP), hence the temperature input is 16 ^{o}C as can be seen in Figure 7.11.

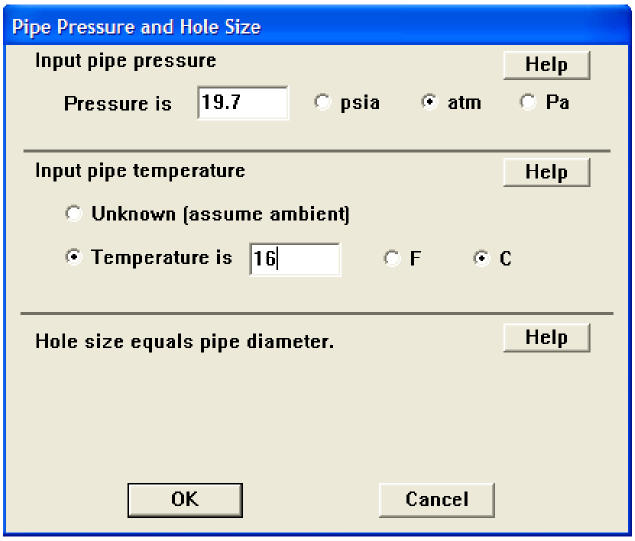

Figure 7.11: Pipe Pressure and Hole Size input entry

To model the worst case scenario, it is assumed that there is a full bore (guillotine) rupture in the pipeline. Figure 7.12 shows the text summary of the modelling.

```
Text Summary
SITE DATA:
  Location: KAYSERI, TURKEY
  Building Air Exchanges Per Hour: 0.65 (unsheltered single storied)
  Time: May 31, 2008  0020 hours DST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: METHANE                  Molecular Weight: 16.04 g/mol
  TEEL-1: 15000 ppm   TEEL-2: 25000 ppm   TEEL-3: 50000 ppm
  LEL: 44000 ppm     UEL: 165000 ppm
  Ambient Boiling Point: -163.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 1.8 meters/second from S at 3 meters
  Ground Roughness: open country         Cloud Cover: 0 tenths
  Air Temperature: 17.5° F               Stability Class: F
  No Inversion Height                    Relative Humidity: 50%

SOURCE STRENGTH:
  Flammable gas is burning as it escapes from pipe
  Pipe Diameter: 6 centimeters           Pipe Length: 5000 meters
  Unbroken end of the pipe is connected to an infinite source
  Pipe Roughness: smooth                 Hole Area: 28.3 sq cm
  Pipe Press: 19.7 atmospheres           Pipe Temperature: 16° C
  Max Flame Length: 5 meters
  Burn Duration: ALOHA limited the duration to 1 hour
  Max Burn Rate: 558 kilograms/min
  Total Amount Burned: 1,230 kilograms
```

Figure 7.12: Text summary of jet fire resulting from natural gas leak

Thermal radiation threat zone of such a jet fire could be seen in Figure 10.25.

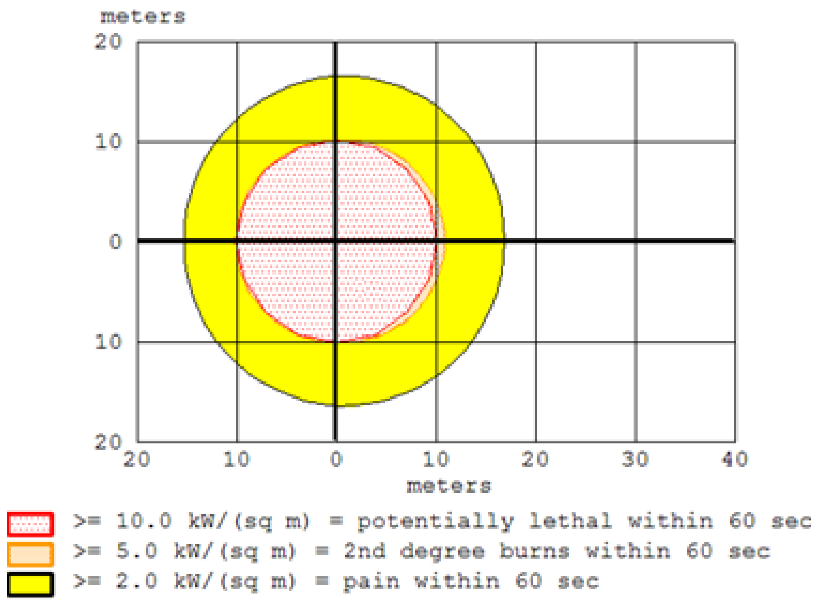

Figure 7.13: Thermal radiation threat zone

According to the modelling of jet fire in ALOHA, within 17 m of radius, first, second and third degree burns would occur as a result of heat radiation. Modelling of natural gas jet fire is also conducted for low temperature average value. It is seen that the radius of effect does not change seasonally. The results of this modelling can be found in Appendix D.

7.3. Natural Gas Vapour Cloud Explosion

In this scenario, it is assumed that there is a leak at the pipelines carrying natural gas to the cogeneration unit and the gas does not get ignited instantaneously, but instead gathers inside the building. There are two separate units in cogeneration unit of the manufacturing plant: the unit where turbines reside in and the unit where evaporators, etc. exist as it is shown in Figure 7.14. Both of these two confined areas include gas pipelines. Hence, modelling will be conducted for each area separately. Scenario will be modelled by Multi-Energy Vapour Cloud Explosion Model.

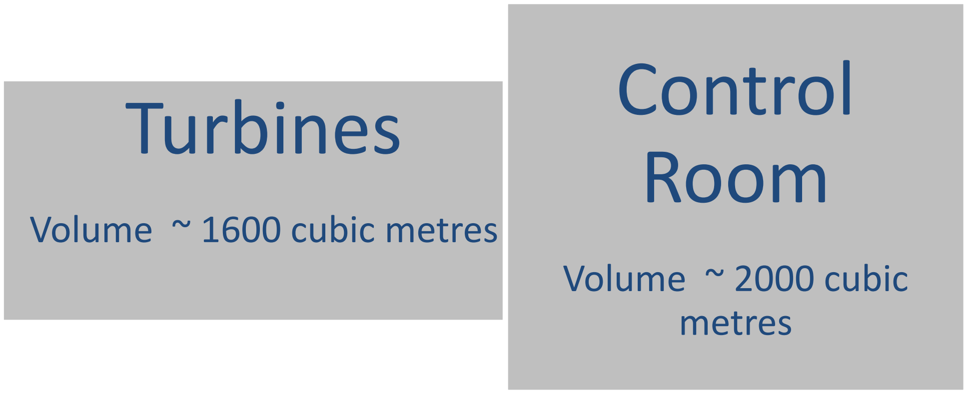

Figure 7.14: Cogeneration unit layout

As natural gas mostly composed of methane [68] while modelling the effects of explosion, natural gas can be assumed as pure methane for the ease of calculations.

Natural gas leaks through the pipelines and forms an explosive mixture in the air. First of all, the concentration of methane previous to explosion in building should be calculated and it should be checked whether this concentration is within flammable limits. Flammable limits for natural gas are between 5% and 15% [107]. Methane, on the other hand, has a flammability range within 5% and 15% as well [108].

Complete combustion of methane occurs as the reaction below:

$$\mathbf{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

Combustion of methane has the following properties which are set out in Table 7.9.

Table 7.9: Heat of Combustion of Methane [64]

Heat of Combustion (288 K, 1 atm) (MJ/m^3)	Stoichiometric Volume Ratio (%)	Heat of Combustion Stoichiometrically Mixed with Air (MJ/m^3)
34	9.5	3.23

To explain the Stoichiometric Volume Ratio in a more detailed manner:

CH_4 + $2O_2$ → CO_2 + $2H_2O$

1 mol 2 mol

1 V 2 V

2V O_2 is present in $2V \times \frac{100}{21} = 9.52\ V\ air$

Stoichiometric volume ratio of methane = $\frac{100\ V\ mixture}{9.52\ V\ air + 1\ V\ methane} = 9.5\ \%$

Stoichiometric Volume Ratio is the proportion of volume of air, necessary for complete combustion of methane, to volume of methane. This ratio is 9.5% for methane which means that 9.5 m^3 of air is necessary for 1 m^3 of methane to completely burn. While modelling the effects of natural gas (methane) explosion, efficiency of combustion will be 100%, hence the concentration of natural gas inside the building should be 9.5% just before combustion.

$$C_{methane,turbine} = \frac{\forall_{Methane-air\ mixture\ in\ turbine\ compartment}}{\forall_{Methane}} = \frac{1600}{x} = \frac{100}{9.5}$$

$$x = 152\ m^3\ methane$$

$$C_{methane,control} = \frac{\forall_{Methane-air\ mixture\ in\ Control\ compartment}}{\forall_{Methane}} = \frac{2000}{x} = \frac{100}{9.5}$$

$$x = 190\ m^3\ methane$$

Methane has a density of ρ = 0.656 g/L [73], (25°C and 1.0 atm)

$$M_{methane,turbine} = 152\ m^3\ \times \frac{656\ g}{m^3} = 99.7\ kg$$

$$M_{methane,control} = 190\ m^3\ \times \frac{656\ g}{m^3} = 124.64\ kg$$

Methane explosion is modelled according to Multi Energy Vapour Cloud Explosion Model of TNO [64].

7.3.1. Turbine Compartment

For this modelling, energy – scaled distance R will be used and corresponding overpressure values will be calculated. Table 7.10 shows calculation parameters.

Table 7.10: Calculated Sachs Scaled Distances for Various Real Distances

R (m)	$[E / P_0]^{1/3}$	$\bar{R}$
10	37.08	0.27
20	37.08	0.54

Table 7.10: Calculated Sachs Scaled Distances for Various Real Distances (cont'd)

R (m)	$[E / P_0]^{1/3}$	$\bar{R}$
50	37.08	1.35
100	37.08	2.70
350	37.08	9.44
700	37.08	18.88
3708	37.08	100

During calculations, Charge Combustion Energy is calculated as below:

$E = 3.23\ MJ/m^3 \times 1600\ m^3 = 5168\ MJ$

$$[E / P0]^{1/3} = \frac{5168 \times 10^6\ J}{101325\ Pa} = 37.08$$

Corresponding Sachs scaled distances used to read the dimensionless maximum side-on overpressure from Sachs scaled side-on peak overpressure of blast graph in Figure F.1 in Appendix F. Corresponding Sachs scale side-on blast overpressures, are converted to side-on blast overpressure as shown in Table 7.11. Table 7.12 illustrates the reals distance vs. side-on blast overpressure.

Table 7.11: Side-on Blast Overpressures

R (m)	$\bar{R}$	$\Delta\bar{P}_s$	P_0 (Pa)	ΔP_s (Pa)
10	0.27	1.0	101325	101325
20	0.54	0.86	101325	87139.50

Table 7.11: Side-on Blast Overpressures (cont'd)

R (m)	$\bar{R}$	$\Delta\bar{P}_s$	**P_0 (Pa)**	**ΔP_s (Pa)**
50	1.35	0.34	101325	34450.50
100	2.70	0.12	101325	12159
350	9.44	0.025	101325	2533.13
700	18.88	0.014	101325	1418.55
3708	100	0.0018	101325	182.385

Table 7.12: Real distance vs. Side-on blast overpressure

R (m)	**ΔP_s (Pa)**	**ΔP_s (psi)**
10	101325	14.5
20	87139.50	12.47
50	34450.50	4.93
100	12159	1.74
350	2533.13	0.3625
700	1418.55	0.203
3708	182.385	0.0261

Figure 7.15 demonstrates the overpressure vs. distance in case of such an explosion.

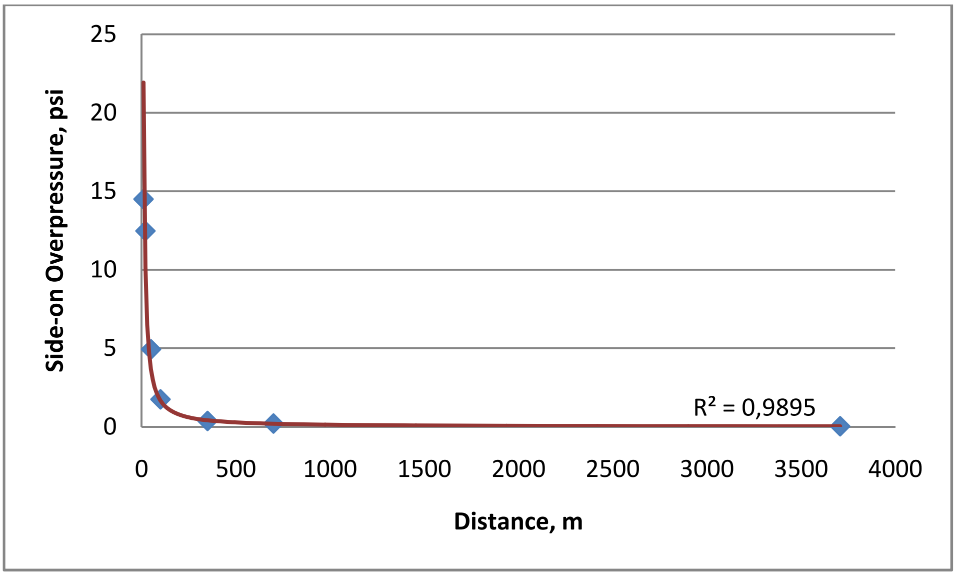

Figure 7.15: Side-on Overpressure vs. Distance

Probable effects of these pressures are explained in Table 7.13.

Table 7.13: Probable effects of overpressure caused by explosion

R (m)	**ΔP_s (psi)**	**Effects of side-on overpressure**
10	14.5	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
20	12.47	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
50	4.93	Collapse of buildings Probable serious injury or fatality of some occupants
100	1.74	Possible minor structural damage to buildings and severe damage to un-reinforced masonry load-bearing wall buildings Personnel injury from debris is likely

Table 7.13: Probable effects of overpressure caused by explosion (cont'd)

R (m)	**ΔP_s (psi)**	**Effects of side-on overpressure**
350	0.3625	Threshold of glass breakage No injury to occupants
700	0.203	Threshold of glass breakage No injury to occupants
3708	0.0261	Below regulatory concern

Such an explosion inside Turbine Department would cause a massive destruction. People within 20 m of the cogeneration unit would be killed and within 50 m there is a serious risk of fatality. On the other hand, the overpressure effect reaches the residential area around the facility, causing glasses to break. Glass breakage could seem to be an unimportant event; however, most of the injuries result from injuries due to glass breakage in case of such an explosion [109].

7.3.2. Control Room

In order to model natural gas explosion within the control room, energy scaled distance R and the corresponding overpressure values in accordance with Multi Energy Vapour Cloud Explosion Model of TNO. Table 10.70 summarizes the Sachs scaled distances vs. real distances.

Table 7.14: Calculated Sachs Scaled Distances for Various Real Distances

R (m)	**$[E / P_0]^{1/3}$**	$\bar{R}$
10	39.95	0.25
20	39.95	0.50

Table 7.14: Calculated Sachs Scaled Distances for Various Real Distances (cont'd)

R (m)	**$[E / P_0]^{1/3}$**	$\overline{R}$
50	39.95	1.25
100	39.95	2.50
350	39.95	8.76
700	39.95	17.52
3995	39.95	100

During calculations, Charge Combustion Energy is calculated as below:

$E = 3.23\ MJ/m^3 \times 2000\ m^3 = 6460\ MJ$

$[E / P_0]^{1/3} = \frac{6460 \times 10^6\ J}{101325\ Pa} = 39.95$

Corresponding dimensionless maximum side-on overpressure values can be read from Sachs scaled side-on peak overpressure of blast graph in Figure F in Appendix F. Corresponding Sachs scale side-on blast overpressures, are converted to side-on blast overpressure as shown in Table 7.15. Real distance vs. side-on blast overpressure can be seen in Table 7.16.

Table 7.15: Side-on Blast Overpressures

R (m)	$\overline{R}$	$\Delta\overline{P}_s$	P_0 (Pa)	ΔP_s (Pa)
10	0.25	1.0	101325	101325
20	0.50	0.95	101325	96258.75

Table 7.15: Side-on Blast Overpressures (cont'd)

R (m)	$\overline{R}$	$\Delta\overline{P}_s$	P_0 (Pa)	ΔP_s (Pa)
50	1.25	0.35	101325	35463.75
100	2.50	0.14	101325	14185.5
350	8.76	0.029	101325	2938.425
700	17.52	0.015	101325	1519.875
3708	100	0.0018	101325	182.385

Table 7.16: Real distance vs. Side-on blast overpressure

R (m)	ΔP_s (Pa)	ΔP_s (psi)
10	101325	14.5
20	87139.50	13.775
50	34450.50	5.075
100	12159	2.03
350	2533.13	0.4205
700	1418.55	0.2175
3708	182.385	0.0261

Figure 7.16 demonstrates the overpressure vs. distance in case of such an explosion.

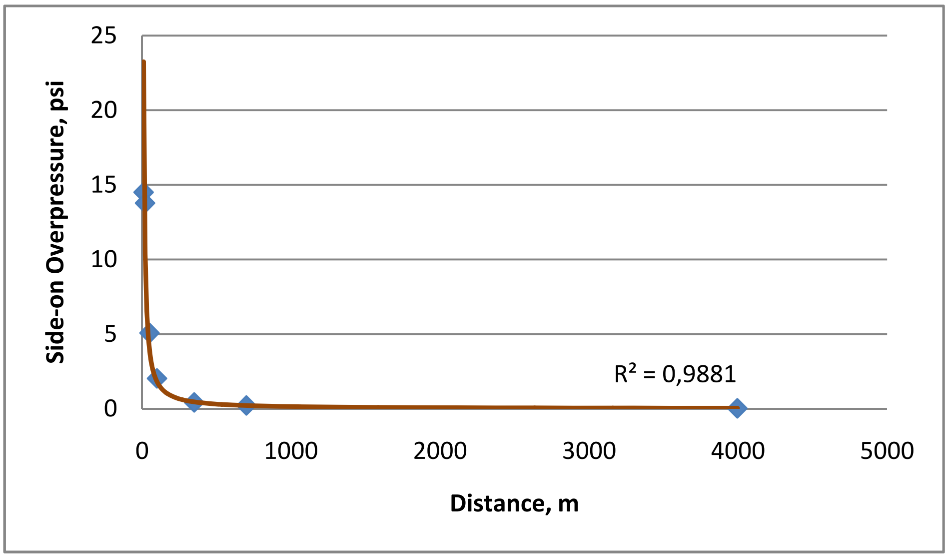

Figure 7.16: Side-on Overpressure vs. Distance

Probable effects of these pressures are explained in Table 7.17 below:

Table 7.17: Probable effects of overpressure caused by explosion

R (m)	**ΔP_s (psi)**	**Effects of side-on overpressure**
10	14.5	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
20	13.775	Probable total destruction of non-blast-resistant buildings Probable 100% fatalities
50	5.075	Collapse of buildings Probable serious injury or fatality of some occupants

Table 7.17: Probable effects of overpressure caused by explosion (cont'd)

R (m)	**ΔP_s (psi)**	**Effects of side-on overpressure**
100	2.03	Local failure of isolated parts of buildings and collapse of un-reinforced masonry load-bearing wall buildings Possible serious injury or fatality of some occupants
350	0.4205	Threshold of glass breakage No injury to occupants
700	0.2175	Threshold of glass breakage No injury to occupants
3708	0.0261	Below regulatory concern

Such an explosion inside Control Room would have worse consequences than that of an explosion inside Turbine Compartment. The effects are similar in the same distances, however an explosion in Control Room would have overpressure effects beyond 700 m.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This study presents semi-quantitative risk assessment in a textile facility. The study was conducted within the scope of IPPC Directive and fire and explosion risk with regards to hazardous substances within the manufacturing plant were assessed. The receptor of the risk assessment study was defined as the people.

The study was composed of six phases. The first phase; initiation phase was composed of on-desk and walk-through inspections in the manufacturing plant. Based on findings from this stage, present hazards were identified via hazard identification phase. Hazard identification stage included utilization of checklist method. Afterwards the hazardous activities/situations were highlighted; consequence and frequency analysis were conducted. Risk evaluation forms were used to integrate both consequence and frequency analysis and then to calculate a mathematical risk value.

Consequence and frequency analysis were conducted after defining categories for consequences and frequencies. Category definitions were formed based on the information gathered during initiation phase (scope of the study, receptors, etc.) and consequence and frequency analysis was conducted according to the information based on hazard identification phase (incident statistics, interviews with employees, literature review, etc.). Risk is calculated as 497,260 $/year.

Conclusions derived from the study can be summarized as follows:

- Highest risks in the denim manufacturing plant can be listed as spreading risk of fire or explosion due to several potential causes, dust explosion risk, natural gas vapour cloud explosion or jet fire risk.

- Highest risk is observed in main warehouse. According to decreasing risk level, departments can be ranked as sizing department, cogeneration unit, finishing department, weaving department, indigo department and cotton mill.
- According to mathematical modelling studies, a dust explosion in the main warehouse led by bursting of one package of starch is likely to kill workers within 22 m and destroy the buildings within the radius. Injury is potential at a distance of 30 m. Glass breakage threshold is exceeded up to a distance of 84 m.
- As a result of modelling dust explosion in sizing department, it is found that workers may be killed within the boundaries of the sizing department. Injuries may occur within a radius of 22 m. The effects of such an explosion may be present up to 80 m.
- A primary explosion in sizing department could lead to a secondary explosion. Such an explosion is much more destructive than primary dust explosion, having a larger radius of effect. It is likely to kill workers within 50 m, which is far beyond the boundaries of the denim manufacturing plant. Such an explosion could also affect the industrial zone and other textile mill which in vicinity. Injury can occur within a radius of 68 m. The effects of overpressure (glass breakage breakthrough point) reach up to 260 m
- Dust explosion in indigo department would result in building destruction and fatalities within 20 m of effect radius.
- Jet fire due to natural gas leak would affect a radius of 17 m. First, second and third degree burns would occur as a result of heat radiation resulting from a jet fire.
- Natural gas explosion within cogeneration unit would result in fatalities of people within 20 m of radius. There is a serious risk of fatality within 50 of radius. Moreover, up to 3700 m of distance, glasses would break as a result of overpressure. Most of the injuries are led by glass breakage in case of such an explosion.

Consequently; risk of a fire or explosion resulting from chemical hazards in the mill, which would affect the employees of the manufacturing mill or the residential people around the plant, is considered as low. Even though the risk is forecasted as low, when the events to present highest risks are modelled, it is calculated that the most destructive event would be natural gas explosion. Natural gas explosion has the highest radius of effect; the destructive effect can reach the residential people living around the facility. Therefore, facility management should take the necessary precautions to reduce the risk; especially special measures should be implemented in cogeneration unit.

Plant management should take the necessary precautions which are listed in Risk Evaluation Forms in Appendix B. The plant managers may find the cost of implementation of these suggestions and compare this cost to the cost of present risk. This will enable the plant managers to conduct cost/benefit analysis and give a strong background whilst deciding to implement these suggestions. For continuous risk assessment, the study should be conducted regularly, hence new hazards may be identified and the effects of suggestions can be set clearly. Contingency plans should be revised according to this study.

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APPENDIX A

CHECKLIST

In Table A.1, the checklist prepared for the study is presented. Chemical names are not given in this table, due to confidentiality of commercial chemicals.

Table A.1: Checklist

APPENDIX B

RISK EVALUATION FORMS

In Table B.1 consequence and frequency categorization is presented. Table B.2, B.3, B.4, B.5, B.6, B.7. B.8 illustrates the risk evaluation forms prepared for the study in a more detailed way. In risk evaluation forms, suggested precautions are also demonstrated.

Table B.1: Risk Categorization

Table B.2: Risk Evaluation Form of Main Warehouse

Table B.3: Risk Evaluation Form of Finishing Department

Table B.4: Risk Evaluation Form of Indigo Department

Table B.5: Risk Evaluation Form of Sizing Department

Table B.6: Risk Evaluation Form of Weaving Department

Table B.7: Risk Evaluation Form of Cotton Mill

Table B.8: Risk Evaluation Form of Cogeneration Unit

APPENDIX C

STARCH EXPLOSION IN MAIN WAREHOUSE MODELLED FOR A SCENARIO OF 10 PACKAGES

In Appendix C, modelling results of a scenario based on 10 packages of starch bursting simultaneously. During modelling, explosion yield of 0.03 and 0.1 are both used.

Explosion of 10 packages of Starch in the Main Warehouse

A bag of starch contains 25 kg of starch. A fork lift can carry up to 10 bags of starch packages. This means that at most and under the worst circumstances 250 kg of starch could be dropped, resulting in dispersion of some dust in the air.

$M_{starch} = 250\ \text{kg}$
$Q_{starch} = 17570\ \text{J/g} = 17.570\ \text{MJ/kg}$

However, it would be unrealistic to assume that all of this starch will go into the dust cloud. Hence, we assume that 1/5 of 250 kg starch participates in the cloud:

$M_{starch,cloud} = 50\ kg$

Volume of main warehouse is 3760 m^3. However, starch which is spread onto the ground cannot cover this huge volume. Instead, the dispersion will occur in a smaller space in the warehouse. The affected volume is assumed as 1/10 of warehouse.

The dust concentration range, within which flames can propagate through a cloud of combustible dust in air, spans from the order of 50 g/m^3 to a few kg/m^3 [110]. The lower boundary of this span, in other words, the lower explosion limit value which is specific to starch is between 30-60 g/m^3 [111].

To check whether 50 kg starch forms a dust cloud within 376 m^3 is within explosive limits or not:

$\frac{50\times10^3 g}{376\ m^3} \cong 132.9\ \mathrm{g/m3}\ \rightarrow$ within explosive limits.

To model starch explosion in the main warehouse, it can be assumed that our fuel is starch. According to "Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs" of TNO, the equivalent charge weight of TNT can be calculated as below:

TNT Equivalence Method with Yield Factor 0.03

Braise and Simpson who developed basic TNT model From analysis of three VCE incidents they obtained values of the yield factor of 0.03-0.04, and on this basis proposed for use tentative values, intended to be conservative, of 0.02 in the near field and 0.05 in the far field, taken as that where the peak overpressure is 1 psi or less [20].

As the warehouse is a confined space, to estimate a more realistic TNT equivalence mass, the yield factor is taken as 0.03. This value is taken as 0.03 by CCPS [65] as well.

$$W_{TNT} = 0.03\frac{50\ \times 17.570}{4.68} = 5.63\ kg$$

Amount of starch that could be dispersed accidentally is equal to the amount of approximately 5.63 kg TNT. To calculate the overpressure effects caused by starch explosion, Hopkinson-scaled distances should be used:

Accordingly for real distances of 5, 10, 20, 25 and 30 m:

$$\check{R} = \frac{5}{5.63^{1/3}} = 2.81$$

$$\check{R} = \frac{10}{5.63^{1/3}} = 5.62$$

$$\check{R} = \frac{20}{5.63^{1/3}} = 11.24$$

$$\check{R} = \frac{25}{5.63^{1/3}} = 14.05$$

$$\check{R} = \frac{30}{5.63^{1/3}} = 16.7$$

$$\check{R} = \frac{32}{5.63^{1/3}} = 18$$

$$\check{R} = \frac{50}{5.63^{1/3}} = 28.1$$

Corresponding overpressure values are read from Side-on overpressure vs. Hopkinson distance graph in Figure E.1 in Appendix E. Corresponding distance and pressure values are listed in Table C.1.

Table C.1: Corresponding values of distance and pressure

Real Distance (m)	**Log Real Distance**	**Side-on Overpressure (bar)**	**Dimensionless Overpressure**	**Log Dimensionless Pressure**
5	0.70	1.600	1.580	0.199
10	1.00	0.400	0.395	-0.403
20	1.30	0.130	0.128	-0.893
25	1.40	0.110	0.109	-0.963
30	1.48	0.081	0.080	-1.097

Table C.1: Corresponding values of distance and pressure (cont'd)

32	1.51	0.070	0.069	-1.161
50	1.70	0.039	0.038	-1.420

$Dimensionless\ Overpressure = \frac{Overpressure\ (bar)}{P_{atm}\ (bar)}$ $where\ 1\ atm = 1.01325\ bar$ [112].

Overpressure effect vs. distance is illustrated in Figure C.1. In order to show the effects in a linear form, logarithmic values for pressure and distance are used.

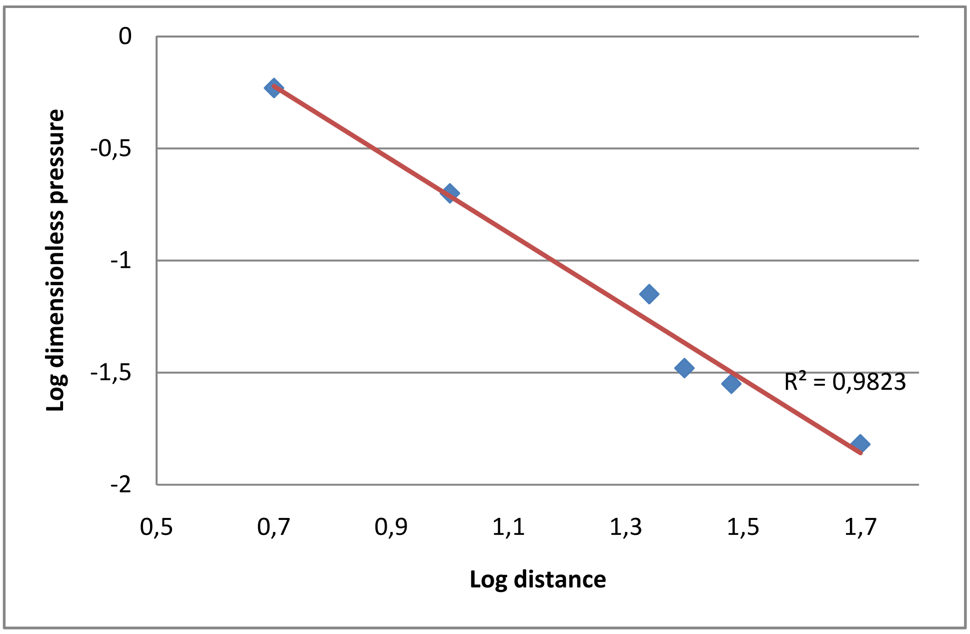


Figure C.1: Side-on overpressure vs. distance

Effects of side-on overpressures are listed in Table C.2.

Table C.2: Effects of side-on overpressure [59]

Peak Side-On Overpressure, bar*	**Consequences to building**	**Consequences to Building Occupants**
0.0138	Threshold of glass breakage	No injury to occupants
> 0.0345	Significant repairable cosmetic damage is possible	Possible occupant injury from glass breakage and falling overhead fixtures.
>0.069	Possible minor structural damage to buildings and severe damage to un-reinforced masonry load-bearing wall buildings	Personnel injury from debris is likely
>0.138	Local failure of isolated parts of buildings and collapse of un-reinforced masonry load-bearing wall buildings	Possible serious injury or fatality of some occupants
>0.207	Collapse of buildings	Probable serious injury or fatality of some occupants
>0.69	Probable total destruction of non-blast-resistant buildings	Probable 100% fatalities

*1 bar = 14.50378 psi [113]

According to the effects of overpressure on people and buildings, probable results of the modelled starch explosion are summarized in Table C.3.

Table C.3: Distance vs. pressure values and probable effects as a result of modelled explosion

Real Distance (m)	Overpressure (bar)	Probable Effect
5	1.6	Probable total destruction of non-blast resistant buildings Probable 100% fatalities
10	0.4	Collapse of buildings Probable serious injury or fatality of some occupants
32	0.070	Possible minor structural damage to buildings and severe damage to unreinforced masonry load-bearing wall buildings Personnel injury from debris is likely
50	0.039	Significant repairable cosmetic damage is possible to buildings Possible occupant injury from glass breakage and falling overhead fixtures
1351.2	0.014	Just below regulatory concern*

*From Figure E.1 in Appendix E, it can be seen that peak side overpressure value of 0.0138 bar can be observed at Hopkinson scaled distance of 80. Corresponding real distance to that distance is 1351.2 m.

According to Table C.3, such an explosion is likely to cause serious damage to buildings and severe injuries or fatalities to people within 32 m of radius. Also, there is a possibility that injuries may occur within a radius of 50 m and that threshold for glass breakage can be exceeded upto 1351.2 m as a result of modelled explosion.

TNT Equivalence Method with Yield Factor 0.1

US EPA requires the yield factor as 0.1 by the law [50]. Also, Exxon [64] suggests yield factor as 0.1 for partially confined or obstructed clouds.

$$W_{TNT} = 0.1 \frac{50 \times 17.570}{4.68} \cong 18.8\ kg$$

Efficiency factor determines the amount of fuel present in the cloud. Hence, as the efficiency/yield factor increases, amount of TNT increases as well.

According to “Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs” of TNO, to calculate the overpressure effects caused by starch explosion, Hopkinson-scaled distances should be used:

Accordingly for real distances of 5, 10, 20, 25 and 30 m:

$$\check{R} = \frac{5}{18.8^{1/3}} = 1.88$$

$$\check{R} = \frac{10}{18.8^{1/3}} = 3.76$$

$$\check{R} = \frac{20}{18.8^{1/3}} = 7.52$$

$$\check{R} = \frac{25}{18.8^{1/3}} = 9.40$$

$$\check{R} = \frac{30}{18.8^{1/3}} = 11.28$$

$$\check{R} = \frac{50}{18.8^{1/3}} = 18.8$$

$$\check{R} = \frac{212.7}{18.8^{1/3}} = 80$$

Corresponding overpressure values are read from side-on overpressure vs. Hopkinson scale distance graph in Figure E in Appendix E. Corresponding distance and pressure values are listed in Table C.4.

Table C.4: Corresponding values of distance and pressure

Real Distance (m)	Log Real Distance	Side-on Overpressure (bar)	Dimensionless Overpressure	Log Dimensionless Pressure
5	0.70	3.90	3.85	0.590
10	1.00	0.83	0.82	-0.086
20	1.30	0.25	0.24	-0.620
25	1.40	0.16	0.16	-0.796
30	1.48	0.14	0.14	-0.854
50	1.70	0.07	0.07	-1.155
181	2.26	0.013	0.013	-1.89

Real distances and overpressure values are illustrated in Figure C.2.

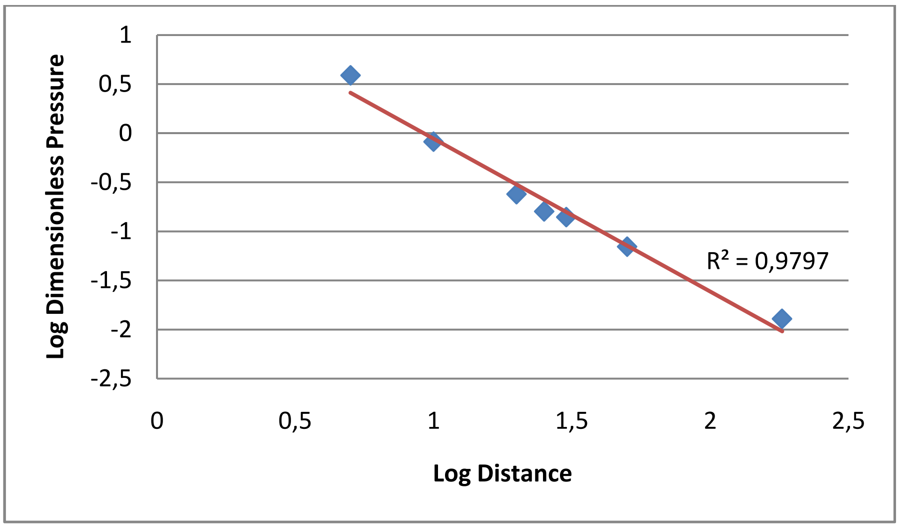


Figure C.2: Side-on overpressure vs. distance

Table C.5 summarizes probable results of the modelled explosion of 50 kg starch with explosion yield 0.1.

Table C.5: Distance vs. Overpressure and Probable Effect of the Modelled Explosion

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
5	3.9	Probable total destruction of non-blast resistant buildings Probable 100% fatalities
10	0.83	Probable total destruction of non-blast resistant buildings Probable 100% fatalities
20	0.25	Collapse of buildings Probable serious injury or fatality of some occupants
25	0.16	Local failure of isolated parts of buildings and collapse of un-reinforced masonry load-bearing wall buildings Possible serious injury or fatality of some occupants
30	0.14	Local failure of isolated parts of buildings and collapse of un-reinforced masonry load-bearing wall buildings Possible serious injury or fatality of some occupants
50	0.07	Possible minor structural damage to buildings and severe damage to unreinforced masonry load-bearing wall buildings Personnel injury from debris is likely
181	0.013	Below regulatory concern

According to Table C.5, such an explosion is likely to cause serious damage to buildings and severe injuries or fatalities to people within 30 m of radius. Also, injury is possible within the radius of 50 m. Effects of explosion extend up to 181 m. Therefore, this explosion may affect the surrounding industries, but not the residential areas.

TNT Equivalence Method with Yield Factor 0.03

Assuming an explosion yield of 0.03, the results are shown in Table C.6. Corresponding overpressure values are read from Side-on overpressure values vs. Hopkinson scaled distance graph in Figure E in Appendix E. Corresponding distance and pressure values for modelling of 5 kg starch explosion with explosion yield of 0.3 are listed in Table C.6.

Table C.6: Corresponding values of distance and pressure

Real Distance (m)	Log Real Distance	Side-on Overpressure (bar)	Dimensionless Overpressure	Log Dimensionless Pressure
5	0.70	0.33	0.33	-0.48
10	1.00	0.14	0.14	-0.85
15	1.18	0.07	0.07	-1.15
20	1.30	0.046	0.046	-1.34
25	1.40	0.033	0.033	-1.48
30	1.48	0.028	0.028	-1.55
50	1.70	0.014	0.014	-1.85
56	1.82	0.013	0.013	-1.89

Real distances and overpressure values are illustrated in Figure C.3.

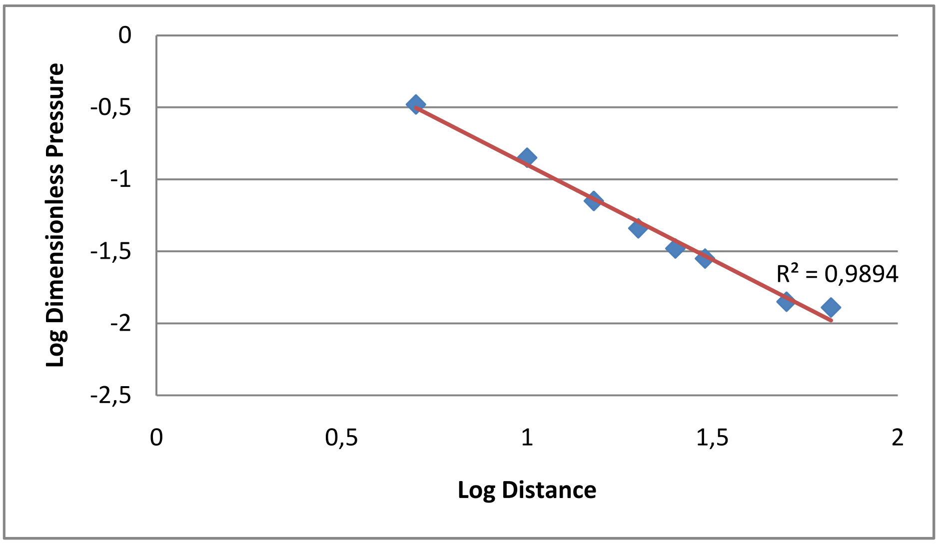


Figure C.3: Side-on overpressure vs. distance

Table C.7 summarizes probable results of the modelled starch explosion.

Table C.7: Distance vs. Overpressure and Probable Effects of Modelled Explosion

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
5	0.33	Collapse of buildings Probable serious injury or fatality of some occupants
10	0.14	Local failure of isolated parts of buildings and collapse of unreinforced masonry load-bearing wall buildings Possible serious injury or fatality of some occupants

Table C.7: Distance vs. Overpressure and Probable Effects of Modelled Explosion (cont'd)

Real Distance (m)	**Overpressure (bar)**	**Probable Effect**
15	0.07	Possible minor structural damage to buildings and severe damage to unreinforced msasonry load bearing wall buildings Personnel injury from debris is likely
20	0.046	Significant repairable cosmetic damage is possible to buildings Possible occupant injury from glass breakage and falling overhead fixtures
56	0.013	Below regulatory concern

According to Table C.7, such an explosion is likely to kill workers within 10 m and destroy the buildings within the radius. Also, injuries may occur within 20 mtres of radius. Overpressure above glass breakage threshold can be observed up to 56 m of distance. The breakthrough point towards glass breakage could injure people as well [60].

APPENDIX D

NATURAL GAS JET FIRE MODELLING AT LOW TEMPERATURE AVERAGE VALUE

In Appendix D, modelling results of a scenario based on low temperature average value is presented. This modelling is carried out to see whether there is a difference in the effects of jet fire with respect to seasonal changes.

Modelling for Low Temperature Average Value

In this section, temperature is entered as 3.1 ^{o}C, Stability Class is assumed to be D, wind speed is assumed as 3 m/s. Complete cloud cover is also selected. Selections are illustrated in Figure D.1.

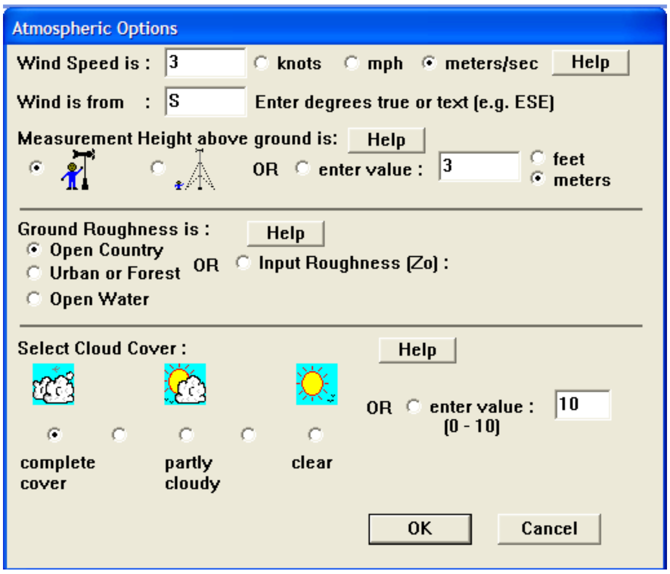


Figure D.1: Input for atmospheric values

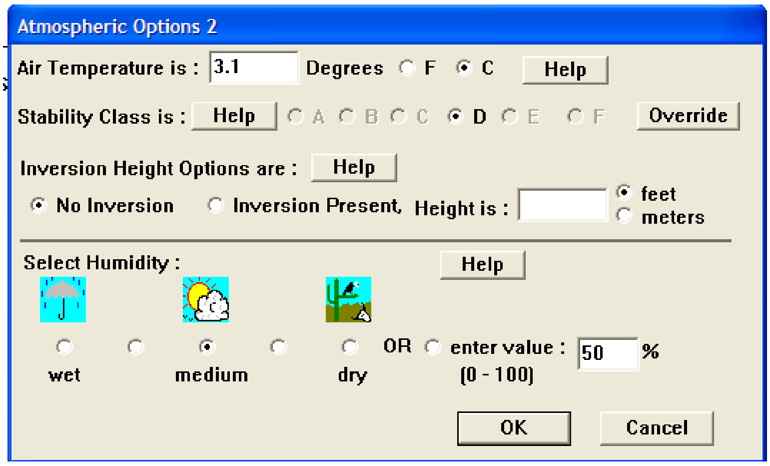
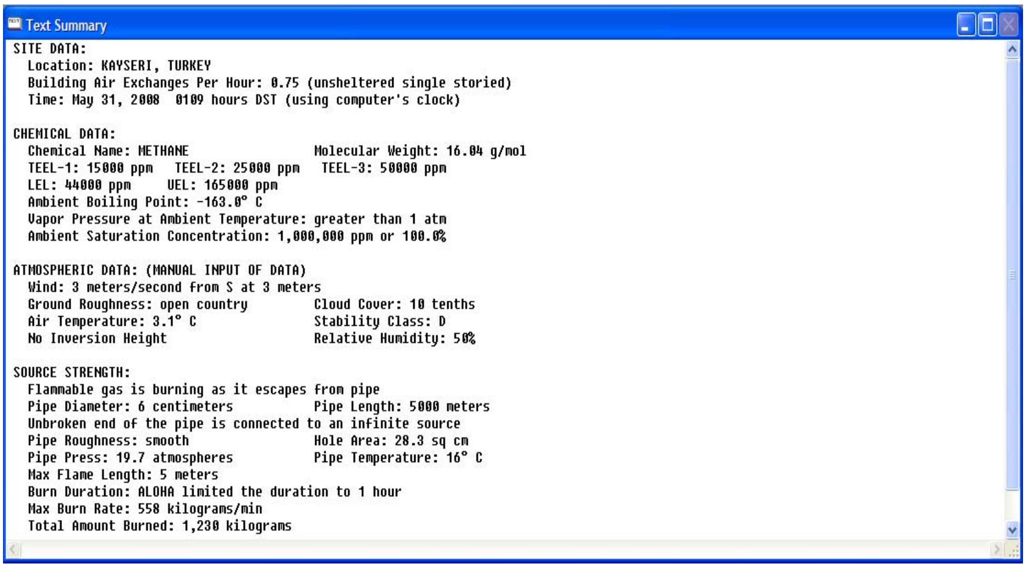


Figure D.2: Data entry of atmospheric values

Air temperature average value for winter season in Kayseri is entered into the user interface as can be seen in Figure D.2. Chemical, source model, and gas pipeline input are selected as the same as high temperature average value modelling.

Figure D.3 shows the text summary of the modelling.



Text Summary

```
SITE DATA:
  Location: KAYSERI, TURKEY
  Building Air Exchanges Per Hour: 0.75 (unsheltered single storied)
  Time: May 31, 2008  0109 hours DST (using computer's clock)

CHEMICAL DATA:
  Chemical Name: METHANE                 Molecular Weight: 16.04 g/mol
  TEEL-1: 15000 ppm   TEEL-2: 25000 ppm   TEEL-3: 50000 ppm
  LEL: 44000 ppm     UEL: 165000 ppm
  Ambient Boiling Point: -163.0° C
  Vapor Pressure at Ambient Temperature: greater than 1 atm
  Ambient Saturation Concentration: 1,000,000 ppm or 100.0%

ATMOSPHERIC DATA: (MANUAL INPUT OF DATA)
  Wind: 3 meters/second from S at 3 meters
  Ground Roughness: open country          Cloud Cover: 10 tenths
  Air Temperature: 3.1° C                 Stability Class: D
  No Inversion Height                     Relative Humidity: 50%

SOURCE STRENGTH:
  Flammable gas is burning as it escapes from pipe
  Pipe Diameter: 6 centimeters            Pipe Length: 5000 meters
  Unbroken end of the pipe is connected to an infinite source
  Pipe Roughness: smooth                  Hole Area: 28.3 sq cm
  Pipe Press: 19.7 atmospheres            Pipe Temperature: 16° C
  Max Flame Length: 5 meters
  Burn Duration: ALOHA limited the duration to 1 hour
  Max Burn Rate: 558 kilograms/min
  Total Amount Burned: 1,230 kilograms
```

Figure D.3: Text summary of jet fire resulting from natural gas leak

Thermal radiation threat zone of such a jet fire could be seen in Figure D.4.

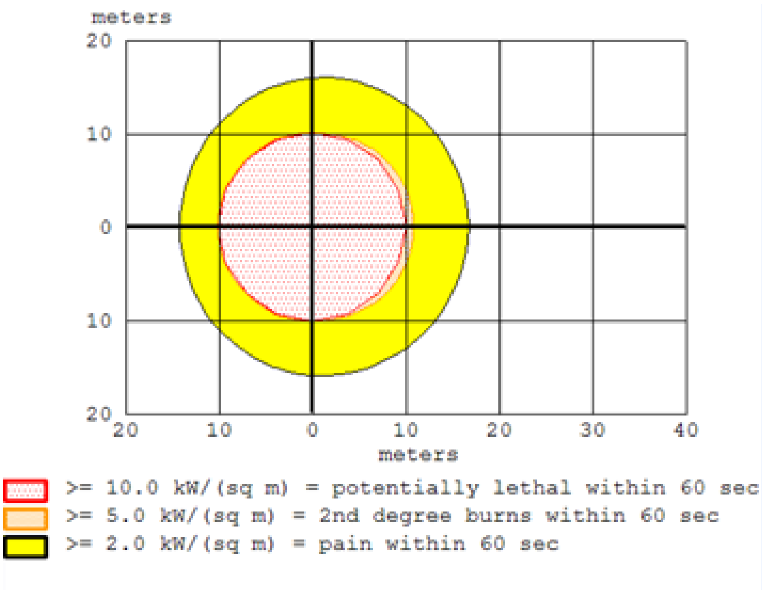


Figure D.4: Thermal radiation threat zone

According to the modelling of jet fire in ALOHA, within 17 m of radius, first, second and third degree burns would occur as a result of heat radiation. As can be seen, the change in ambient temperature and atmospheric conditions does not affect the consequence of jet fire in terms of radius of effect.

APPENDIX E

HOPKINSON SCALED TNT CHARGE BLAST GRAPH

In Appendix E Hopkinson-scaled TNT charge blast is demonstrated. Figure E.1 shown this graph illustrating the relation between side-on overpressure and scaled distance.

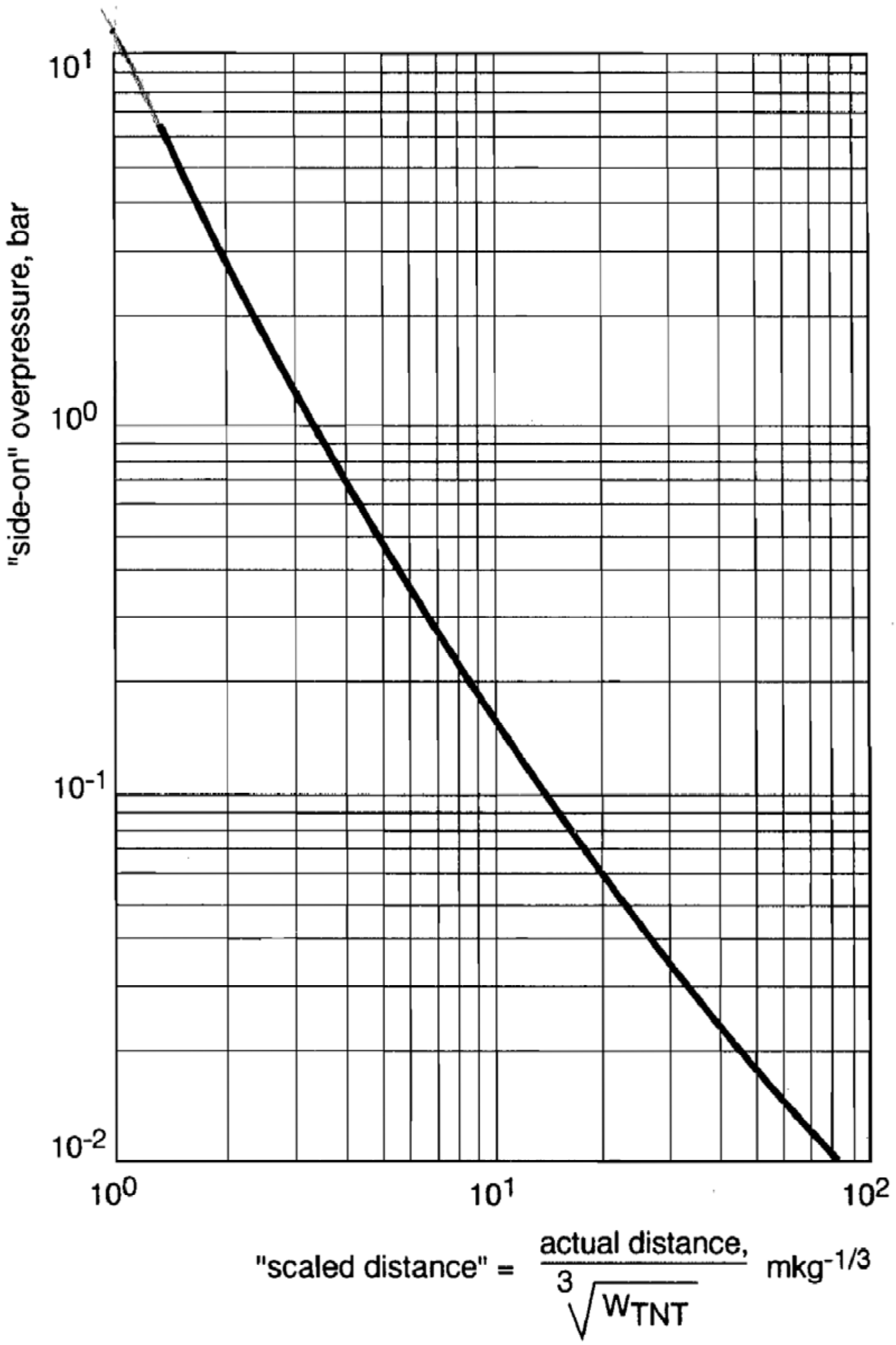


Figure E.1. Hopkinson-scaled TNT Charge Blast Graph [65]

APPENDIX F

SACHS SCALED TNT CHARGE BLAST GRAPH

In Appendix F Sachs scaled side-on peak overpressure of blast from a hemispherical fuel-air charge is presented. Figure F.1 shows this graph demonstrating the relation between dimensionless side-on overpressure and combustion energy-scaled distance.

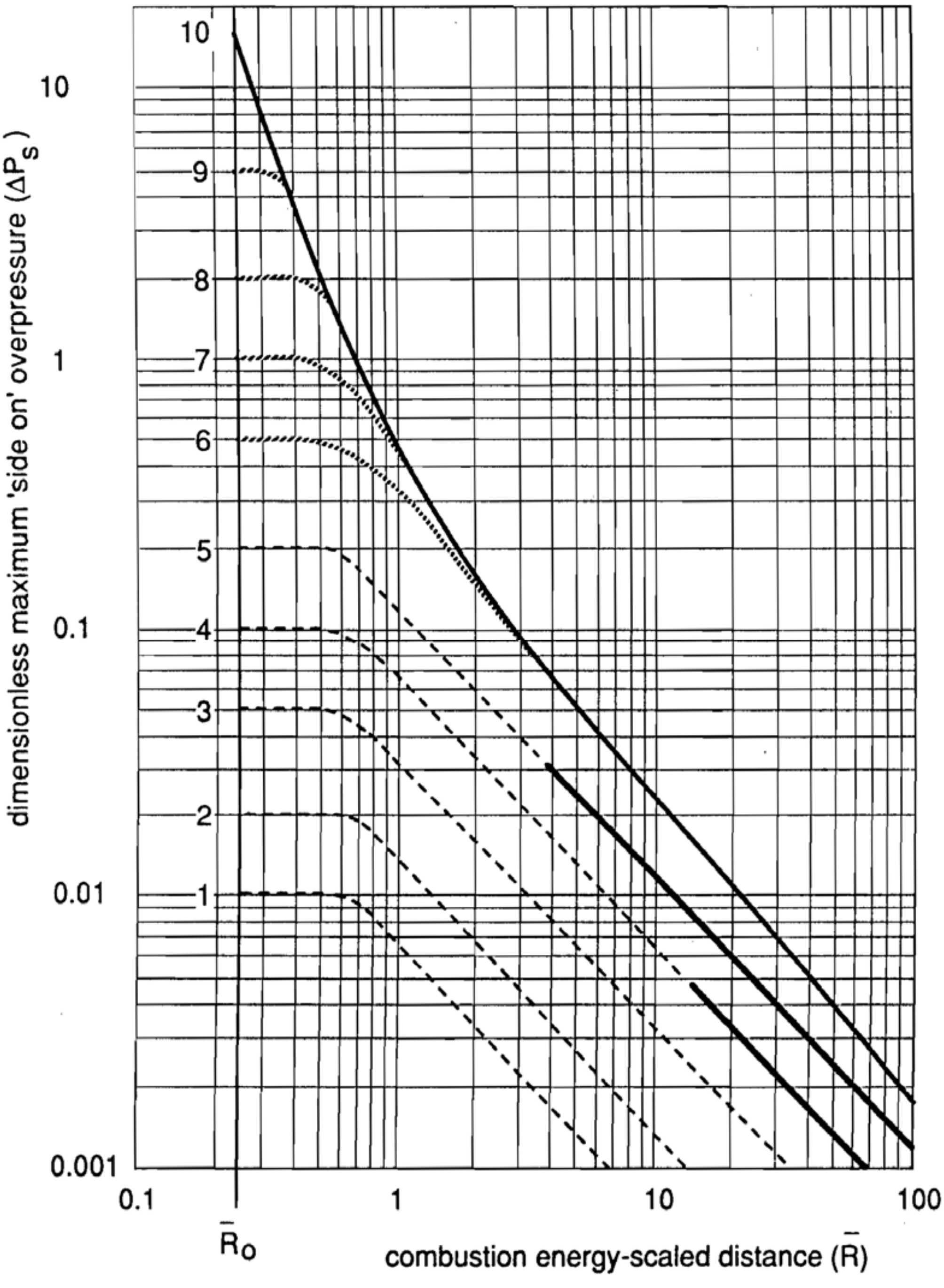


Figure F.1: Sachs scaled side-on peak overpressure of blast from a hemispherical fuel-air charge [65]